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Original article

Frequency of Meteorological Factors of Vessel Icing in the Barents Sea and Ice Accretion on its Coast in a Changing Climate

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Abstract
Purpose. The work is purposed at analyzing the regional characteristics of ice accretion frequency and meteorological conditions of vessel icing in the Barents Sea region as well as long-term trends of these characteristics observed in the context of modern climate change.
Methods and Results. The results of studying the frequency of ice accretions are obtained by statistical processing of standard observations at a network of weather stations located near the coast and on the islands of the Barents Sea for the period of 1966–2022. The frequency of vessel icing is estimated using the D. Overland method which is based on calculating the spray icing intensity involving the data on wind speed, air temperature, sea water temperature and its freezing point. The ERA5 reanalysis for 1979–2022 is used as the input data for the D. Overland method. The average annual number of days with the atmospheric phenomena during which dangerous ice accretions of different types can be formed~~,~~ is obtained based on the observation data. The time trends in the average annual number of days with such phenomena are quantitatively evaluated. The reanalysis data processing has permitted to obtain the average annual number of days with vessel icing for the Barents Sea area. The regions of the highest frequency of extreme vessel icing are identified. The time trends in frequency of the changes in a number of days with vessel icing of different intensity are considered for the period of 1979–2022.
Conclusions. On the Barents Sea coast, about three days with dangerous ice accretions of different types are observed on average annually. From 1966 to 2022, the number of such phenomena decreased on average by 0.58 days every 10 years. The highest frequency of marine icing is revealed in the eastern part of the Barents Sea and near the western coast of Novaya Zemlya where the average number of days with extreme icing exceeds 30 days per year. In course of the period of 1979–2022, both a decrease in the average annual number of days with icing up to three ones per year (south of 75°N and west of 50°E) and their increase up to three days per year (in the northern and eastern parts of the Barents Sea) were observed.

Keywords: Arctic, Barents Sea, climate changes, climate risks, hazardous hydrometeorological phenomena, icing, ice accretion, glaze ice, reanalysis, ERA5

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The paper is dedicated to the memory of Galina V. Surkova, eminent scientist in the field of climatology, a brilliant lecturer and mentor

Introduction

Interest in the Arctic region climate changes has been steadily increasing in recent decades. This is mainly due to the fact that the average annual air temperatures in high latitudes rise much faster than in the world as a whole. The frequency of certain dangerous hydrometeorological phenomena is also increasing [1] [1].

Hydrometeorological conditions of vessel icing in the Barents Sea and ice accretion on its coast are the subject of study in this work. Phenomena of this type have a significant impact on the development of human economic activity [2]. Atmospheric and marine icing complicates significantly the process of gas and oil exploration and production as well as their transportation [3, 4]. Under conditions of intense icing, sea vessels can lose stability and capsize. The loss of vessels due to icing, much less a threat of their loss, is not such a rare phenomenon in some areas of the World Ocean [2]. It is assumed that marine activities will strongly develop in the polar and subarctic regions as a part of overall economic development including transport, fisheries and tourism [5]. In this regard, the study and understanding of risks associated with icing phenomena in the Arctic are an urgent task.

On land, icing is associated with atmospheric processes. The first process is associated with precipitation icing which causes the formation of ice and wet snow accretion. The second is in-cloud icing which leads to the formation of hard and soft rime. The greatest hazard is posed by ice, hard rime and wet snow accretion [6].

In the sea basins, the most significant type of marine icing is that in the flow of sea spray, formed when waves hit the hull of a vessel. This icing is called spray icing. Mixed icing is formed on vessels under the combined impact of spray and atmospheric icing [3]. According to statistical calculations, ice accretion takes place on the surface of a vessel as a result of spray icing in 90% of cases [7].

Icing intensity depends on various hydrometeorological conditions which, in turn, are subject to atmospheric processes. Ice accumulation increases with

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[1] Kattsov, V.M., 2022. *The Third Assessment Report on Climate Change and Its Consequences on the Territory of the Russian Federation*. Saint Petersburg: Science-Intensive Technologies, 676 p. (in Russian).

[2] Aksyutin, L.R., 1979. [*Icing of Ships*]. Leningrad: Shipbuilding, 128 p. (in Russian).

[3] Kachurin, L.G., Smirnov, I.A. and Gashin, L.I., 1980. [*Icing of Ships*]. Leningrad: LPI, 56 p. (in Russian).

the growth of waves caused by strong winds. High wind speeds can be associated with mesoscale cyclones with a short lifespan [8].

Previously performed studies have shown that both a trend towards the icing frequency decrease in some areas and a trend towards its increase in others have been observed on the Barents Sea coasts and waters over the past decades [9]. Climate warming cannot mean an unambiguous decrease in the number of cases of vessel icing. It is necessary to analyze the combination of factors that lead to ice accretion [10, 11].

The work is purposed at analyzing the regional features of ice accretion frequency and meteorological conditions of marine icing in the Barents Sea area as well as long-term trends in these characteristics observed under modern climate change conditions. As a result of this work, we obtained spatial and temporal distribution of ice accretion on the Barents Sea coast over a long-term period using observation data from weather stations. Spatial distribution of marine icing characteristics over a long-term period using ERA5 reanalysis data was obtained and time trends in the number of days with conditions for spray icing of vessels in the Barents Sea for the modern climate were estimated.

