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Limitation of visibility on the coast of the Kara Sea in the context of modern climate change

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Abstract
An analysis of standard meteorological observations of horizontal visibility was performed, based on instrumental and visual observations at two Russian meteorological stations located on the southern coast of the Kara Sea. Horizontal visibility is an important navigation criterion for choosing safe routes and speeds along the Northern Sea Route. A decrease in horizontal visibility to less than 50 m is a dangerous weather event. The study of the conditions for the occurrence of such a dangerous phenomenon has become especially relevant when using giant ice-class tankers, the length of which reaches 300 m. The analysis showed that the frequency (probability) of unfavorable conditions for horizontal visibility has a pronounced seasonal variation. A relationship was found between the increase in frequency and changing climatic conditions, namely an increase in frequency against the background of modern global warming which is expressed both in a steady increase in surface air temperature in all seasons of the year and in a reduction of sea ice cover in the summer.

Key words: Arctic, climate change, hazardous weather, visibility

List of abbreviations: NSR – Northern Sea Route, HV – horizontal visibility, MS – meteorological station, HWE – hazardous weather events

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Introduction

The relevance and necessity of the studies on horizontal visibility in polar regions is supported by the high resource potential of *e.g.* the Kara Sea, a region which is part of our analysis. The main transport corridor of the Northern Sea Route (NSR) begins at the Kara Sea, and exploratory studies related to the extraction, process-

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ing and transportation of hydrocarbons are carried out there as well (Mironov 2010, Ashik 2021). The planning and implementation of these activities depend on the observed and expected weather and ice conditions of the region, which are determined by changes in the global and regional climate. In the Arctic, these changes have received their own name - "Arctic amplification". It indicates that this process of near-surface air temperature warming is more rapid and more pronounced in Arctic than in other world regions (Shu et al. 2022). It is well established for the region that the warming rates in the northern part of the Barents and Kara Seas are maximum compared to other areas of the Western Arctic (Ivanov 2019, Isaksen et al. 2022, Karandasheva et al. 2024). The warming brings several ecological consequences to the region such as *e.g.* negative impact on the phytoplankton productivity of high Arctic bays and their adjacent areas (Demidov et al. 2024). Warming is most pronounced in the winter months and occurs 2-3 times faster than in middle latitudes, which seriously affects weather and ice conditions in different seasons of the year (Kohnemann et al. 2017). Sea ice extent recently decreases (Yamagami et al. 2022) in the region, in spite of interannual variability and local anomalies (Prokhorova et al. 2023). New challenges arise in the context of observed climate change, and they are associated with extreme changes in weather and ice conditions, which can significantly limit industrial activities in the Kara Sea. Seasonal and long-term changes in hydrometeorological parameters can be both favorable and complicating for the above activities. These are not only ice conditions, but also some hazardous weather phenomena. For example, limited horizontal visibility. Critical changes in this parameter are especially important when operating giant Arc7 ice-class tankers on the NSR, such as the “Christophe de Margerie”, the length of which is about 300 m. Under severely limited horizontal visibility operational capabilities and navigation of the tankers are significantly reduced. Thus, the conditions for the occurrence of limited horizontal visibility and possible changes in this parameter on different time scales are in demand by navigators and are the subject and goal of our research.

Long-term changes in horizontal visibility

Horizontal visibility (HV) is determined at meteorological stations (MS) during standard meteorological observations. HV characterizes the optical properties of the atmosphere and shows the degree of attenuation of the electromagnetic radiation flux in the visible wavelength range. The content of water vapor in the surface layer of the atmosphere, especially in the form of water droplets, as well as the content of various aerosols, including snowflakes, has a significant impact on HV. Operational information on HV is important information for the safe operation of maritime transport, cargo and other operations, such as *e.g.* helicopter flight operations. A decrease in HV to 50 m is considered critical in accordance with the accepted standards for extreme values of hazardous weather events (HWE). For polar regions, HWE are caused mainly by fog, mist, haze, precipitation like snow, rain and low cloud boundary (close to the sea surface. In this study, we consider a slightly larger critical value than 50 m, namely a HV of 200 m or less. A decrease in HV to this value already significantly complicates the operation of Arc7 ice-class tankers, of which the “Christophe de Margerie” is a prominent example.

Material and Methods

We analyzed long-term changes in the HV at two coastal Russian meteorological stations (MS), "Dikson" and "Chelyuskin", located near the main NSR route in the Kara Sea for the period 1966–2021 (*see* Fig. 1). At the selected MS, the HV data were the most complete and without significant gaps. The selected period includes the moment of change of sigh of the surface air temperature trend. Thus, the cooling trend of 1960–1990 was replaced by a warming trend, which continues to the present day. This allows us to consider the features of change of HV in a relatively cold climatic period and in the period of modern warming in the Arctic (Ivanov 2019, Przybylak 2000, Serreze and Francis 2006).

At the MS, measurements of the HV were made using either instruments, or, in their absence, visually using specially selected landmarks. The M-53AV polarization visibility meter was used during daylight hours, and the M-71 nephelometric backscattering unit was used during the dark hours. Pre-selected landmarks on the terrain were used for visual assessment, and the HV value was estimated in points on a special scale.

For the analysis, data from standard meteorological observations were used (RIHMI-WDC[1]). Such observations were carried out 8 times a day at synoptic times linked to Greenwich Mean Time. As mentioned above, only the two MS had the most complete series of observations and, therefore, they were selected for the study.

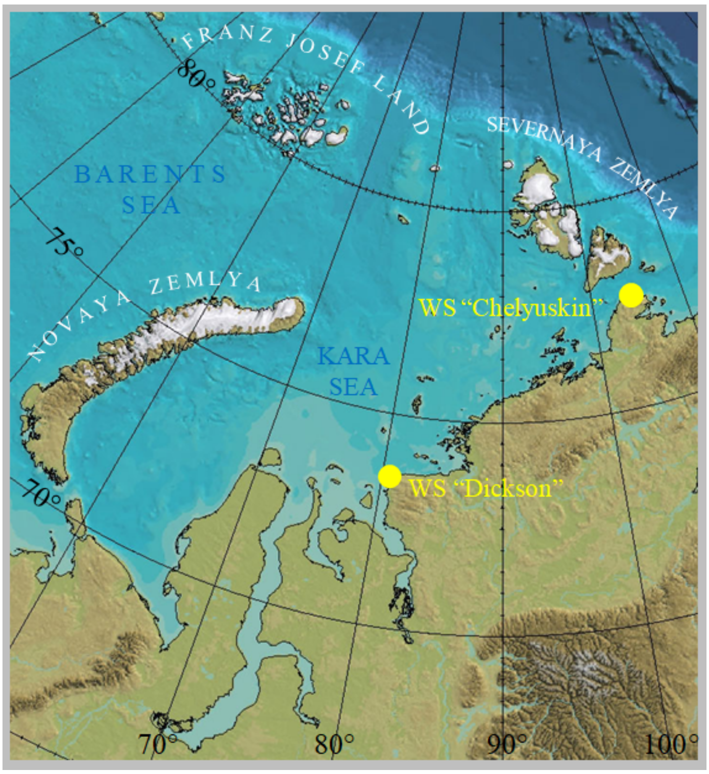

Fig. 1. Position of meteorological stations Dikson and Chelyuskin in the Kara Sea.

Results and Discussion

The objects of the study were the values of repeatability (probability) of occurrence of conditions of limited HV during standard observation periods. Seasonal changes in long-term values of the repeatability of limited horizontal visibility range are considered. A significantly expressed seasonal variation in repeatability of the studied (low, ≤200 m) HV values has two maxima during the year. One maximum is observed in January–February, the second, mostly, in July. There are two main reasons for the decrease in HV. In winter, HV decreases due to the transfer of snow during snowstorms that occur when the surface wind speed increases, starting from wind speeds of 6 m/s and more. In summer, the main reason is the formation of fog. High relative humidity, as well as weather with low wind speeds contributes to this. The highest average monthly values of relative humidity are observed in the summer months (90% and more). The maximum is observed in July, while throughout the year the relative humidity is more than 80%. Such seasonal variation of short-range visibility recurrences is typical for the entire Kara Sea region (Ashik 2021). However, Bryazgin and Dementyev (1996) report that the spatial distribution of snowstorms in the winter season and fogs in the summer, and accordingly the conditions for limiting the HV, were different.

