

Icing conditions over Northern Eurasia in changing climate

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Icing conditions over Northern Eurasia in changing climate

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Olga N Bulygina^{1,3,4}, Natalia M Arzhanova¹ and Pavel Ya Groisman^{2,3}¹ All-Russian Research Institute of Hydrometeorological Information—World Data Centre, Obninsk, Russian Federation² University Corporation for Atmospheric Research at NOAA National Climatic Data Center, Asheville, NC, USA³ P.P.Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russian Federation⁴ Author to whom any correspondence should be addressed.E-mail: bulygina@meteo.ru, ashatan84@mail.ru and Pasha.Groisman@noaa.gov**Keywords:** icing and hoar frost events, long-term means, linear trend coefficient**Abstract**

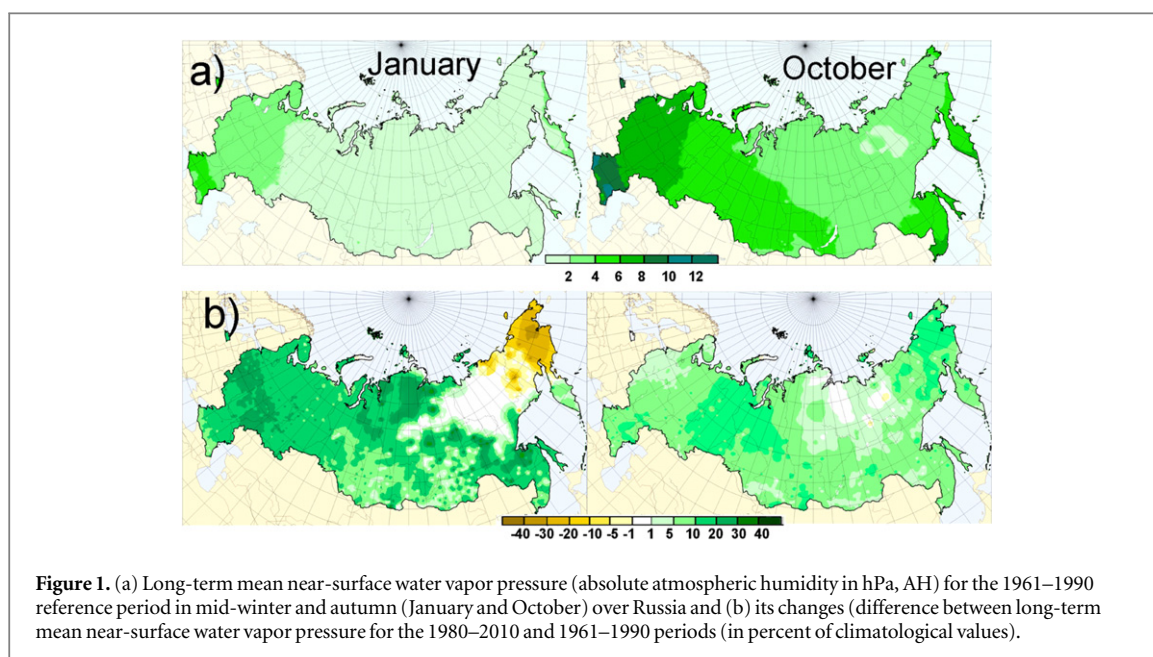
Icing conditions, particularly in combination with wind, affect greatly the operation of overhead communication and transmission lines causing serious failures, which result in tremendous economic damage. Icing formation is dangerous to agriculture, forestry, high seas fishery, for land and off coast man-made infrastructure. Quantitative icing characteristics such as weight, thickness, and duration are very important for the economy and human wellbeing when their maximum values exceed certain thresholds. Russian meteorological stations perform both visual and instrumental monitoring of icing deposits. Visual monitoring is ocular estimation of the type and intensity of icing and the date of ice appearance and disappearance. Instrumental monitoring is performed by ice accretion indicator that in addition to the type, intensity and duration of ice deposits reports also their weight and size. We used observations at 958 Russian stations for the period 1977–2013 to analyze changes in the ice formation frequency at individual meteorological stations and on the territory of quasi-homogeneous climatic regions in Russia. It was found that hoar frosts are observed in most parts of Russia, but icing only occurs in European Russia and the Far East. On the Arctic coast of Russia, this phenomenon can even be observed in summer months. Statistically significant decreasing trends in occurrence of icing and hoar frost events are found over most of Russia. An increasing trend in icing weights (IW) was found in the Atlantic Arctic region in autumn. Statistically significant large negative trends in IWs were found in the Pacific Arctic in winter and spring.

1. Introduction

A general increase in atmospheric humidity (AH) is expected with global warming, as projected by GCMs and reported from remote sensing and *in situ* observations (IPCC 2007, Trenberth *et al* 2007, Dessler and Davis 2010, Zhang *et al* 2010). Overall, the annual warming over the territory of the Russian Federation (as well as over Northern Eurasia north of 40°N) is 0.43 °C/decade during the 1977–2012 period. This is higher than the annual warming over the Northern hemisphere for the same period, 0.30 °C/decade, and is well above of the mean rate of the hemispheric warming for the entire period of mass instrumental observations, 0.083 °C/decade during the 1881–2013 period (Lugina *et al* 2007 updated). The Arctic coast of the country experiences a particularly rapid increase in mean annual temperature (0.8 °C/decade) on the

Taimyr Peninsula off the Laptev Sea Coast. In the Arctic, this increase has been and will be especially prominent due to the dramatic retreat of the sea ice (Fetterer *et al* 2002, updated). In the warm season, this retreat provides an abundant water vapor supply into the dry Arctic atmosphere (Bintanja and Selten 2014) while in the cold season even a small fraction of open Arctic water delivers a substantial latent heat flux to the atmosphere (Groisman *et al* 1999). Now this flux is further funneled by the prevalence of the one-year-old sea ice near the Eurasian shelf Seas. The contemporary sea ice changes are especially prominent in the Eastern hemisphere and after the two extremely anomalous low-ice years (2007 and 2012) it is the right time to look for the impact of these changes in the high latitudinal hydrological cycle (see, Screen 2013).

Figure 1 shows the pattern of the long-term mean near surface absolute AH (hPa) over Russia for two



central months of winter and autumn seasons. Standard climatology in the top panels (figure 1(a)); mean values for the 1961–1990 period used for a long time in Russia for climatological assessments) are appended with the estimates of changes in the last three decades (figure 1(b)) that presents the changes in between the last three decades (1981–2010) and the reference period of 1961–1990. According to recommendations of the 16th session of the WMO Commission for Climatology (Heidelberg, Germany, 3–8 July 2014), the last 30 yr period, 1981–2010, is used to calculate normals (documents of...2014). This figure shows an increase of spatial inhomogeneity in the humidity field distribution over Russia in the winter season. More humid Western regions of the country became even more humid while the Northeast became drier in the past decades. In the shoulder seasons, autumn and spring (not shown), a general increase of AH is observed. In section 4, we shall show that this increase and the winter pattern of humidity changes are in line with the regional temperature increase.