Research materials and methods

This paper examines various types of hydrometeorological phenomena that lead to icing of sea vessels as well as offshore structures on the coast and in the sea basins. In this regard, various approaches to the analysis of these phenomena were chosen.

The analysis of ice accretion distribution on the Barents Sea coast was based on urgent observation data from weather stations. The main meteorological parameters were obtained from the FSBI “RIHMI-WDC”open data archive [4].

This archive contains urgent observation data from 521 stations for the observation period from 1966 till the present. The list of stations is based on that of Roshydromet stations included in the Global Climate Observing Network. During the study, weather stations located on the coast of the Barents Sea and on the islands in its waters were selected. In addition, several weather stations located on the coasts of the White, Greenland and Kara Seas were selected.

To assess the frequency, spatial distribution and temporal changes, the average annual number of days with atmospheric phenomena potentially leading to severe ice accretion was obtained for each weather station. Days with such phenomena were considered to be the ones when at least one meteorological period corresponds to a certain weather code.

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[4] Bulygina, O.N., Veselov, V.M., Razuvaev, V.N. and Aleksandrova, T.M., 2014. *Description of the Dataset of Observational Data on Major Meteorological Parameters from Russian Weather Stations*. Database State Registration Certificate No. 2014620549 (in Russian).

Time periods during which the observer recorded freezing precipitation were taken as glaze ice cases. Glaze ice accretions have high density and strength, therefore, all periods during which we observed freezing precipitation were considered potentially dangerous.

The KN-01 code does not differentiate between hard and soft rime. Therefore, the analysis was carried out on days corresponding to fog with rime accretion. In order to filter out soft rime accretion, we selected only those rime cases that were observed in the air temperature range from –10.3 to –0.7 °C and at a wind speed of 2 m/s or more. Previously, based on the processing of instrumental observation data, it was indicated that 90% of hazardous (more than 50 mm in diameter) hard rime accretions in Russia were formed precisely within this temperature and wind range [12]. Such data filtering makes it possible to remove the majority of soft rime accretions from the sample as it does not pose a serious hazard and is formed under light winds and air temperatures below –10 °C.

Filtering of samples was also performed for identifying days with wet snow, for which the KN-01 code does not provide a separate code. To identify wet snow, we selected days on which precipitation was observed in the form of moderate continuous or heavy snow, falling at an air temperature from 0 to 0.6 °C and a wind speed under 1 m/s. This range was previously substantiated by the authors of the work as the most favorable one for the formation of dangerous wet snow accretions [12].

As a result, the average annual number of days with atmospheric phenomena potentially leading to the formation of ice, hard rime and wet snow was obtained for each weather station for the period of 1966–2022. Only years without gaps in observations during the cold period were considered. Linear time trends were obtained for each type of accretions; these trends were tested for reliability using the Mann–Kendall criterion [13, 14]. This criterion was previously used by other authors to assess trends in the ice accretion characteristics [15].

Next, spray icing was considered. This type of icing is the most intense and poses the greatest hazard to seagoing vessels. Icing probability and factors contributing to spray icing can be determined by various statistical methods [16]. Most of the methods are based on determining the sea icing probability as a set of specified intervals of values of meteorological parameters: wind speed, water and air temperature. For example, the methodological guidelines for preventing the threat of vessel icing developed at AARI to determine the icing probability and intensity include a combination of wind speed and air temperature [5]. Similar methods are also applied in the fishing industry [6].

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[5] Borisenkov, E.P. and Pchelko, I.G., eds., 1972. [*Methodological Guidelines for Preventing the Threat of Icing on Ships*]. Leningrad: AANII, 81 p. (in Russian).

[6] Giprorybflot, 1983. [*Instruction on Prevention of Accidents and Struggle for Survivability of Vessels of the USSR Fishing Industry Fleet*]. Leningrad: Transport, 120 p. (in Russian).

In this paper, the method proposed by D. Overland was applied for calculating the intensity of marine spray icing. This method provides the determination of icing rate of sea vessels using the icing index [17]. In addition to wind speed and air temperature, this icing index also considers the values of sea water temperature as well as its freezing temperature.

The formula for calculating icing index *PPR* has the following form:

$$PPR = \frac{V_\mathrm{a}(T_\mathrm{f} - T_\mathrm{a})}{1 + 0.4(T_\mathrm{w} - T_\mathrm{f})},$$

where *PPR* is icing index proportional to its intensity; V_a is wind speed, m/s; T_f is sea water freezing point; T_a is air temperature and T_w is water temperature, °C.

The obtained values of icing index *PPR* correspond to different intensities of icing rate (Table 1).

Table 1

Ratio between icing index *PPR* and icing rate *IR*

Parameter	Icing class				
	Light	Moderate	Heavy	Extreme	Particularly extreme
PPR, (m·°C)/s	> 0	> 20.6	> 45.2	> 70.0	> 83.0
Icing rate *IR*, cm/h	> 0	> 0.7	> 2.0	> 4.0	> 5.3

The following empirical formula exists for converting icing index into icing rate *IR* (cm/h):

$$IR = A(PPR)+B(PPR)^2+C(PPR)^3,$$

where *A*, *B*, *C* are empirical constants ($A = 2.73\cdot10^{-2}$, $B = 2.91\cdot10^{-4}$, $C = 1.84\cdot10^{-6}$).