Snowstorms, as the main reason for low HV in winter, can be observed simultaneously at a number of stations, and the formation of fogs, as the main reason for low HV in summer, simultaneously at several stations is a rare phenomenon.

Seasonal changes in the frequencies of limited HV at MS Dikson (southwestern part of the Kara Sea coast) and MS Chelyuskin (eastern part of the Kara Sea coast) are shown in Figs. 2 and 3. An increase in the frequencies of limited HV in the summer (June–August) and winter (December–February) seasons was apparent in both cases.

The maximum frequency of limited HV in the cold season was observed in January, in the summer season – in July. The minimum values of frequency were observed in the transition seasons – in May and October. The time series of observations used for the analysis cover a time interval with two different trends in the change of surface air temperature in the Arctic. The first trend reflects a decrease in surface air temperature, the second (subsequent) indicates its increase and characterizes the modern warming of the Arctic. The change of sign of trends was observed in different regions of the Arctic in the late 1980s – early 1990s. In our case, the change of sign was in 1991–1992.

Regarding the whole period of investigation, we have to pay attention to the change in the seasonal course of the repeatability of the limited HV at the Chelyuskin MS separately for the period 1966–1991 and 1992–2021. While in the first period the annual maximum repeatability was observed in winter (Fig. 2b), in the second period the maximum was noted in the summer season (Fig. 3b). Meanwhile, at the MS Dikson the nature of seasonal changes in repeatability has not changed (Figs. 2a, 3a).

Long-term changes in the frequencies of limited HV visibility are shown in Figs. 4 and 5. The maximum interannual (relative) changes in repeatability at both MS reached 10% in both warm and cold seasons of the year. At the same time, the maximum absolute values of the repeatability of the limited HV in winter at the MS Dikson did not exceed 4% (Fig. 4b), while at the MS Chelyuskin similar values reached 16%. The general trend of changes in the frequencies of limited HV is similar for both MS and both seasons of the year. It consists of a decrease in values, starting from the 1960s, until approximately 1990–2000. Then the trend changed to the opposite - an increase was observed. This process can be described by a second-degree polynomial (Figs. 4, 5 red lines). Change in the sign of the trend approximately (with a small delay) coincided with the beginning of the recent warming in the Arctic (Kohnemann et al. 2017).

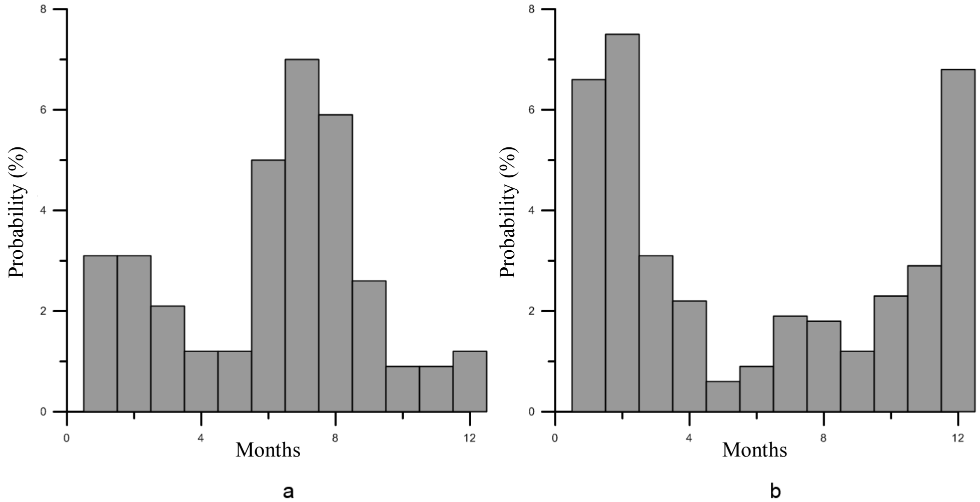

Fig. 2. Seasonal changes in the frequency of HV equal to 200 m and less at MS Dikson (**a**) and MS Chelyuskin (**b**), average for the period 1966–1991.