The focus of this paper is on icing and hoar frost events and their changes during the past several decades over Russia. The sign of these changes cannot be taken for granted even when we know the tendencies of changes in regional temperature and humidity. Warmer temperatures in the cold season allow more water vapor in the low atmosphere but they also reduce the duration of the cold season and affect the atmospheric transportation of the water vapor from the oceans into the continent interior (see, Groisman *et al* 2003, ACIA 2004, 2005, Groisman and Soja 2009).

Potential increase of extreme icing events in the regions with high AH when temperatures are just slightly below 0 °C represents a serious natural hazard. In Russia, these regions are located along the

oceanic coasts and in the Westernmost part of the country. Usually, humidity (unless extremely high or low) does not critically affect human activities and life style. However, in the high latitudes, this characteristic has an additional facet: higher humidity causes higher ice condensation from the air (icing and hoar frost) on the terrestrial and off-shore infrastructure and ships, even in the absence of precipitation. Hoar frost and icing events (in Russian: ‘gololed’) are routinely measured at the Russian meteorological network and reports of icing of the wires are quantitative measurements. While hoar frost can be considered as a minor annoyance, icing may have important societal repercussions. In the Arctic, icing occurs mostly during relatively warm months when atmosphere holds maximum amount of water vapor (and is projected to have more). Freezing rain and drizzle contribute to icing formation. When icing loading exceeds certain thresholds, it can affect the infrastructure and became a socially important climatic variable. The North American ice storm of 1998 (Saunders 1998) is an example of catastrophic economic impacts of icing. Icing events have a particularly large effect on the operation of overhead communication lines and power transmission lines (Rudneva 1998). The formation of icing and hoar frost deposits on different structures produces additional loads. Climatic zoning of Northern Eurasia with respect to icing loads was conducted by Zakharov (1984) and has been widely used in infrastructure planning. However, the latest information about the icing and hoar frost deposits in Russia refers to the 1980s and since that time has never been updated.

Therefore, the goal of the present study is to update the climatology (presented in detail in

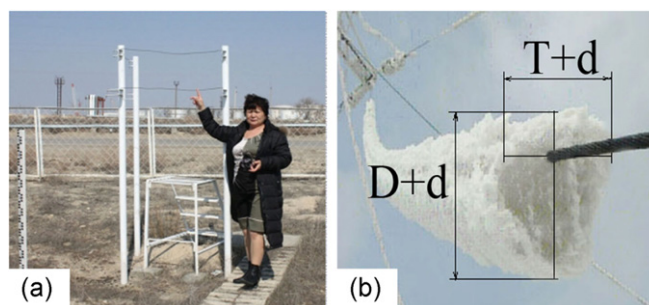


Figure 2. Instrumental observations of icing and hoar frost events: (a)-instrumental monitoring of icing and hoar frost; (b)- deposit diameter (D) and thickness (T), wire diameter (d).

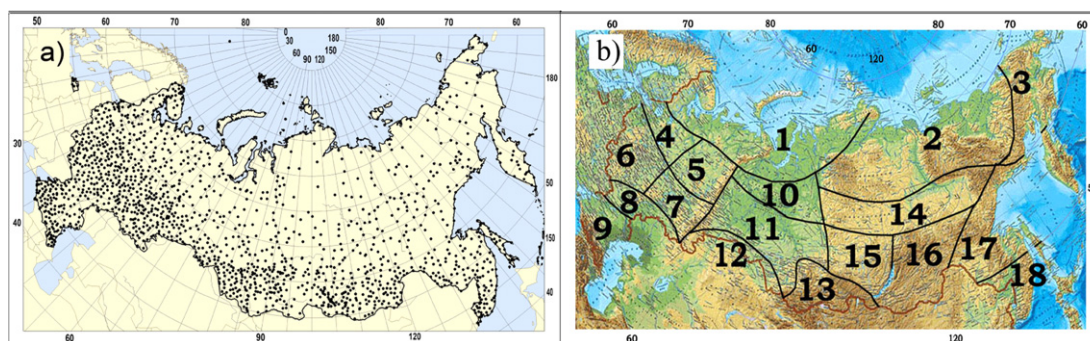


Figure 3. (a) Location of 958 meteorological stations with icing and hoar frost observations that were used in this study. (b) The quasi-homogeneous climatic regions based on the Alisov (1956) classification that were used in this study for snow cover climatology: 1, 2 and 3—Atlantic, Siberia and Pacific Arctic, respectively; 4, 5, 6, 7 and 8—Northwestern, Northeastern, Southwestern, Southeastern and steppe parts of the Great East European Plain, respectively; 9—Northern Caucasia Steppes and Piedmont; 10 and 11—Northern and Southern parts of the forest zone of West Siberia, 12—steppe zone of West Siberia; 13—Altai and Sayany Mountains and Piedmont; 14, 15 and 16—Eastern Siberia: Central, the Angara River Basin, and Trans-Baikal regions, respectively; 17 and 18—Russian Far East, between 50°N, and 60°N and South of 50°N (Maritime Territory and South of the Sakhalin Island), respectively.

appendix) and quantify the latest dynamics of icing conditions over Northern Eurasia.

2. Data and methods of analyses

Observations of icing and hoar frost events started in the former USSR in the 1940s. Icing and hoar frost deposits are categorized into icing proper, granular and crystal hoar frost, sleet formation and frozen sleet formation. Icing normally forms at weak frosts, 0 to -3° , but may also occur at lower temperatures. Granular hoar frost normally forms at air temperature -2° to -7°C , and sometimes below that. Crystal hoar frost forms at air temperature -11° to -25°C , and may also form at both higher and lower temperatures.

Both visual and instrumental observations of ice formation are conducted at Russian meteorological stations. Visual observations use no instruments in determining the type of ice formation, its intensity and the time, when ice appears and disappears. These qualitative ('yes/no') observations are made every three hours at the meteorological site and its visible vicinity.

Instrumental observations allow determining (in addition to the type and duration of ice deposits) their

weight and size. Instrumental observations are performed by using ice accretion indicator. Ice deposits on wires are often of irregular geometric shape; therefore, the sizes of the deposits are characterized by measuring their diameter and thickness. The diameter of the deposit is the length of the largest cross-section axis of the deposit minus the wire diameter (figure 2(b)).

The deposit thickness is the distance between the two outermost points of the deposit's cross-section in the direction perpendicular to the diameter's line, without regard to the wire diameter. In the idealized form the icing deposit may have an elliptic form of a frozen drop with the diameter of the deposit axis directed to the ground and the 'thickness axis' directed parallel to the ground. By definition, thus defined diameter is always larger than thickness. The weight of the deposit is determined from the volume of the melted deposit sample taken from the wire's length as long as 25 cm. Water volumes are measured in units of the rain gage measuring glass. Deposit sizes are measured in millimeters.

