Comparative analyses of changes in the ice cover of the Tatar Strait in relation to 1961-1990 and 1991-2020 climate normals

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Abstract. Current warming in the Northern Hemisphere has encompassed not only the surface atmosphere, but also manifested itself in a change in the state of the sea ice cover, as an integral part of the climate system. One of the indicators of the warming was a reduction in ice cover observed in the water area of the Far Eastern seas since the late 1980s. The prospective areas of hydrocarbon deposits discovered in the Tatar Strait, as well as the existing needs for the transportation of hydrocarbons along the shipping routes in the strait, led to the emerging interest in researching the ice regime of the Sea of Japan in the modern climatic era. The proposed paper analyses the changes in ice cover of the Tatar Strait in relation to 1961–1990 and 1991–2020 climate normals. The regularities of the long-term variability of ice cover within non-overlapping 30-year periods were revealed. The analysis of the dynamics of ice cover anomalies, calculated for each normal separately, was carried out. An assessment of the distribution of winter types in the periods under study was carried out. The characteristic features of variations in the intra-seasonal course of ice cover and the dates of the onset of ice phases in different types of winters were identified.

1. Material and Methods

According to the provisions of the World Meteorological Organization guidelines for the calculation of climate normals [1], non-overlapping 30-year time periods starting from 1901 were taken as climatological standard normals. The period from 1961 to 1990 was defined as the standard reference period for long-term assessment of climate change. The purpose of this work was to make a comparative analysis of changes in the elements of the ice regime of the Tatar Strait for the periods corresponding to the standard reference period 1961–1990 and the standard climate normal 1991–2020 (figure 1).

From 1960 to 1991, calculation of the area of ice extent was carried out according to the data obtained from the maps of regular aircraft ice reconnaissance [2, 3]. From 1971 to the present, the main source of information was satellite imagery of the ice extent from spacecrafts carried out in the microwave range. Accuracy assessment of calculated data for aeronautical observations did not exceed 5% [2], for satellites – 2% [4; 5].

The calculation of the ice cover of the Tatar Strait was carried out using ICE software package [6, 7] according to the data of colour-coded schematic maps of ice concentration [8]. The calculations were carried out within the boundaries of the strait, determined by the Main Directorate of Navigation and Oceanography of the Ministry of Defence of the Russian
The value of ice cover for the season was calculated by averaging the values of the ice extent area on the 15th day of each month for the period from December to April.

The analysis of ice cover anomalies was carried out by the method of integral curves, which allowed one to identify the characteristic patterns of its long-term variability [10]. The integral curves were calculated by sequential algebraic addition of ice cover anomaly values.

The typification of winters was determined by the anomaly of ice conditions using 0.8 σ criterion (σ is the standard deviation) [11], according to which extremely severe winters (ESv ≥ 1.2 σ) were identified; as well as severe (+0.4 σ ≤ Sv < +1.2 σ); moderate (−0.4 σ < M < +0.4 σ); soft (−1.2 σ ