Snow cover basal ice layer changes over Northern Eurasia since 1966

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Abstract
An analysis is made of changes in basal ice crust layer characteristics from snow cover surveys made at 958 Russian stations since 1966. The analysis revealed that substantial changes have occurred in response to two competing processes: an increase in thaws associated with strong regional warming and an increase in the duration of the basal ice layer presence on the ground, and a shortening of the snowmelt period associated with a decrease in basal ice layer event frequency and severity. The latter appears to be the more significant process over the past 40 years. Our findings support the notion that the entire spring snowmelt process has become shorter in duration and more intense when taking into account a concomitant trend toward increasing snow depths over large regions of Russia. A more intense spring melt period has important consequences for spring flood dynamics and deserves further study.

Keywords: snow cover, basal ice crust, Northern Eurasia, climate change

1. Introduction

In many parts of the world the melting of seasonal snow cover can be a lengthy process. The initial amount of heat that ‘arrives’ to the snowpack might be insufficient for complete snowmelt, during the colder nights refreeze of the melted snow may occur (thus creating the basal ice layers), and a new cold front (or the departure of the warm front that initiated melt) can decrease temperatures below the freezing point again and stop the snowmelt completely (Gray and Male1981, Pomeroy and Brun 2001). Even the first such melt initiates a process of snow metamorphosis on its surface, changing snow albedo and generating snow crust, as well as on its bottom, generating a basal ice layer (figure 1(A)). Melting of snow cover in the high Arctic begins at below-freezing air temperatures owing to the influence of solar radiation. The process of melting is most intense when the air temperature increases to −5 or −4 °C, and the total solar radiation reaches values of 600 W m−2. With further increases in the air temperature, the role of solar heating in melting the snow decreases (Radionov et al 1996). Over Russia, the average duration of the snowmelt process exceeds one month but is decreasing (figure 1(B)).

Once formed, the crusts will not disappear until complete snowmelt. Furthermore, these crusts have numerous modes of impact on the wild birds and animals in the Arctic environment, as well as on domesticated reindeers. In extreme cases, the crusts may kill some wild species and prevent reindeers’ migration and feeding. As yet there have been no studies of large-scale changes in the basal ice crust over Eurasia. During the period of widespread instrumental observations in Northern Eurasia (since 1881), the annual surface air temperature has increased by 1.5 °C (over Northern Asia by 1.8 °C and in the winter season by 3 °C; Groisman and Soja 2009). Close to the north in the Arctic Ocean, the late summer sea ice extent has decreased by 40% (Serreze et al 2007, Levinson and Lawrimore 2008, Groisman and Soja 2009) providing a near-infinite source of water vapor for the dry Arctic atmosphere in the early cold season months. As
a result of these changes during the past 50 years, (a) in autumn the number of days with snow on the ground has not changed noticeably despite the strong temperature increase in this season (Groisman et al. 2006); (b) in late spring, the snow cover extent has decreased, retreating by 1–2 weeks earlier (Groisman et al. 2006, Robinson 2009); and (c) in winter the maximum snow depth has increased over most of Russia (Bulygina et al. 2007, 2009b) with the increases being mainly confined to the western and central part of the country. There is also evidence of more frequent thaw days over northern latitudes of western Eurasia (Groisman et al. 2003, McBean et al. 2005). For example, in Fennoscandia in the second half of the 20th century, the number of days with winter thaw increased by six days in 50 years, or by 35% (Groisman 2010). Spring warming and earlier snowmelt appear to be a hemispheric phenomenon (Déry and Brown 2007, Robinson 2009) which suggests that the ‘shoulder’ spring period when the basal ice layer remains on the ground may be shortening (cf., figure 1(b)). This notion is supported by the ‘state of the ground’ observations (Groisman et al. 2006). Their analyses show that in the past 50 years the statistically significant increase of the duration of the period with ‘unfrozen ground’ is compensated, not by an appropriate decrease of days with snow cover, but by a statistically significant reduction of the ‘intermediate period’ duration (when only remnants of snow cover, frozen bare soil, and ice glaze are observed). Keeping in mind potential detrimental impacts of winter thaws and associated basal ice layer development, it is worthwhile to study directly what are the major features of the basal ice layer over Eurasia and what are their dynamics. The following sections present a description of the data and basal ice layer climatology (sections 2 and 3, respectively), with an analysis of changes in basal ice layer characteristics over the Russian Federation from 1967 to 2007 in section 4. The analysis includes crust characteristics of practical importance for reindeer husbandry, transportation, and agriculture. A summary and discussion of the results is provided in section 5.