For this study, we retrieved results of visual and instrumental observations of icing and hoar frost events at 958 Russian meteorological stations

(figure 3(a)) stored at the Russian Institute for Hydro-meteorological Information- World Data Center. Prior to archiving, these meteorological data were quality controlled as described by Veselov (2002).

The following characteristics are considered:

- number of days with icing and hoar frost events from visual observations for the 1977–2013 period;
- weight, thickness and duration of ice loading from instrumental observations for the 1984–2013 period.

Regional analysis of goled characteristics was carried out using quasi-homogeneous climatic regions (figure 3(b)), which we had already used in our other studies (see, Bulygina *et al* 2011). The Alisov classification (1956) was used in determining quasi-homogeneous climatic regions and is based on specific features of atmospheric circulation, type of soil and plant cover, and surface radiation budget considerations. This classification makes it possible to use these regions in studying regional features of different meteorological characteristics.

Maps (climatology and trends) are presented mostly for visualization purposes. The area-averaging technique uses the station values converted to anomalies with respect to a common reference period. These anomalies were first arithmetically averaged within $1^{\circ} \text{N} \times 2^{\circ} \text{E}$ gridcells and thereafter used for mapping by an area-weighted averaging of the gridcell values over our quasi-homogeneous climatic regions. This approach provides a more uniform spatial field for averaging.

Trend analysis is a rather simplistic way to describe what has happened on average over the period under consideration. Linear trend coefficients are calculated for each station and region for the three seasons (except summer), the distribution of regionally-averaged characteristics behave closely to a normal distribution. Therefore, a two-tailed t-test was used to estimate 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 icing and hoar frost events), a non-parametric Kendall -test (tau-test) for significance of systematic changes was also applied (Kendall 1975). Only when both these tests confirmed statistical significance of the change at the 0.05 level, the trend estimates were further discussed.

3. Changes in icing and hoar frost characteristics

The large area of Russia and the variety of its physical and geographical conditions are responsible for

differences in regional hoar frost icing characteristics. Their climatology is presented in appendix. In this section we show their dynamics during the past several decades. These changes are characterized by linear trend coefficients using data at individual meteorological stations and those area-averaged over quasi-homogeneous regions shown in figure 3(b).

In autumn, winter and spring, the seasonal number of days with icing and hoar frost events tends to decrease over most of Russia (figure 4). However, in each season, this number has increased by 10–15 days/decade in the Amur and Kolyma River Basin and in the spring season, positive linear trends were obtained in the Central and Eastern Chukotka Peninsula and on the Eastern coast of the Laptev Sea.

Regional averaging revealed no significant positive trends of the seasonal number of days *with icing and hoar frost events* in any of 18 regions used in our partition of Russia. However, most of these regions are characterized by statistically significant negative trends in the number of days with icing and hoar frost events. In autumn, negative trends of –20% per decade and less were recorded in the steppe zone of West Siberia, Altai and Sayany Mountains, and the Southern Siberia around the Baikal Lake (regions 15 and 16). In winter, a maximum negative trend (28–29% per decade) is recorded in the vicinity of the Altai and Sayany Mountains and in the Pribaikalie (region 15).

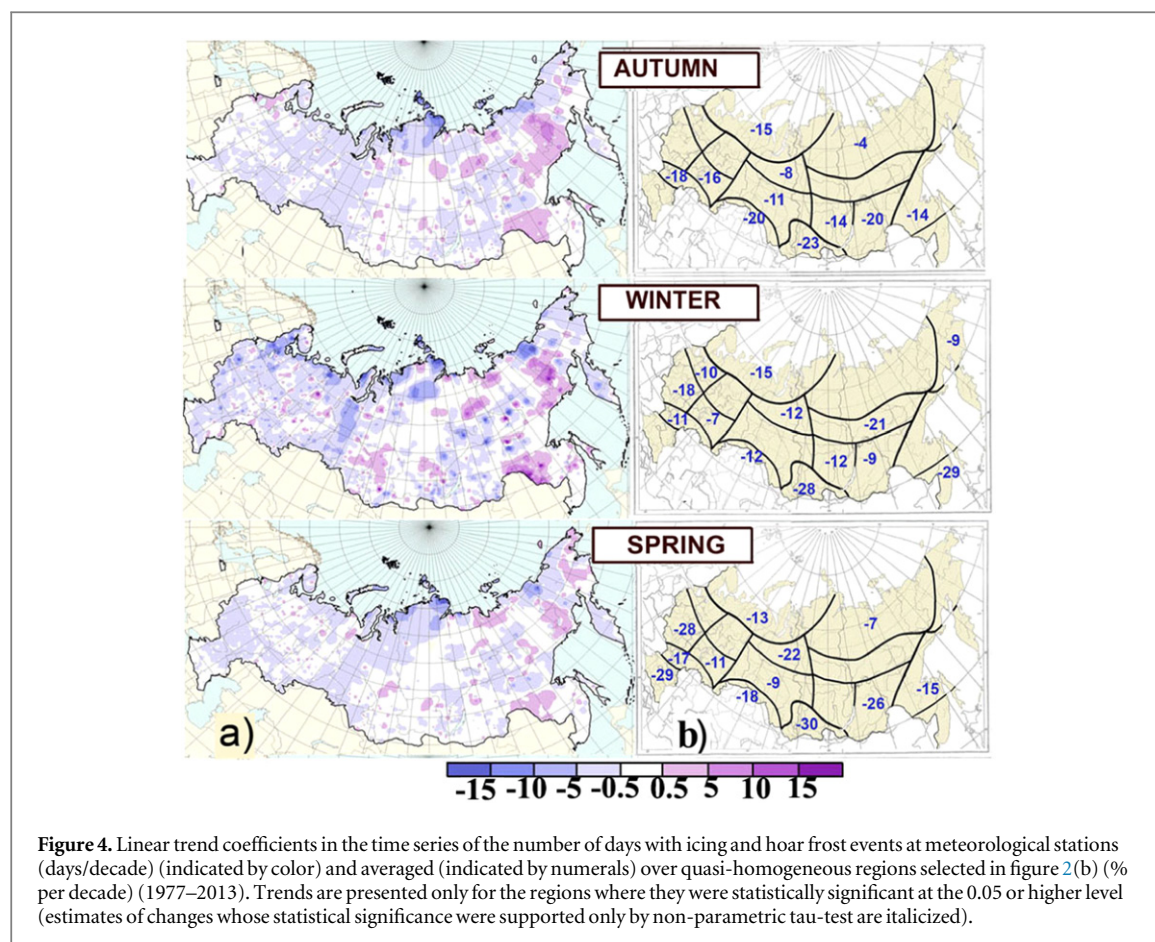
The damage caused by icing events is related to the weight and size of the icing deposit. Data from meteorological stations were used to estimate trends in the time series of icing weights (IW; figure 5).