The meteorological data applied for constructing the icing rate fields by the D. Overland method were the ERA5 reanalysis data available on regular latitude and longitude grids with a resolution of 0.25° × 0.25° [18]. The calculations for the Barents Sea area from 1979 to 2022 were carried out with one-hour frequency.

The *PPR* index was calculated for each period from 1979 to 2022. The index was calculated only for grid cells that contained sea surface temperature data (corresponding to “sea” cells) as well as for cells in which sea ice occupied less than 50% of the cell area. If the proportion of sea ice in a cell was more than 50%, then we assumed that spray icing was absent.

Next, the average monthly and average annual values of number of days with sea vessels icing of varying intensity (all cases of icing and extreme icing) were calculated. Any day during which icing of a given intensity was observed at least in one of 24 periods of hourly reanalysis data was considered to be an icing day. To identify all days with icing, the intensity *PPR* > 0 was set as well as *PPR* > 83 for days with extreme icing.

After estimating average values using the least squares method, long-term linear trends in the number of days with sea icing were obtained. The resulting trends were tested for reliability using the Mann–Kendall criterion [13, 14].

Results and discussion

Table 2 presents the obtained data on the average annual number of days with atmospheric phenomena that can lead to the formation of hazardous ice accretion on the Barents Sea coast and in its waters.

Based on these data, a schematic map of the frequency of days with dangerous phenomena of each type was constructed. The map-scheme for each weather station represents a circular diagram indicating the share of average annual number of cases of atmospheric phenomena that cause the formation of various-type ice accretions. The obtained data indicate that it is impossible to single out the predominance of any atmospheric phenomenon in the region under consideration (Fig. 1).

The highest frequency of fogs with rime accretion formed at sufficient wind speed and a temperature range favorable for hard rime formation is observed in the southeastern part of the Barents Sea. A fog with rime accretion is also often observed at several weather stations located far from the coast – Murmansk and Polyarny.

The spatial distribution pattern of the number of days with freezing precipitation is extremely heterogeneous. However, we can make some assumptions regarding this distribution. Glaze ice is least common at Konstantinovsky Cape and Fedorov station. These are weather stations located in the southeast of the Barents Sea and in the Kara Strait on the Kara Sea side, respectively. In this location, there is a low frequency of warm fronts with thermal stratification of the “warm nose” type with a characteristic raised layer of warm air, leading to the formation of freezing precipitation. Low frequency of freezing precipitation in the Murmansk area can be due to the immediate proximity of the Murmansk Coastal Warm Current which promotes the existence of a warm lower layer of the atmosphere preventing the formation of freezing precipitation.

Spatial features of wet snow frequency are traced more clearly. It is known that wet snow accretion is most often formed at air temperatures from −0.1 to 0.3 °C and at low wind speeds (from 1 to 4 m/s) or in calm weather [12]. This is due to the physical properties of snow: snowflakes are large in size, with high windage, easily blown away by strong winds from objects on which icing occurs. Therefore, the wind should not be too strong throughout the icing phase for the formation of hazardous wet snow accretion. This is associated with the fact that the highest frequency of hazardous wet snow accretion is observed in the White Sea area as well as at some weather stations with a high frequency of near-zero air temperatures and low wind speeds due to their location in orographically protected relief forms. For example, Barencburg is located on the Isfjord coast and Vaida Bay weather station is located in the bay of the corresponding name. Murmansk and Polyarny are also located in the Kola Bay.

Table 2

Average annual number of days with potentially hazardous weather events (AN) and linear trend values (days/10 years) for the period of 1966–2022

Weather station	Rime fog		Freezing precipitation		Wet snow		All events	
	AN	trend	AN	trend	AN	trend	AN	trend
Krenkel	0.72	**-0.28**	2.72	**-0.97**	0.35	-0.01	3.79	**-1.26**
Barencburg	0.33	0.08	0.71	0.14	2.50	0.18	3.54	0.40
Malye Karmakuly	0.37	**-0.20**	1.19	**-0.65**	0.23	-0.03	1.79	**-0.88**
Fedorov	2.93	-0.33	0.23	-0.08	0.09	-0.04	3.25	-0.45
Vaida Guba	0.38	0.11	0	0	0.43	-0.05	0.81	0.06
Polyarny	1.47	-0.01	0	0	0.84	0.01	2.31	0
Teriberka	0.12	-0.03	0	0	0.55	-0.08	0.67	-0.11
Kolguyev Severny	2.06	**-0.27**	0.81	**-0.27**	0.31	-0.06	3.18	**-0.60**
Murmansk	1.71	-0.19	0.08	0	1.51	-0.04	3.30	**-0.24**
Svyatoy Nos	0.25	**-0.17**	0.19	-0.06	0.31	-0.01	0.75	**-0.24**
Kanin Nos	4.06	-0.17	0.32	0.11	0.28	0.06	4.66	0
Kandalaksa	0.16	-0.02	0.63	0.1	2.33	**0.38**	3.12	**0.46**
Sojna	5.52	0.18	1.73	-0.16	0.2	-0.03	7.45	-0.02
Indiga	1.33	**-0.61**	0.63	0	0.27	-0.07	2.23	**-0.67**
Umba	0.81	-0.04	0.56	**-0.33**	1.17	**0.31**	2.54	-0.06
Sosnovets Island	1.24	**-0.41**	0.59	**-0.24**	0.37	-0.12	2.2	**-0.77**
Gridino	0.43	**-0.26**	1.11	**-0.61**	0.54	-0.08	2.08	**-0.95**
Zizgin	1.38	**-0.37**	0.4	**-0.18**	0.32	**-0.11**	2.10	**-0.65**
Kem port	0.95	0.09	0.27	-0.02	0.82	0.12	2.04	0.18
Arhangelsk	0.57	**-0.17**	1.12	-0.01	1.12	**0.23**	2.81	0.06
Onega	0.21	**-0.07**	1.68	**0.37**	1.88	-0.02	3.77	0.28
Konstantinovsky Cape	3.60	**-0.28**	0.50	-0.09	0.17	-0.03	4.27	0.33