2. Data and their pre-processing

For the purpose of this study, we employed the national snow survey data set archived at the Russian Institute for Hydrometeorological Information (State Committee on Hydrometeorology and Environment Protection of the USSR 1985, Sherstyukov et al. 2007). The dataset has routine snow surveys that run throughout the cold season every ten days (every five days during the intense snowmelt) at all meteorological stations of the former USSR, thereafter, in Russia since 1966. Prior to 1966 snow surveys are also available, but the methodology of observations changed substantially in that year. Therefore, this analysis includes only data from Russian stations with more-or-less complete data from 1966 to 2007 (the 958 stations shown in figure 2). The snow year was defined from July of the previous year and to June of the current year.

Snow surveys were run separately along representative 1–2 km transects for different land cover types (fields, forest, and ravines5). Snow depth measurements were made at 10 (forest) to 20 (field) meter intervals with a more comprehensive suite of measurements at 100–200 m intervals including snow density, state of the ground (frozen or not), depths of the melt water layer, presence of wet snow and basal ice layer. Other snow cover information available for analysis included: basal ice layer, the fraction of snow cover in the vicinity of the station, its spatial homogeneity and type (old, wet, etc), mean characteristics of snow crust, maximum and minimum snow depth, mean density, mean depth of wet snow, snow water equivalent, depth of the water layer and total water storage above the surface, and finally two basal ice layer characteristics, which are the mean thickness and fraction along the survey pass. The last two characteristics present the input information for our study.

Regional analysis of snow crust data was carried out using Russian national climate monitoring regions (Alisov 1956, Bulygina et al. 2003). Maps (climatology, trends) are presented mostly for visualization purposes. Major conclusions about crust changes are only made using area-averaged time series where some measure of statistical significance can be attached to the results.

4 It should be noted that these surveys have continued in the Baltic States, Belarus, the Ukraine, and Kazakhstan and can be included in an expanded analysis when data become available to the research team.

5 Separate snow surveys in ravines are infrequent (are consistently conducted at only a handful of stations), are run mostly in the steppe and forest-steppe climatic zones, and are not assessed in this study.
The area-averaging technique follows Groisman et al. (2005) using station values converted to anomalies with respect to a common reference period (in this study, 1967–2007). Anomalies were arithmetically averaged first within $1^\circ N \times 2^\circ E$ grid cells and thereafter by a weighted average derived over the regions shown in figure 2. This approach provides a more uniform spatial field for averaging. Past experience has shown it delivers results that are close to optimal averaging routines (cf, Kagan 1997) without requiring information about the spatial covariance function.

One more precaution in pre-processing of the basal ice layer data was employed. For each survey course, the observers report two basal ice layer values when they exist: a fraction of the course with the basal ice layer presence and the mean crust thickness. Occasionally, along the course they can run across a frozen stream and/or a mini-pond frozen within the micro-relief. To ensure that we were analyzing the larger, more spatially uniform basal ice layer phenomena, we applied a minimum threshold of 30% for the fraction of the course with the basal ice layer presence.

### 3. Basal ice layer climatology

To characterize the basal ice layer thickness dynamics (along the field and forest courses separately), we selected the following characteristics within the cold season.

- Probability of a non-zero basal ice layer report in a given cold season, $P_{\text{crust}}$. We can expect that during the snowmelt period basal ice layers would develop in response to diurnal freeze/refreeze events. However, where snow cover melts quickly and/or is very shallow, such as in many areas of East Siberia, snow surveys may miss this.
- Maximum observed basal ice layer thickness during the cold period (this variable is of critical importance for wildlife and domesticated reindeer survival, Baskin 1970, 2000, Formozov 1990, Kaz’min and Abaturov 2009a, Kaz’min and Abaturov 2009b).
- Duration of the basal ice layer presence on the ground as well as the duration of above selected thickness thresholds. We used thresholds of 5 and 20 mm, which are considered dangerous events for reindeer husbandry and winter wheat harvest, respectively (Guiding Documents No. 52.88.699-2008 2008).