In autumn (October), IW trends show increase in the Atlantic Arctic region (region 1) and decrease in the Southern and steppe parts of the Great East European Plain.

In winter, the increase in IW is recorded in the Southern part of the Plain (figure 5(a)), however, according to regional average, no significant trends were found in this region. IW tends to decrease in West Siberia.

In spring, regional averaging revealed significant negative linear trends in the Eastern part of European Russia with the decreases being 3.5–3.7% per decade (figure 5(b)).

In winter and spring the largest negative trends in IWs (–3.8% per decade) is recorded in the Pacific Arctic (region 3) that corroborates with a significant precipitation decrease here during the past 60 yr (Groisman *et al* 2014), reduction of the near surface AH (cf, figure 1(b)), and changes in the Aleutian low intensity (see, Overland *et al* 1999, 2002). As well as for region 1, we paid a particular attention to this humid polar region because the cold season storms in the North Pacific are strong and the probability to encounter heavy icing events (and, therefore, related to them natural hazards) along this part of Russia is high. Apparently, the IW in region 3 has significantly



decreased in the winter and spring seasons (figure 5(b)).

4. Discussion

Icing event occurrences depend upon near surface air temperature and humidity. In shoulder seasons (autumn and spring), when surface air temperatures are around 0 °C and the hoar frost and icing events are most probable, the temperature increase should induce a reduction of their numbers. Correspondingly, in the past 37 yr (1977–2013), in spring and autumn temperatures increase over entire Russia (table 1) and the number of days with hoar frost and icing events went down. We can assume that the same factor (warming) may be responsible for the winter reduction of hoar frost and icing events over the European Russia (regions, 4, 6, and 8 in figure 3(b)). In the Asian part of Russia in winter, the temperatures are too low (well below −20 °C) and their changes cannot be responsible for dynamics of the icing and hoar frost events (correlations between regional temperatures and the frequencies of these events are statistically insignificant). Climatology of icing events (figures A2–A4) shows that in the Asian part of Russia both the maximum monthly IWs and the frequency of icing events are low. We conclude that low temperatures and low absolute humidity (cf, figure 1(a)), while

preventing substantial icing, do not affect the winter frequency of occurrence of hoar frost and icing events combined (figure A1). In the past two decades, the substantial reduction in winter AH in the North-eastern part of Asia (figure 1(b)), and the simultaneous strengthening of the Siberian high intensity (Jeong *et al* 2011) can be partially responsible for decrease in the hoar frost and icing events frequency in these regions during our study period.

For better understanding of the dynamics in icing events in the humid areas of Russia (Northwestern part European Russia, areas adjacent to the Black Sea, The Sakhalin Island, cf, figure 1(a)), we have to assess the changes in other climatic variables, first of all the near-surface AH.

In autumn and winter in the regions with high AH we can expect sizeable manifestation of icing events when the weather permits as well as the impact of AH changes. In the Westernmost and Southernmost regions of European Russia (regions 6 and 9 respectively), in the autumn and winter seasons the temperatures are frequently close to 0 °C (e.g., in October over region 6 and in January over region 9), while the AH in these months is high (figure 1(a)) and has increased (figure 1(b)). As a result we observed in these months and regions 8% per decade increases in maximum IW. These increases were documented on the background of general seasonal decrease in mean and maximum IW over most of European Russia (figure 5).

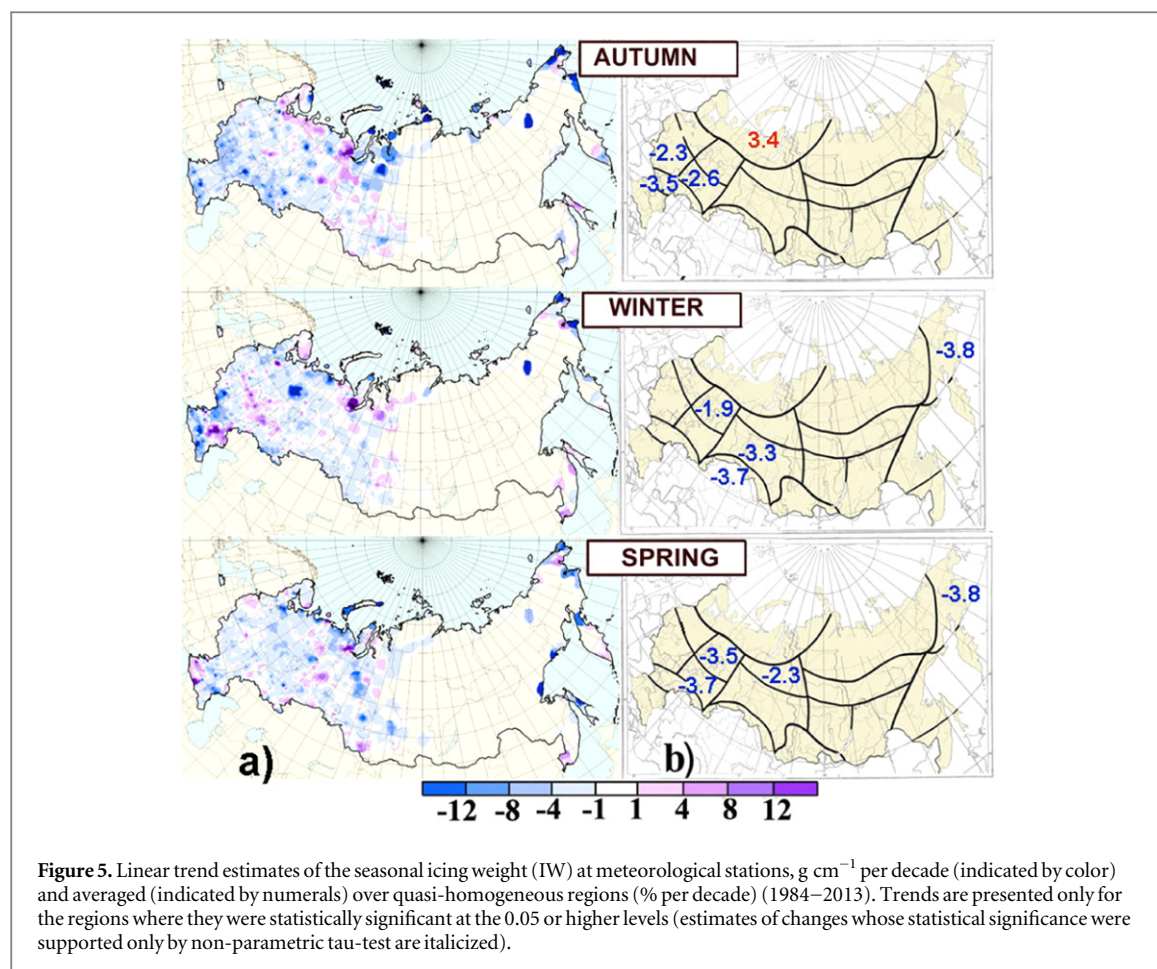
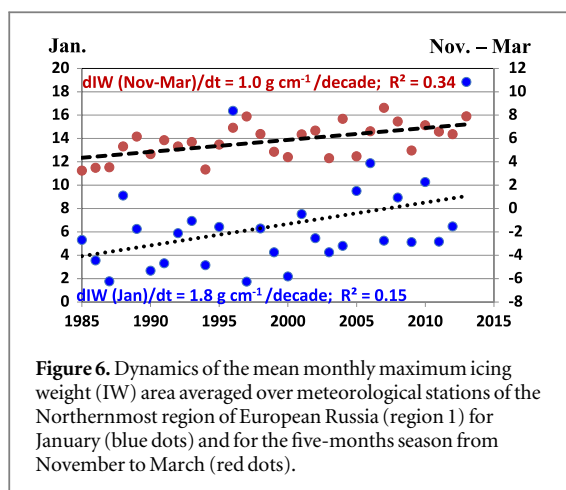