Note. Significant trends are in bold.

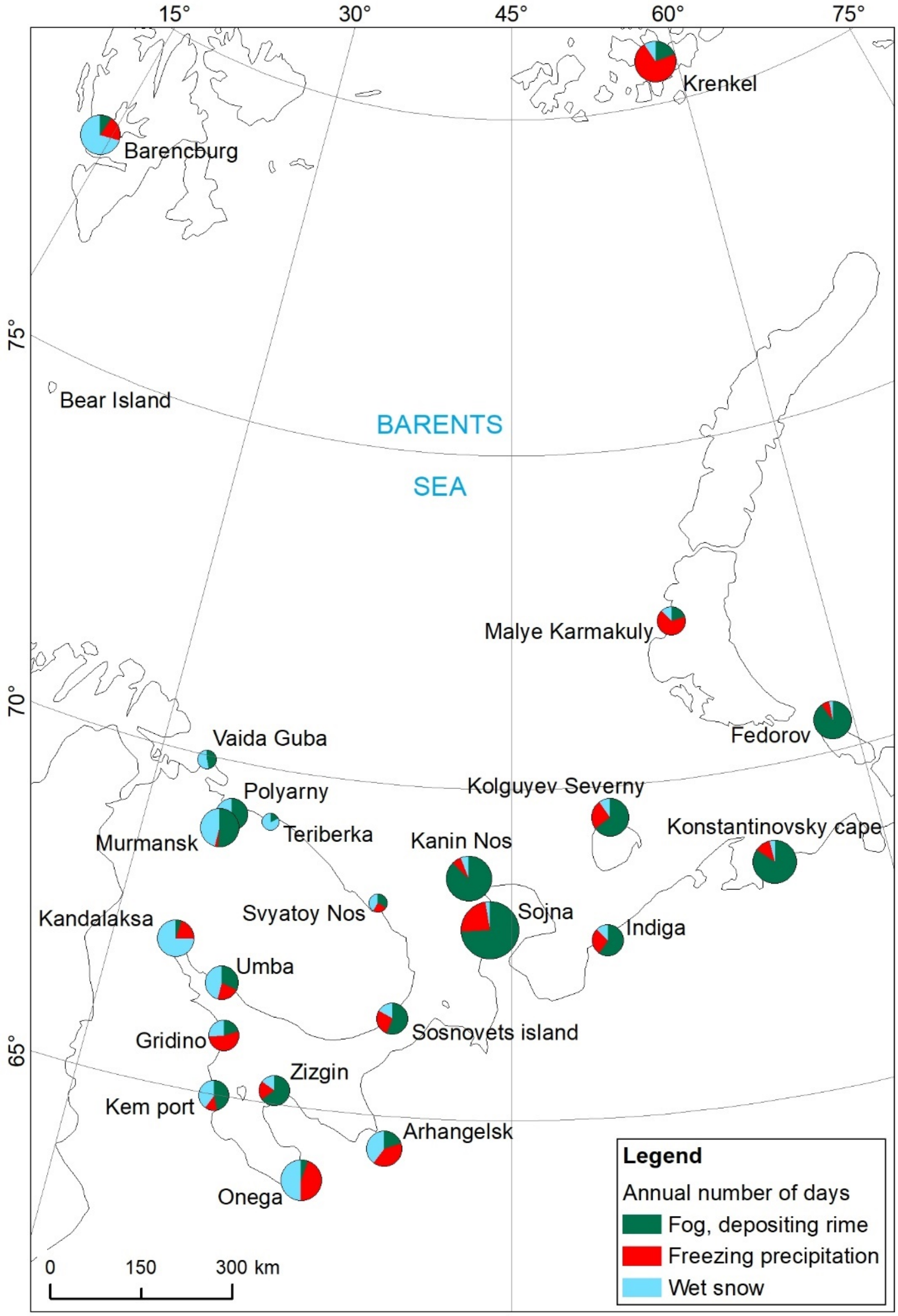


Fig. 1. Map of the average annual number of days with hazardous atmospheric phenomena for the period of 1966–2021 based on visual observations

This work is mainly focused on the phenomena that can result in the formation of hazardous ice accretion. As already noted in Research Materials and Methods, the work involved filtering the data of the main observations with regard to previously obtained ranges of air temperature and wind speed characteristic of hazardous ice accretion of each type.