Generally, snow cover stays longer in forested than open (or field) environments, and snow depths are higher. However, snow in fields is subjected to stronger transformation due to wind and solar radiation. The latter causes an earlier onset of basal ice layer formation and the comparison of basal ice layer characteristics (cf, figures 3, 4, and table 1) at forest and open sites at the same locations (112 stations) shows that the maximum basal ice layer thickness and basal ice layer duration in the forest are 5–10 times less than in the neighboring open areas, while $P_{\text{crust}}$ is 2–4 times less. This characteristic of forested areas provides a refuge for wildlife when the open areas (fields) have basal ice layers. In light of the different basal ice layer regimes between open and forested sites, we focus our analyses on snow course observations from fields (open locations) which are also of interest from an environmental and agricultural perspective.

For example, figure 4 shows that in the forest, the mean maximum basal ice layer thickness barely exceeds 5 mm while the same values in the open locations of agricultural regions of Russia as well as in the Atlantic sector of the Arctic reach and exceed the previously defined dangerous thresholds of 5 and 20 mm, respectively.

The basal ice layer duration and maximum thickness in years when basal ice layer are present are moderately correlated spatially (cf, figures 4 and 6) and at each location (median station correlation coefficient for these two variables is 0.71). Therefore, we assumed similar forms of distribution functions for these two quantities:

$$ F(x) = P_{\text{crust}} + \int_{x}^{0} p(y, \eta, \beta) \, dy, \quad (1) $$
Figure 3. Probability $P_{\text{crust}}$ (%) of an observed basal ice layer presence over the Russian Federation at least once during the cold period. Estimates over the field (A) and forest (B) snow course routes for the 1967–2007 period.

Table 1. Long-term mean values of basal ice layer duration (days) and maximum thickness (mm) during the cold season, and the duration (days) of ‘dangerous’ basal ice layer events at open locations (basal ice layer thicker than 5 mm over a ten day period or thicker than 20 mm over a five day period) regionally—averaged within the regions shown in figure 2.

| Region number in figure 1 | Number of stations | Duration of the ice crust presence (days) | Mean annual maximum ice crust depth during the cold season (mm) | Duration (days) of the dangerous ice crust on the ground at the open sites |
|---------------------------|--------------------|------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------------|
|                           | Field | Forest | Field | Forest | Field | Forest | Above 5 mm in the consequent 10 days | Above 20 mm during 5 days |
| 1                         | 46    | 43     | 15.0  | 2.5     | 3.5   | 0.9    | 8.0                           | 2.0                     |
| 2                         | 4     | 31     | 0.5   | 0.6     | 1.5   | 0.4    | 0.0                           | 0.0                     |
| 3                         | 3     | 6      | 9.0   | 0.7     | 2.0   | 0.2    | 6.0                           | 1.0                     |
| 4                         | 37    | 28     | 14.0  | 2.4     | 4.0   | 0.7    | 7.0                           | 2.0                     |
| 5                         | 39    | 32     | 3.5   | 0.5     | 1.5   | 0.2    | 1.5                           | 0.0                     |
| 6                         | 127   | 37     | 24.0  | 4.4     | 8.0   | 1.8    | 16.0                          | 4.0                     |
| 7                         | 58    | 11     | 11.0  | 0.8     | 3.5   | 0.5    | 7.0                           | 2.0                     |
| 8                         | 30    | —      | 15.0  | —       | 6.0   | —      | 11.0                          | 4.0                     |
| 9                         | 23    | —      | 1.5   | —       | 0.8   | —      | 0.7                           | 0.0                     |
| 10                        | 1     | 16     | —     | 0.7     | —     | 0.6    | —                             | —                      |
| 11                        | 73    | 41     | 7.0   | 0.8     | 3.5   | 0.4    | 3.5                           | 0.7                     |
| 12                        | 41    | 2      | 11.0  | —       | 3.5   | —      | 6.0                           | 0.8                     |
| 13                        | 50    | 26     | 3.5   | 1.0     | 1.5   | 1.1    | 2.0                           | 0.5                     |
| 14                        | 6     | 36     | 4.0   | 0.5     | 2.0   | 0.5    | 1.0                           | 0.0                     |
| 15                        | 27    | 21     | 1.5   | 0.1     | 0.8   | 0.2    | 0.5                           | 0.0                     |
| 16                        | 52    | 51     | 0.3   | 0.2     | 0.2   | 0.3    | 0.0                           | 0.0                     |
| 17                        | 25    | 26     | 3.0   | 0.6     | 1.0   | 0.3    | 2.0                           | 0.5                     |
| 18                        | 23    | 18     | 3.5   | 0.9     | 2.0   | 0.5    | 2.0                           | 0.8                     |

where $p(y, \eta, \beta)$ is a two parameter $\Gamma$-distribution density function: $p(x) = Cx^{\eta-1} \exp(-x/\beta)$ of the basal ice layer quantity when it is observed, $C$ is a constant, and $P_{\text{crust}}$ is the probability of the basal ice layer observed presence (figure 3).