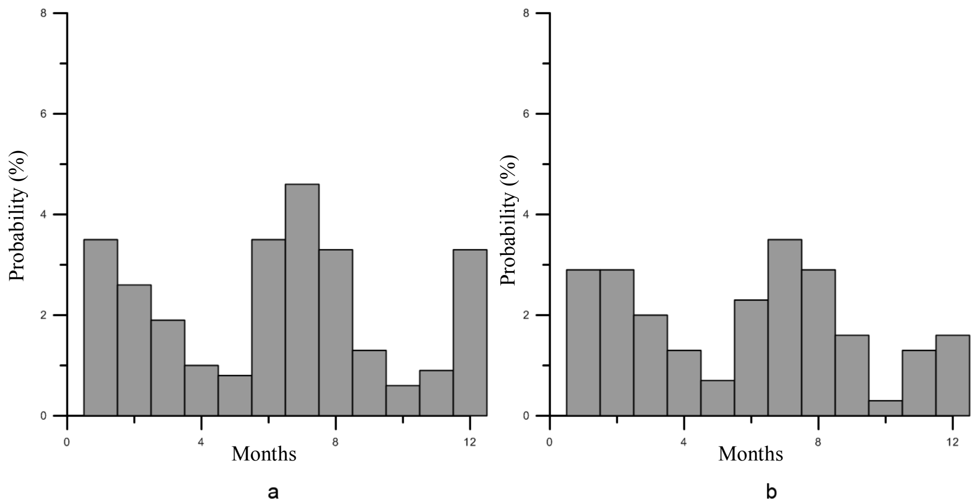

Fig. 3. Seasonal changes in the frequencies of HVs equal to 200 m and less at MS Dikson (**a**) and MS Chelyuskin (**b**), average for the period 1992–2021.

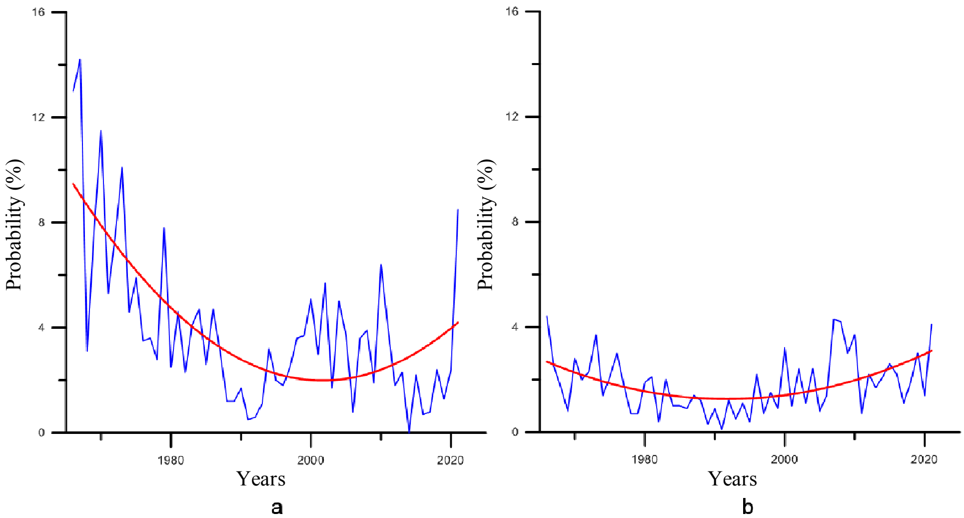

Fig. 4. Frequency of observations with a HV of 200 m or less at the Dikson MS in the summer (**a**) and winter (**b**) seasons, 1966–2021.