The process of data filtering can be approached in different ways. The use of stricter criteria leads to a significant reduction in the selected events. For example, when selecting the wet snow events, it was assumed that wet snow accretion can be formed at a speed of up to 1 m/s, inclusively. If it were assumed that dangerous wet snow accretion could only form in calm weather, the number of selected wet snow events would be reduced threefold. On the contrary, if potentially hazardous snowfalls were considered to be the snowfall events at air temperatures from −2 to 2°C at any wind speed, then the average number of days with wet snow in the Barents Sea region would increase by 45 times – from 0.75 to 33 days per year.

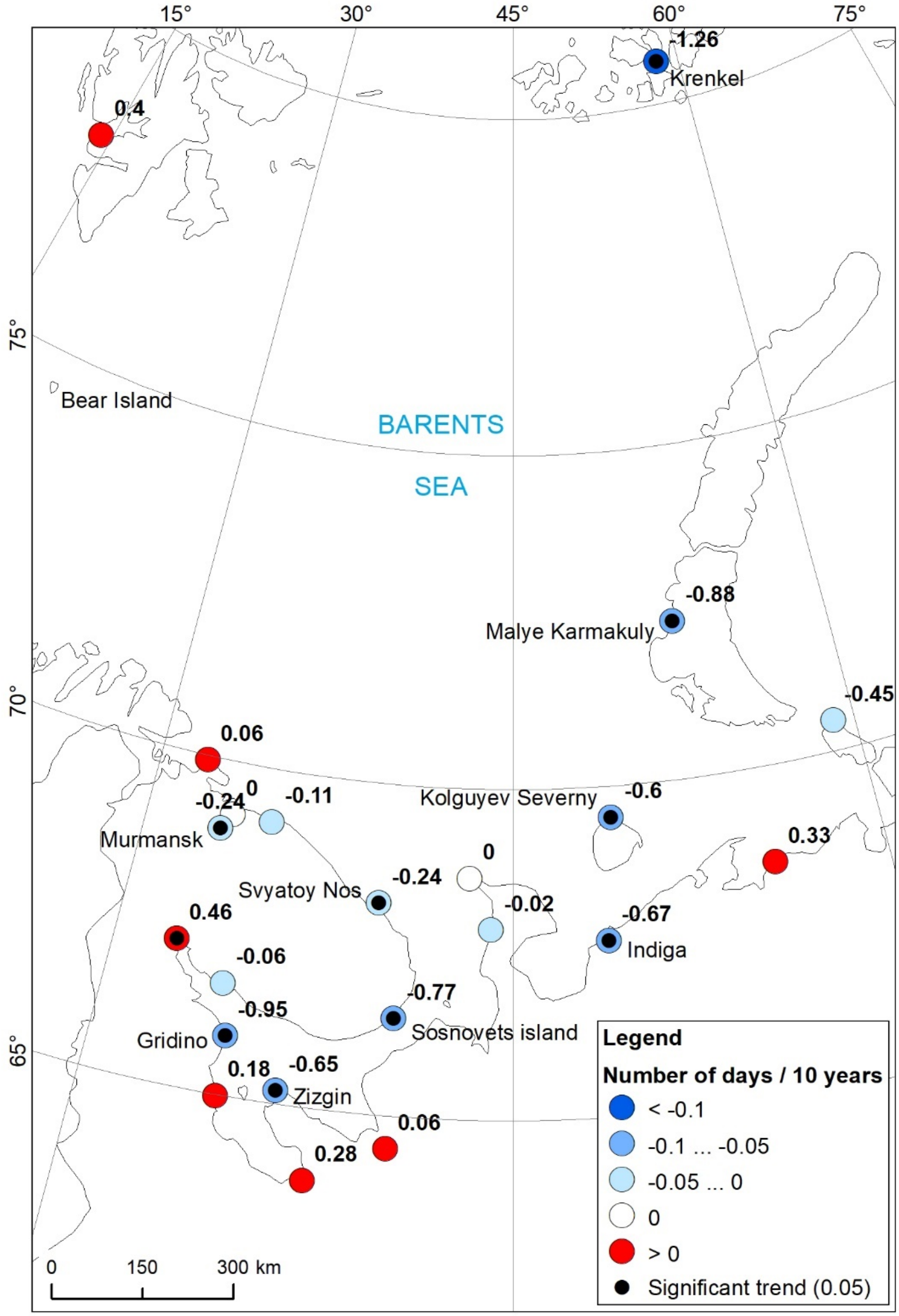
The same applies to fogs with rime formation. To tighten the selection criteria, we can rise the wind speed, increasing the density of the flow of supercooled fog droplets and thereby leaving the cases of the most intense hard rime deposits and excluding an increasing part of the cases of soft rime.