Parameters $\eta$ and $\lambda$ are responsible for shape and scale of the distribution density function. In particular, when $\eta = 1$, this distribution density function becomes an exponential distribution. Using these parameters, the long-term mean value of this distribution with $p(x)$ density function is equal to the product $\beta \eta$ and its variance coefficient $C_v = [\text{standard deviation}] / \text{mean} = \eta^{-0.5}$, the long-term mean value, AVG, of the variable with the distribution function depicted by equation (1) is equal to the product $P_{\text{crust}} \beta \eta$.

The left panel of figure 5 shows direct $C_v$ estimates for field snow courses estimated only for the sites with $P_{\text{crust}} > 0.25$. The estimates show that $C_v$ varies in the range of 0.5–1.0 and rarely exceeds 1. Typical forms of $p(x)$ for the $\Gamma$-density distribution of such shapes are shown in the inset to this panel. Having estimates of these three parameters (or $P_{\text{crust}}$ and two of their derivatives such as $C_v$, and AVG), we can estimate the probability of exceedance of the given thresholds. For example, in the Central Black Soil Region (the bread basket of Russia and part of region 6) the probability of observing a dangerous condition for winter wheat basal ice layer thickness above 20 mm reaches 0.2, and in the Atlantic Arctic the probability to observe a dangerous situation for wildlife with crust thickness above 5 mm is about 0.16 (i.e. $\sim$ once per 6 years). For the Arctic this is less than might be expected from the AVG values in figure 4 due to significant asymmetry of distribution (1). Furthermore, the probabilities of observing the basal ice layer above 50 mm in these two regions are approximately once in 40 years and once in 65 years, respectively. The right panel of figure 5 shows the pattern of the maximum basal ice layer thickness during the entire 41 cold seasons that indicates a high potential of large basal ice layer anomalies (above 50 mm) nearly everywhere across the open sites in the Russian Federation covered by the snow courses network. This is in accord with the probabilities.
mentioned above and justifies our selection of equation (1) to fit the distributions of basal ice layer duration and maximum thickness.

Panels in figures 3–6 show long-term means of selected characteristics of the basal ice layer over Russia separately for field and forest courses. It can be seen that spatially the mean characteristics change quite smoothly, but a high interannual variability (with $C_2$ close to 1) and poor spatial correlation$^6$ nearly guarantee that in each cold season in each region we can observe stations with very high and very low values of the basal ice layer characteristics. Indeed, analyses of regional extremes show that their long-term values are ten times higher than the AVGs (cf, figure 5(B)). For example, in the Atlantic Arctic, the AVGs for the basal ice layer duration and maximum thickness are 15 days and 4 mm (table 1) while the mean regional extremes for the same variables are 165 days and 45 mm, respectively.

4. Changes in basal ice layer characteristics during the 1967–2007 period

Figures 7–9 present major results of our analyses of the changes in basal ice layer characteristics during the past 41 years. Trend analysis is a rather simplistic way to describe what has happened on average over the period under consideration and linear trend estimates presented in these figures give mean rates of change during the past four decades. Linear trend coefficients are calculated for each station and region for the cold seasons during the 1967–2007 period using ordinary least-squares regression. While the individual station time series have highly asymmetric distributions, the distribution of regionally averaged characteristics are close to a normal distribution. Therefore, a two-tailed $t$-test was used to estimate the statistical significance of the trends for regionally averaged time series (Draper and Smith 1966). As an additional precaution against deviations from the normal distribution of errors of the trend analysis (e.g., in regions with a small number of stations and/or with rare occurrence of the basal ice layer events) a non-parametric Kendall $\tau$-test for significance of systematic changes was also applied (Kendall 1975). Only when both these tests confirmed the statistical significance of the change at the 0.05 level, were the trend estimates further discussed. On several occasions the $\tau$-test was more conservative in rejecting the null hypothesis of ‘no systematic changes’ than was the $t$-test. Estimates of systematic changes that were found statistically significant by the $\tau$-test but insignificant by the $t$-test are shown in figures 7–9 in italics, but are not further discussed.