Table 1. Linear trend estimates of the number of days with icing and hoar frost events (trends are presented only for the regions where they were statistically significant at the 0.05 or higher level) and temperature averaged over quasi-homogeneous regions. 1977–2013.

Region	Season								
	Autumn			Winter			Spring		
	Temperature			Temperature			Temperature		
	Nday (%/decade)	Trend (°C/ decade)	Mean 1981 –2010	Nday (%/decade)	Trend (°C/ decade)	Mean 1981 –2010	Nday (%/decade)	Trend (°C/ decade)	Mean 1981 –2010
1	–15	0.56	–1.2	–15	0.60	–15.2	–13	0.50	–4.7
2	–4	0.77	–11.6				–7	0.94	–13.1
3				–9	–0.43	–22.3			
4				–10	0.58	–8.8			
5									
6				–18	0.45	–6.7	–28	0.39	5.8
7	–16	0.70	3.6	–7		–10.8	–11	0.52	4.1
8	–18	0.62	6.7	–11	0.22	–7.8	–17	0.62	7.0
9							–29	0.41	9.6
10	–8	0.22	–4.7	–12	–0.21	–23.0	–22	0.86	–6.1
11	–11	0.48	0.3				–9	0.68	0.9
12	–20	0.53	2.9	–12	–0.57	–4.2	–18	0.74	3.2
13	–23	0.33	–0.4	–28	–0.42	–17.9	–30	0.52	0.8
14				–21		–33.0			
15	–14	0.24	–1.9	–12	–0.43	–20.9			
16	–20	0.28	–3.9	–9	–0.19	–24.7	–26	0.33	–2.0
17	–14	0.48	–0.8				–15	0.34	–2.2
18				–29	0.28	–13.9			



We paid a particular attention to West Arctic (region 1). In this maritime region severe cold season storms arriving from North Atlantic, open surface of the Barents Sea, relatively high AH (figure 1(a)) and strong winds (Bulygina *et al* 2013) can generate heavy icing events and, therefore, trigger natural hazards for land and off-shore infrastructure and to intense shipping and fishing activities in the high seas of the region. In figure 6 we show changes of IW at meteorological stations in this Northernmost region of European Russia. In this region, we witness a very significant increase in AH related to strong warming (table 1; figure 1(b)) and a sizeable retreat of the Eurasian Arctic sea ice (Fetterer *et al* 2002, updated; https://nsidc.org/data/seaice_index/). Throughout the entire cold season from November through March, we observe here an increase in IW (figure 6) that is most significant in the late autumn when the sea ice extent is low and/or is still not well established, leaving a space for evaporation from the open sea surface and leads.

5. Conclusions

In this study, we used data from both visual and instrumental observations of hoar frost and icing. Quantitative icing characteristics such as weight, thickness, and duration are very important for economy and human wellbeing when their maximum values exceed certain thresholds. We calculated their climatology for the last 30 yr (long-term mean values) and evaluated the tendencies of their change expressed as lineal trend estimates.

We found that

- hoar frosts are observed in most parts of Russia, but icing only occurs in European Russia and the Far East. On the Arctic coast of Russia, this phenomenon can even be observed in summer months.
- Maximum icing thickness is recorded in European Russia in the Northern and Southernmost regions, as well as along the Volga River Basin known for its

expansive reservoirs. The largest IWs are recorded in the North Caucasus and the Western Arctic (over 25 g cm^{-1}). Maximum icing duration, 48–72 h and up to 96 h at individual meteorological stations, is recorded in December and January in Northeastern Russia.

- Statistically significant decreasing trends in occurrence of icing and hoar frost events are found over most of Russia. In particular, statistically significant large negative trends in IWs were found in the Pacific Arctic in winter and spring seasons where high IWs represent natural hazard for both land and off-shore infrastructure and trawling fleet.
- This study revealed increasing trends in the number of days with icing and hoar frost events only in some parts of the Russian Far East (in the Amur River Basin in the South and in the Kolyma River Basin in the North).
- An increasing trend in IWs was found in the Atlantic Arctic region in autumn and early winter. Here, it is collocated with an increase in the atmospheric moisture (figure 1(b)) and the frequency of winter cyclones in the region (Tilina *et al* 2013). We hypothesize that these changes may be partially related to a decrease in sea ice area in the Eurasian sector of the Arctic.

Acknowledgments

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Appendix. Climatology of icing and hoar frost characteristics over Russia

The large area of Russia and the variety of its physical and geographical conditions are responsible for differences in regional icing characteristics. Figure 3 shows spatial distributions of mean long-term values (normals) of the monthly numbers of icing and hoar frost events derived from visual observations. According to recommendations of the 16th session of the WMO Commission for Climatology (Heidelberg, Germany, 3–8 July 2014), the last 30 yr period, 1981–2010, is used to calculate normals. From instrumental observations in this study, we consider only characteristics of icing events. Since digitized instrumental observations are only available after 1984, mean long-term