Table 2 presents the estimates of linear trends for the number of days with atmospheric phenomena leading to the formation of hazardous ice accretion for the 1966–2022 period. Estimates for fogs with rime accretion, freezing precipitation and wet snow are given separately. Estimates of the trend for the number of days with all phenomena are also presented. The Mann–Kendall test [13, 14] revealed that some of the obtained trends were reliable for the 5% significance level.

It is shown that significant trends in the number of days with rime have negative values from −0.61 to −0.07 days per decade. The number of days with freezing precipitation also tends to decrease. Linear trends in the number of days with wet snow are significant only at 4 stations out of 22. In general, the trends in the number of days with wet snow can be assessed as near-zero, weakly significant, with individual remarkable positive changes at Kandalaksha, Umba and Onega weather stations.

Since in this paper the trends in the number of days with atmospheric phenomena causing the formation of ice accretion were considered in the context of climate risks in the Arctic, it is appropriate to estimate the trend in the total number of such phenomena.

Fig. 2 represents a schematic map showing the linear trend value of the total number of days with observation of all potentially hazardous atmospheric phenomena for each weather station over the 1966–2022 period. The trend of the number of days for 10 years is shown for convenience.



F i g. 2. Map of time trends (number of days / 10 years) of the hazardous atmospheric phenomena frequency for the period of 1966–2021

It follows from the map that negative trends are observed mainly in the territories facing the coasts of the White and Barents Seas. Positive trends are usually observed at weather stations with a more continental location. Almost all significant trends have a negative sign. The exception is Kandalaksha weather station where the wet snow have contributed to the positive trend the most.

Previously published works estimated the trends in the average annual number of days with ice on the territory of Russia [19]. In general, a weak negative trend (−0.2 days/year) in the number of days with freezing rain was obtained for the Atlantic Arctic. The negative trend in the number of days with hazardous ice phenomena obtained in this work is in good agreement with the previously presented estimates.

Despite the fact that this study provides average estimate only for significant trends, it is impossible to make an unambiguous and reliable conclusion about long-term changes in the frequency of potentially hazardous atmospheric icing phenomena in the region under consideration. This is due to the fact that the obtained values of linear trends are characterized by a large scatter, and the initial data of ice accretion visual observations are highly heterogeneous.

According to the report on the climate features on the Russian Federation territory, trends in modern changes in the ice accretion characteristics in Russia obtained by instrumental observations reveal that there is an insignificant positive trend in the number of days with glace ice and a significant trend in the number of days with wet snow accretion for the quasi-homogeneous climatic region of the Atlantic Arctic [7].

Thus, it is possible to expect about three days per year when atmospheric phenomena leading to the formation of heavy ice accretion will be observed in the Barents Sea region. A number of days with atmospheric icing will probably decrease by an average of 0.2 days per decade. The reduction in the number of days with icing and the decrease of its impact on vessels and seaport infrastructure can be considered to be a positive effect of climate change in the Arctic. However, despite the substantial proportion of significant trends, such estimates should be treated with caution, considering the complexity of atmospheric observations which affects the processed data quality as well as the climate variability of this region.

The approach based on the data of the main urgent observations can be applied to the assessment of changes in the frequency of ice accretion of different intensity, primarily for those regions where no instrumental observation data are available. However, it should be noted that this method requires testing in territories located in other climatic regions of Russia.