Geographical patterns of linear trend estimates at individual sites in the left panels of figures 7 and 8 provide a visual impression of the major tendencies of changes in duration and thickness of the basal ice layers under the snow cover. Usually, micrometeorological and weather variability makes each of these point estimates statistically insignificant, and in some areas we observe point trend estimates of opposite signs located close to each other. However, within most of the quasi-homogeneous regions selected in figure 2, we can observe a prevailing sign of trends in these major basal ice layer characteristics. With the exception of the Northern Caucasus and West Siberian steppes and, possibly, the monsoon region of the Russian Far East south of 50°N, the sign of the changes in both characteristics is negative, indicating a decrease in both duration and maximum thickness of the basal ice layer. It is also apparent that changes along the field snow course routes are higher than along the forested routes (figures 7 and 8, left panels).

The quantitative estimates of the mean regional changes in figure 9 and in the right panels of figures 7 and 8 are presented in per cent of the mean regional values (available in table 1) only when the trends for the regional time series were statistically significant at the 0.05 or higher level. These estimates show that while absolute trend values of the basal ice layer characteristics (left panels) for field routes are in most cases higher than those for forest routes, the same trend estimates in per cent (right panels) for both route types are quite close.

The duration of the basal ice layer presence characterizes the crust for the entire cold season while the maximum basal

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$^6$ For example, for the forest snow courses, the radii of spatial correlation, $\rho$, for the maximum observed basal ice layer thickness during the cold period and the duration of the basal ice layer presence on the ground are on the order of 15 km. The spatial correlation model used for these estimates was $R(r) = C_2 \exp(-r/\rho)$, where $r$ is the distance between two locations and the form of the spatial correlation function, $R(r)$, assumes spatial isotropy (more on this issue can be found in Gandin et al 1976). For both these basal ice layer characteristics at the field snow courses, a micrometeorological variability is responsible for 80%–85% of their variance ($C_2$ is in the range of 0.15–0.2). However for the same characteristics at the field snow courses, we observe large-scale components responsible for 15%–20% of the variance. These components are well correlated spatially with $\rho$ in the range of 600–800 km.
Figure 5. (A) Pattern of the variance coefficient ($C_v$) estimates for maximum annual basal ice layer thickness along the field snow course routes and typical distribution density functions, $p(x)$, that correspond to these $C_v$ values (as an inset). The variance coefficients were calculated only when the non-zero basal ice layer thickness was observed at least in 10 cold seasons during the analyzed period of 41 cold seasons. (B) Pattern of the maximum basal ice layer thickness along the field snow course routes during the 1967–2007 period.

Figure 6. ((A)–(C)) Duration (days) of the basal ice layer above 0 mm, 5 mm, and 20 mm, respectively, for the field/tundra snow course routes; (D) the same but for the forest snow course routes for the basal ice layer duration above 5 mm. Long-term mean values (AVG).

ice layer thickness may be observed only once per season. Nevertheless, we found that these two characteristics are reasonably well correlated and the pattern of their trends is very similar (figures 7 and 8). Absolute values of trend estimates of the basal ice layer characteristics in the European part of Russia are much higher than throughout Eastern Siberia, especially along the field/tundra snow courses. This is in line with the drier (compared to the West) continental climate of the eastern half of Russia affected by the Siberian High during most of the cold season. Single digit monthly totals of precipitation and a swift switch to the short warm season (accompanied with intense snowmelt) do not support the development of prolonged and/or deep basal ice layer here (cf, table 1). However, relative changes (shown in the right panels of figures 7 and 8) are of the same order in western and eastern Russia.