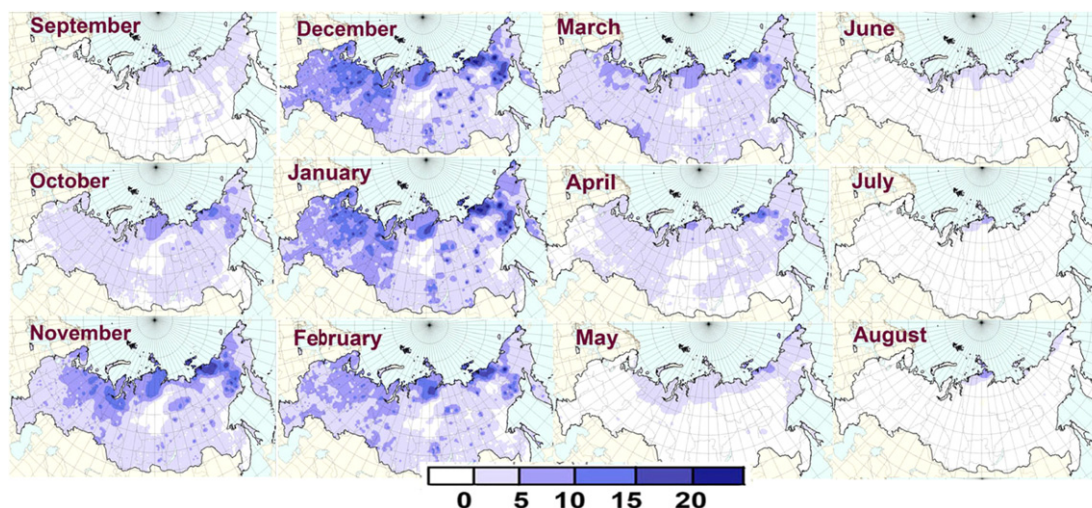


Figure A1. Long-term means of number of days with icing and hoar frost events (1981–2010).

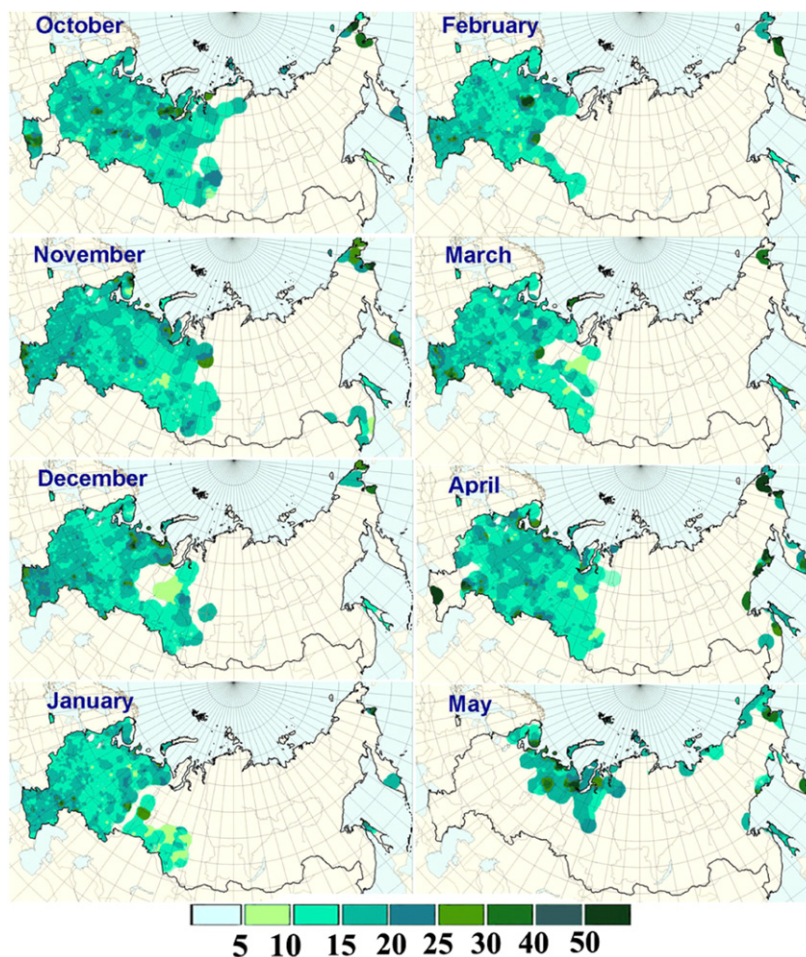


Figure A2. Long-term averages of maximum monthly icing weight (1984–2013) (g cm^{-1}).

values of weight, thickness, and duration of icing were calculated for the 1984–2013 period.

Icing and hoar frost events are reported over almost the entire Russian Federation. However, the

Asian part of the country is less exposed to these events than European Russia. This is due to low winter surface air temperatures and humidity over the Asian part of Russia in the cold season (Alisov 1956; figure 1(a)).