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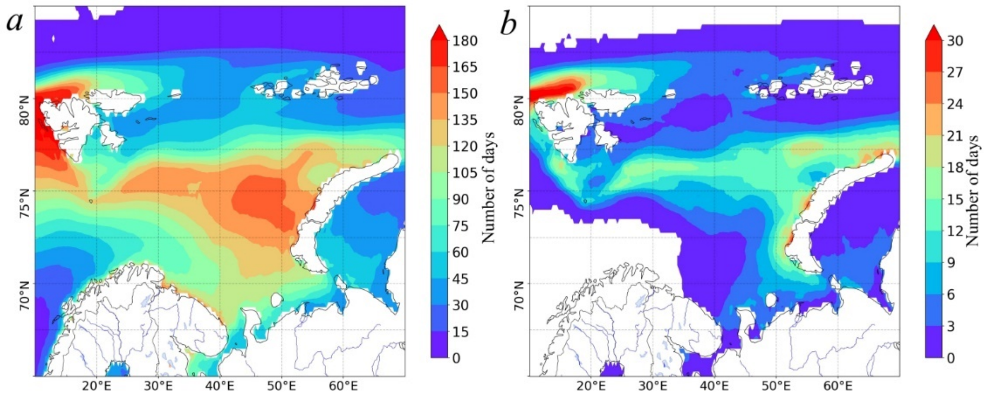
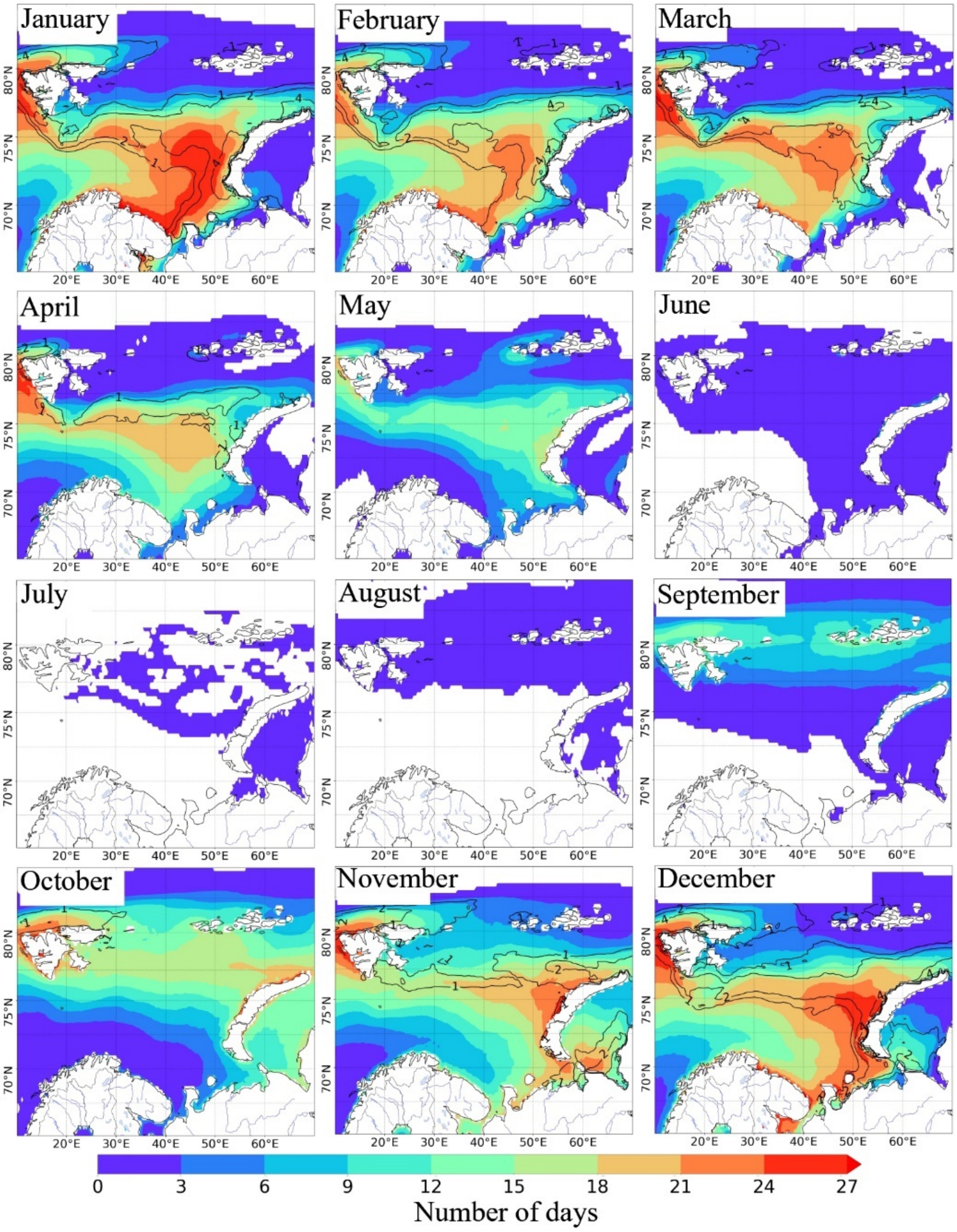
[7] Roshydromet, 2022. *A Report on Climate Features on the Territory of the Russian Federation in 2021*. Moscow: Roshydromet, 110 p. (in Russian).

Climatology of spray icing in the Barents Sea is further examined in the paper. In this case, icing is a set of meteorological factors that contribute to the icing formation according to the D. Overland method. The frequency of vessel icing in the Barents Sea was obtained for the 1979−2022 period. The highest values of the average number of days with icing are recorded westwards of Svalbard and Novaya Zemlya as well as on the Kola Peninsula northern coast (Fig. 3, *a*). Thus, on average, more than 150 days with icing are observed in these areas per year. Along the mainland coast, the average annual number of days with icing has a non-uniform distribution. Along the coastline of Arkhangelsk Oblast and the Nenets Autonomous Okrug, vessel icing is observed less frequently than along the Murmansk Oblast coastline. Absolute heights above sea level on the Kola Peninsula are higher; this can lead to strong katabatic winds and an increase in the number of icing events. Under effect of the warm Norwegian Current, the probability of vessel icing is significantly reduced, its contribution can be traced to 40°E. In this case, on average, no more than 120 days with ice accretion on the vessel surface as a result of spray icing are observed during the year. The highest values of the average number of days with extreme icing have similar distribution (Fig. 3, *b*). Thus, extreme icing is most often encountered westwards of Svalbard and Novaya Zemlya. In these areas, the number of days with conditions for extreme icing is approximately six times less than the average number of days with icing in general and ranges from 21 to 30 days per year. Northwards of the islands, the icing frequency is relatively low due to the formation of a long-term ice cover; on average, less than 10 days with icing of vessels are observed per year. Southwards of Svalbard, higher temperatures are observed due to the warm Norwegian Current; this also leads to a lower frequency of icing.