In the Central East Siberia and in the Altai-Sayany regions, we still found a statistically significant decrease of the occurrence of potentially dangerous basal ice layer events with basal ice layer $>5$ mm during the consequent 10 days (figure 9(a)). But another critical threshold ($>20$ mm at least once per year) is practically unobserved east of the Yenisei River (cf, figure 6(c)). Therefore, all other statistically significant trends in both of these potentially dangerous basal ice layer events are found in the Atlantic Arctic and agricultural regions of European Russia (figure 9). Contemporary climate models project significant increases in precipitation over northern Siberia, of around 25%, by the end of the 21st century (Kattsov and Kallen 2005, Christensen and Hewitson 2007). While these are large % changes the actual amounts are quite small (e.g., 5 mm month$^{-1}$ will increase to 6–7 mm month$^{-1}$), so these projected precipitation changes (all other factors being equal) will probably not be responsible for more dangerous basal ice layer events in this region of Russia.
Figure 7. Maximum basal ice layer thickness during the cold period over the Russian Federation. Pattern of the linear trends of the thickness in mm per 10 years over the field (A) and forest (C) snow course routes and their regionally averaged values in % per 10 years (B) and (D), respectively. Trends in (B) and (D) are presented only for the regions where they were statistically significant at the 0.05 or higher level (estimates of changes whose statistical significance were supported only by the non-parametric tau-test are italicized).

Figure 8. Number of days with basal ice layer during the cold period over the Russian Federation. Pattern of the linear trends in days per 10 years over the field (A) and forest (C) snow course routes and their regionally averaged values in % per 10 years (B) and (D), respectively. Trends in (B) and (D) are presented only for the regions where they were statistically significant at the 0.05 or higher level (estimates of changes whose statistical significance were supported only by the non-parametric tau-test are italicized).

5. Discussion and conclusions

This is the first time that a comprehensive analysis has been carried out of basal ice layer data over a large area of the Northern Hemisphere snow covered lands. The data form a unique observational dataset that is unfortunately unmatched in North America and Fennoscandia. There is some potential to further expand the dataset with data from Kazakhstan,
the Ukraine, Belarus, and the Baltic States basal ice layer. The 'pioneering' nature of this study brought an additional responsibility and work load. We could not take anything for granted: distribution functions, spatial correlation, and even the long-term mean values of the basal ice layer variables. All had to be estimated, quantified, and/or tested (section 3) prior to the assessment of changes in these variables.

When the study was initiated we anticipated the following results: strong surface air warming and snow cover retreat observed in spring over Russia (Groisman et al. 2006, Robinson 2009) should reduce the duration of the snowmelt period and therefore the period with the basal ice layer on the ground. At the same time we realized that an increase in thaw day frequency across Northern Eurasia west of the Ural Mountains (McBean et al. 2005, Groisman et al. 2003, Groisman 2010) and increased maximum snow depths in the high latitudes of Eurasia (Bulygina et al. 2009b) could act in an opposite direction, lengthening the duration of the snowmelt period and promoting a higher maximum basal ice layer thickness. Analyses presented in section 4 clearly indicate that the first group of factors prevailed in the most humid forest and forest-steppe regions of Russia east of the Ural Mountains and in the Altai-Sayany region. In these regions forest and field courses (when available) show statistically significant decreases in frequency and/or maximum thickness of basal ice layer under snow cover. Without the actual snow depth and basal ice layer data at hand for most of Northern Eurasia, concerns were raised that with global change the reindeer pasture accessibility (due to icing events, heavier winter snow accumulations with corresponding longer spring snowmelt) will detrimentally affect its quality and animal population dynamics (Nuttall et al. 2005). Our analysis indicates that this has not been the case in the Atlantic Arctic, at least during the past four decades. The data sets that have now become available through the World Data Centers (in Obninsk, Russia and in Asheville, the United States) provide a solid basis for realistic parameterizations of snow characteristics in appropriate ecosystem models (e.g., Wolf et al. 2008, Rees et al. 2008) and their application for assessments of the vulnerability of European reindeer husbandry to global change.

The observed changes are not always of practical importance though. For example, in dry Eastern Siberia regions, the mean of regional maximum durations of days with basal ice layer above 5 mm does not exceed five days in the forest and tundra courses. This indicates the near-absence of dangerous basal ice layer events for reindeer husbandry (DER) in these regions, defined as at least ten days of basal ice layer above 5 mm on the ground (Guiding Documents No. 52.88.699-2008 2008). On the contrary, in the Atlantic sector of the Arctic the presence of the basal ice layer under the snow cover is quite frequent, especially in tundra (one DER per year on average with years when the region wide DER duration reached 25 days). Moreover, we found a significant group of stations within this region (~20%) of the total 46 tundra/field sites, located mostly along the Arctic Ocean coast, where the average DER duration could be up to three months. In this region, a substantial decrease in the DER frequency during the 1967–2007 period (figure 10) represents an important improvement for the reindeer husbandry industry. Indeed, while in the first two decades of the analyzed period, the DER events were observed at 10–30% of the open sites of the area, in the 2000s the fraction of sites with observed DER events declined below 5%. During the same period in the field courses over this region, the mean maximum basal ice layer thickness has decreased by 4 mm (or more than twofold).