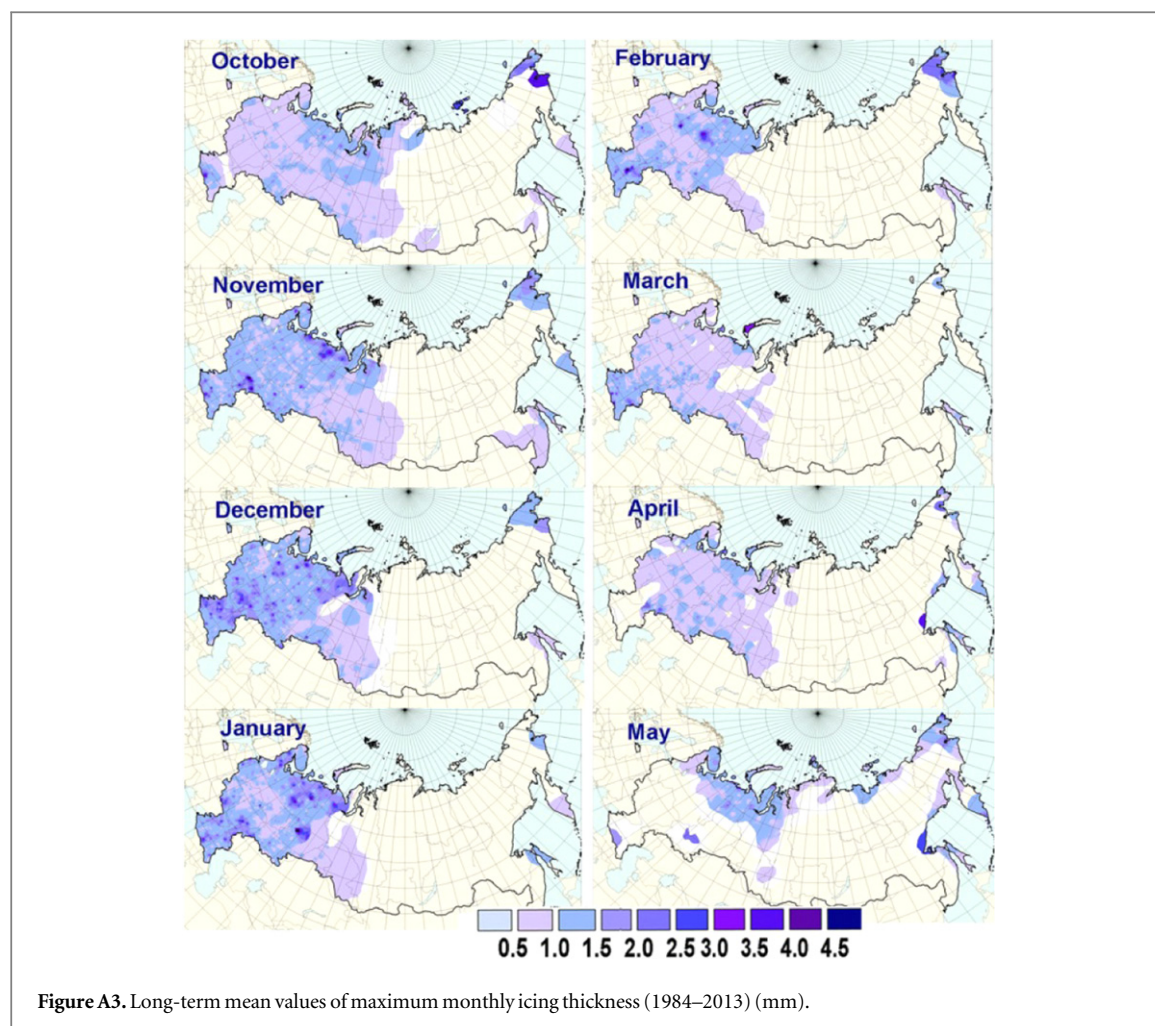


Figure A3. Long-term mean values of maximum monthly icing thickness (1984–2013) (mm).

Among the total number of icing and hoar frost events, the solely icing events are almost unobserved in Eastern Siberia and over much of the Far East, where hoar frost deposits are recorded. The annual cycle pattern of the icing and hoar frost events occurrence is shown in figure A1.

- In September, icing and hoar frost events are only observed in Northern Asian Russia, the Irkutsk region, and Southern Yakutia (0.2–5 days). European Russia experienced relatively high September temperatures at which no icing and hoar frost events form. In European Russia, where long-term September temperature averages (for the period 1981–2010) vary from 6 to 12 °C, icing and hoar frost events do not form.
- In October, icing and hoar frost events are observed over nearly the entire Russia, except the South of the country. These events remain frequent nationwide throughout the entire cold season up to April and in May still can be observed in the Arctic.
- In winter (December through February), the number of days with icing and hoar frost events in Northeastern European Russia varies from 5 to 15, attaining 20 in places. In the vicinity of the Gulf of Ob, icing and hoar frost events also occur rather frequently in winter, from 10 to 15 days. On the Taimyr Peninsula, on the coast of the East Siberian Sea and in the Magadan region, 15–20 days with icing and hoar frost events are recorded in winter. In December, the maximum IW, 20–30 g cm⁻¹, is recorded in Southern and Northeastern European Russia.
- In early spring (March), icing and hoar frost events are still recorded over nearly the whole of the Russian area, but these are not as frequent as in winter. In March, icing deposits weighing more than 20 g cm⁻¹ are observed in the South of European Russia. In late spring (May), icing and hoar frost events are only recorded in the Russian Extreme North and Sakhalin, with long-term averages of the number of days being no more than five.
- Even in July, the Arctic coast of Russia experiences up to ten days with icing and hoar frost events. Cold and saturated Arctic air masses come to the continent, where temperature conditions contribute to icing formation (e.g. mean July temperature on the Taimyr is –0.1 °C).

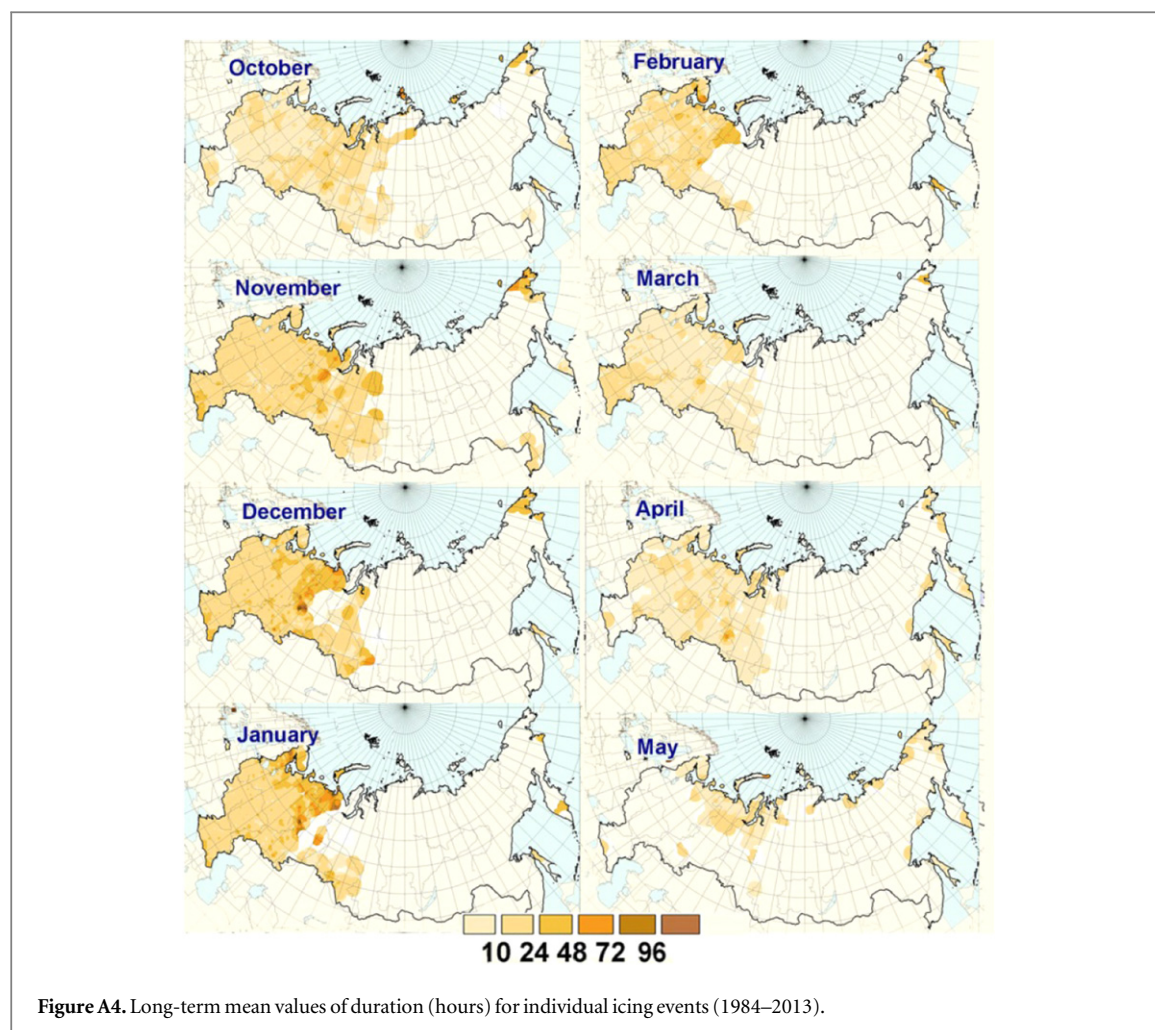


Figure A4. Long-term mean values of duration (hours) for individual icing events (1984–2013).