F i g. 3. Average annual number of days with vessel icing (*a*) and extreme icing (PPR > 83) (*b*) in the Barents Sea for the period of 1979–2022



F i g. 4. Average number of days with vessel icing in the Barents Sea for each month during the period of 1979–2022. Black isolines show the number of days with extreme icing (*PPR*>83) per month

Further, we will consider annual course of number of days with spray icing in the Barents Sea (Fig. 4). Maps of the number of days with sea icing were plotted for each month of the year. The results revealed that the greatest number of days with icing were observed from October to April. In the areas most favorable for icing, this phenomenon is observed, on average, almost every day (more than 27 days per month). The smallest number of days with icing is observed in July.

Fig. 4 also shows the average long-term number of days with extreme vessel icing. During the year, extreme icing is observed most frequently in January (up to five days per month). During the warm period of the year from May to September, the average number of days with extreme spray icing is less than one per month.

Let us consider the obtained time changes in the frequency of the total number of days with icing per year and the number of days with extreme icing during the year (Fig. 5). The distribution fields of these two indicators are similar.

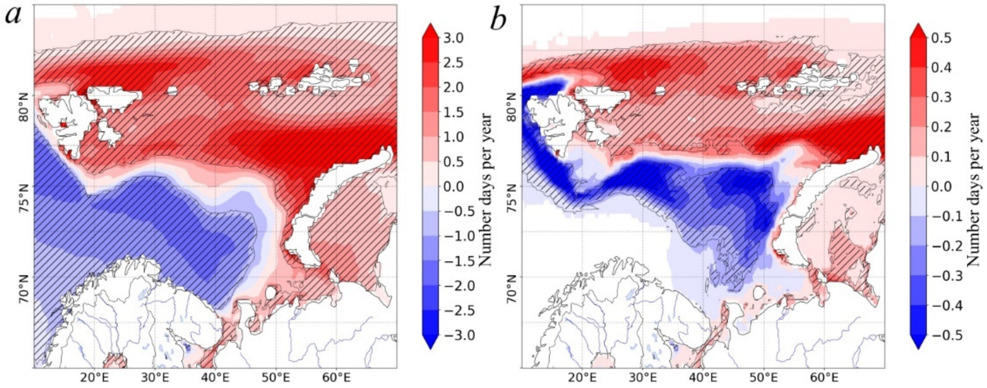


Fig. 5. Temporal change in the frequency of vessel icing in the Barents Sea for the total number of days with icing (*a*) and for the number of days with extreme icing (*b*) in 1979–2022. Shading shows the areas in which the obtained trends are reliable at the 1% significance level

Due to the average annual increase in air temperature, the sea ice area decreases. The areas previously covered by sea ice are water surfaces that are a source of sea spray which contributes to the spray icing formation. In this regard, there is an increase in the frequency of vessel icing in the Barents Sea area located between Svalbard, Franz Josef Land and Novaya Zemlya. In some areas, the icing frequency can increase by three days per year and more.

In the south of the Barents Sea below 75°N and west of 50°E, the influence of the warm Norwegian Current is observed. Due to the most intense climate warming in the Arctic, the average air temperature in this area, not covered by sea ice, increases, which leads to a decrease in the frequency of sea icing. In this case, the frequency of icing changes by approximately three days per year, now in the direction of decreasing cases with ice buildup on the vessel surface.

For the period from October to April, 53 synoptic events were analyzed and conditions for extreme icing during them were diagnosed. It was found that such conditions were recorded most often in January (14 cases out of 53), February and

December (11 and 10 cases, respectively). In the overwhelming majority of cases, conditions for extreme icing were created in the rear parts of cyclones characterized by high wind speed and powerful advection of cold air. Both high wind speeds and low air temperatures contribute to ice formation and accretion on the vessel surface as a result of spray icing. In addition, extreme values were noted in the prefrontal region in some cases. Icing was traced in a narrow strip ahead of the warm front. The prefrontal region is characterized by wind gustiness decrease and simultaneous increase in wind speed. It can be assumed that extreme values of vessel icing in the prefrontal region are associated with a wind speed increase.

Conclusion

The work has studied the spatial and temporal changes in sea vessel icing in the Barents Sea and ice accretion on its coast under modern climate conditions.

It was demonstrated that in this region, on average, there are about three days a year with atmospheric phenomena during which hazardous ice accretion can be formed on the coast. From 1966 to 2022, a trend towards decrease in the average annual number of days with such phenomena was traced. Statistically significant linear trend was, on average, about −0.58 days over 10 years. A significant positive trend was observed only at Kandalaksha weather station, with other positive trends being statistically insignificant. In general, the trends have a large scatter which results in the ambiguous conclusion about long-term changes in the frequency of atmospheric icing phenomena.

Frequency of meteorological conditions for seagoing vessel icing is obtained using ERA5 reanalysis data for 1979–2022 period. The areas with maximum and minimum frequency of the average annual number of days with icing of varying intensity are identified. It is revealed that the average number of days with extreme icing is more than 30 days per year in some areas of the Barents Sea. The highest marine icing frequency is observed in the eastern part of the Barents Sea including the area near the Novaya Zemlya western coast.

It is shown that significant changes in the frequency of vessel icing in the Barents Sea have occurred over the past decades. Both a decrease in the average annual number of days with icing to three days per year (southwards of 75°N and westwards of 50°E) and an increase to three days per year (in the northern and eastern parts of the Barents Sea) were observed.

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