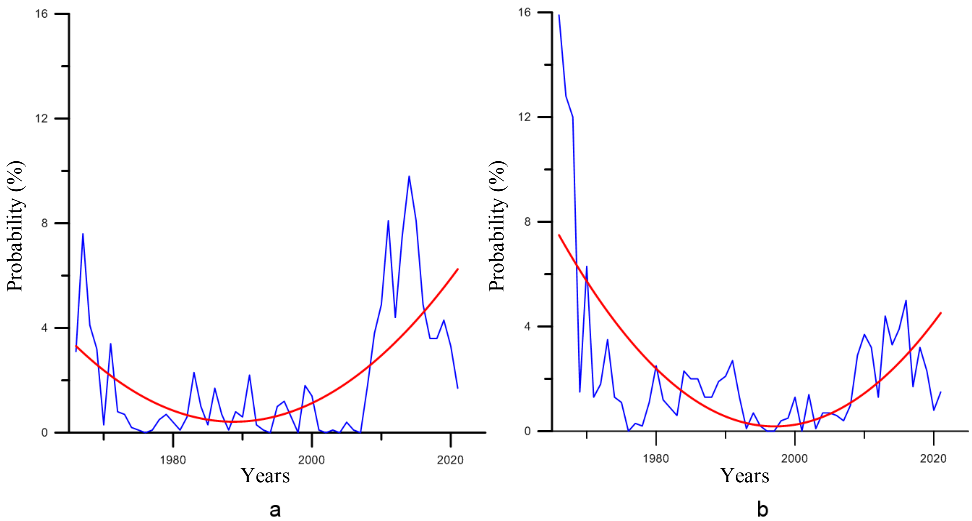

Fig. 5. Frequency of observations with a HV of 200 m or less at the Chelyuskin MS in the summer (**a**) and winter (**b**) seasons, 1966–2021.

The explanation of the causes of the changes in the limited HV trends requires further follow-up special studies. Global and regional processes associated with an increase in surface air temperature and heat fluxes from/to Atlantic waters contribute to a decrease in the sea ice area and an increase of open water areas in summer (Alexeev et al. 2013, Alekseev et al. 2015, Karandasheva et al. 2021, Isaksen et al. 2022, Mokhov and Semenov et al. 2022). The latter circumstance (an increase in the area of open water in summer) contributes to the formation of fogs due to the entry of more water vapor into the atmosphere. It is possible that one of the reasons for the occurrence of poor visibility conditions was an increase in heat transfer to the atmosphere, namely the latent heat flow (Surkova and Romanenko 2021). Another possible reason might have been the conductivity heat flow through the snow-ice cover from the underlying water layers (Liu and Zhang 2025). Magnitude of the conductivity heat flux changes through snow-ice cover are comparable to those in surface both sensible/latent heat and long-wave surface irradiance. Changes in atmospheric circulation parameters (Sviashchennikov et al. 2020), an increase in interannual variability of weather conditions characteristic of the modern warming regime (Ilyushchenkova et al. 2023), as well as an increase in the advection of Atlantic waters into the Barents and Kara Seas (Asbjørnsen et al. 2020, Yamagami et al. 2022) may, in combination, favor the identified trend.

Conclusions

The presented studies of seasonal and long-term changes in the HV in the Kara Sea were performed for a limited number of observation points. Nevertheless, an increase in the frequency of limited HV in the summer (June–August) and winter (December–February) seasons of the year was revealed. In winter, snowstorms were the cause of the increase in the frequency of limited HV. In summer, the cause was a fog. At the same time, the probability of a snowstorm in summer and fog in winter is extremely small. A change in the sign of the long-term trend in the frequency of limited HV was found: an increase started from 1990–2000, which almost coincided with the beginning of the observed recent warming of the Arctic (Kohnemann et al. 2017, Rostov et al. 2019, Sviashchennikov and Drugorub 2022). It is necessary to pay special attention to the detailed study of the connections between frequency of limited HV and observed climate changes, taking into account revealed increase of limited HV frequency at the NSR.

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