It should be noted that in some regions in Russia no icing and hoar frost events are observed (e.g., in some areas of the Maritime Territory).

The largest October long-term average of the maximum icing deposit weight (figure A2) was observed in the North Caucasus (Stavropol Krai) and the Western Arctic (the Taymyr Peninsula; over 25 g cm^{-1}). In November through April, the maximum monthly icing deposit weight higher than 15 g cm^{-1} is recorded over most of European Russia and in the Urals. Maximum cold season monthly deposit weights are reported in Northeastern European Russia and the Northern Urals; they vary between 20 and 40 g cm^{-1} .

The largest monthly thickness of icing (figure A3) is recorded in late autumn (November) and winter. Its maximum monthly values can reach 4 mm.

According to the analysis of the distribution of the icing duration over Russia (figure A4), the longest icing duration, 48–72 h and up to 96 h at some individual meteorological stations, is recorded in December and January in Northeastern Russia.

References

- Alisov B P 1956 *Climate of the USSR* (Moscow: Moscow University) 127 p (in Russian)
- Arctic Climate Impact Assessment (ACIA), Impact of a Warming Arctic 2004 (Cambridge: Cambridge University Press) p 140
- Arctic Climate Impact Assessment (ACIA) 2005 Scientific report: ch 2 *Arctic Climate: Past and Present* Cambridge University Press pp 22–60
- Bintanja R and Selten F M 2014 Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat *Nature* **509** 479–82
- Bulygina O N, Groisman P Y, Razuvaev V N and Korshunova N N 2011 Changes in snow cover characteristics over Northern Eurasia since 1966 *Environ. Res. Lett.* **6** 045204
- Bulygina O N, Korshunova N N and Razuvaev V N 2013 Change of the near-surface winds over Russia during the past decades *Transact. Voeikov Main Geophys. Observ.* **568** 156–72 (in Russian)
- Dessler A E and Davis S M 2010 Trends in tropospheric humidity from reanalysis systems *J. Geophys. Res.* **115** D19127
- Documents of the 16th Session of the Commission for Climatology (CCI-16), 2014: CCL-16/Doc.8.1. *Final Report with resolutions and recommendations WMO-No. 1137* (<https://docs.google.com/a/wmo.int/file/d/0B-Uo8XYH2gzqUFhJUlhzM0ExSmc/edit?pli=1>)
- Draper N R and Smith H 1966 *Applied Regression Analysis* (New York: Wiley) p 407
- Fetterer F, Knowles K, Meier W and Savoie M 2002 (updated daily): *Sea Ice Index* (National Snow and Ice Data Center, Boulder, CO: Digital media)
- Groisman P Y, Bogdanova E G, Alexeev V A, Cherry J E and Bulygina O N 2014 Impact of snowfall measurement deficiencies on quantification of precipitation and its trends over Northern Eurasia *Ice and Snow* **2** 29–43
- Groisman P Y, Genikhovich E L, Bradley R S and Sun B M 1999 Trends in turbulent heat fluxes over Northern Eurasia

- Interactions Between the Cryosphere, Climate and Greenhouse Gases Proc. IUGG 99 Symp. HS2* ed M Tranter, R Armstrong, E Brun, G Jones, M Sharp and M Williams (Birmingham, UK, and July 1999) *IAHS Publ. No. 256* (Wallingford, UK: IAHS Press) pp 19–25
- Groisman P Ya and Soja A J 2009 Ongoing climatic change in Northern Eurasia: justification for expedient research *Environ. Res. Lett.* **4** 045002
- Groisman P Y, Sun B, Vose R S, Lawrimore J H, Whitfield P H, Førland E, Hanssen-Bauer I, Serreze M C, Razuvaev V N and Alekseev G V 2003 Contemporary climate changes in high latitudes of the Northern hemisphere: daily time resolution *Proc. 14th AMS Symp. on Global Change and Climate Variations. CD-ROM with Proc. Annual Meeting of the American Meteorological Society (Long Beach, California, 9–13 February 2003)* American Meteorological Society p 10
- IPCC 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon et al (Cambridge: Cambridge University Press) p 996
- Jeong J-H, Ou T, Linderholm H W, Kim B M, Kim S J, Kug J S and Chen D 2011 Recent recovery of the Siberian high intensity *J. Geophys. Res.* **116** D23102
- Kendall M G 1975 *Rank Correlation Methods* 4th edn ed C Griffin (London: Charles Griffin)
- Lugina K M, Groisman P Y, Vinnikov K Y, Koknaeva V V and Speranskaya N A 2007 Monthly surface air temperature time series area-averaged over the 30° latitudinal belts of the globe, 1881–2007 *Trends: A Compendium of Data on Global Change* (Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Lab., US Department of Energy)
- Overland J E, Adams J M and Bond N A 1999 Decadal variability of the Aleutian low and its relation to high-latitude circulation *J. Clim.* **12** 1542–8
- Overland J E, Bond N A and Adams J M 2002 The relation of surface forcing of the Bering sea to large-scale climate patterns *Deep-Sea Res. II* **49** 5855–68
- Rudneva A V 1961 *Icing and Wire Icing Over The USSR Territory* (Leningrad: Gidrometeoizdat) p 175 (in Russian)
- Saunders R B 1998 Assessment of the January 1998 ice storm in Eastern Canada (Environment Canada) www.weatheranswer.com/public/canada_northeast_Ice_Storm_January_4th_-_10th_1998_.pdf
- Screen J A 2013 Influence of Arctic sea ice on European summer precipitation *Environ. Res. Lett.* **8** 044015
- Tilinina N, Gulev S K, Rudeva I and Koletermann P 2013 Comparing cyclone life cycle characteristics and their inter-annual variability in different reanalyses *J. Clim.* **26** 6419–38
- Trenberth K E et al 2007 Observations: surface and atmospheric climate change *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 235–336
- Veselov V M 2002 PC archives of the state data holding and technology of their organization *Proc. RIHMI-WDC* **170** 16–30 (in Russian)
- Zakharov A G 1984 Distribution of icing loads over the USSR territory *MGO Proc.* **1984** 78–93 (in Russian)
- Zhang X, Wang J, Zwiers F W and Groisman P Y 2010 The influence of large scale climate variability on winter maximum daily precipitation over North America *J. Clim.* **23** 2902–15