The Arctic tundra areas are the only regions where the presence of the basal ice layer under the snow cover has implications for transportation. Southward, the icing on the roads has no relation with snow course data. The first track converts any freshly fallen snow (if it was not removed) into ice and this process does not depend upon snowmelt on the surrounding fields or forest. However, in the Arctic tundra trucks and snowmobiles may choose traveling over the virgin snowfields, and for them the presence of the ice just below the snow surface might be an unpleasant surprise. Results shown in figure 8 indicate that during the past 40 years, the frequency of events when such surprises have occurred went down at a

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Figure 9. Number of days with basal ice layer thickness > 5 mm during the consequent 10 days (A) and >20 mm (B) during the cold period over the Russian Federation. Linear trends of regionally averaged values (% per 10 years) over the field snow course routes. Trends are presented only for the regions where they were statistically significant at the 0.05 or higher level (estimates of changes whose statistical significance were supported only by the non-parametric tau-test are italicized).
rate of 30%–40% per 10 years across the Atlantic sector of the Russian Arctic.

Other areas where the changes in the duration, frequency, and maximum thickness of the basal ice layer under the snow cover represent practical importance are agricultural regions of Russia west of the Ural Mountains and the Altai-Sayany Region. From 49°N to 62°N over the Great East European Plain, the field snow courses report a significant decrease in the mean maximum basal ice layer with a mean rate of 20%–40% per 10 years. The mean regional maximum snow depth across the field courses in this zone varies from 4 mm in the northeast to ~25 mm in the southwest and the mean regional duration of the mean presence of the basal ice layer above 20 mm under the snow cover varies, increasing from the northeast towards the southwest from 1 pentad to 5 pentads, respectively. The presence of the basal ice layer above 20 mm during a single pentad is considered a dangerous event for winter crops (DEC) and, when it occurs, most probably causes re-planting (Guiding Documents No. 52.88.699-2008 2008). The DEC decrease in the southwest (figure 11) represents a significant improvement of harvesting in this major agricultural region of the Russian Federation.

In the Altai-Sayany Region, the mean maximum basal ice layer thickness decreased by more than twofold during the 1967–2007 period, and the frequency of pentads with basal ice layer above 0, 5, and 20 mm has decreased with the mean rates of 40%–45% per 10 years. The estimate of the change in the number of days with basal ice layer above 20 mm in this region in figure 9(b) is shown in italics, because the null hypothesis about the absence of significant systematic changes was rejected by the tau-test but passed the two-tailed t-test.

In the two southernmost steppe regions (Northern Caucasus and steppes of West Siberia), we did not find significant changes in maximum basal ice layer thickness and/or in DEC. Figure 7 indicates that at least in a part of these regions (as well as in the south of the Russian Far East), an increase in maximum snow basal ice layer thickness has been observed. However, after the region wide averaging, this increase appeared to be statistically insignificant.

After the submission of this letter, we updated our archive with data for the last two cold seasons (2008 and 2009). Based on updated time series (Bulygina et al 2009a), the results do not discernibly differ from those presented here. Therefore, we took the liberty to update the time series shown on our figures 10 and 11 to 2009.

In summary, we conclude that during the period of contemporary instrumental observations of the snow cover basal ice layer characteristics across Northern Eurasia, substantial changes have occurred, some of which have practical importance for wildlife and human activity in the Arctic, as well as in the major agricultural regions of Russia. Our results show that among the two competing factors that can cause a systematic change in the basal ice layer characteristics over the humid half of Northern Eurasia, i.e., the increase in thaws due to strong regional warming and a potential shortening of the period of snowmelt, the second factor appeared to be more significant (at least during the past 40 years). A significant reduction of the duration of the spring days with ephemeral snow cover, first reported by Groisman et al (2006) together with the findings of this paper, support the notion that the entire process of the spring snowmelt has become shorter in duration and (taking into account a parallel rise in the maximum snow depth across most of the Eurasian Arctic, cf Bulygina et al 2009b) more intense. This might have important repercussions in contributing to an increasing frequency and severity of spring floods reported elsewhere (cf, Shiklomanov and Lammers 2009, Rawlins et al 2009), and require further studies.

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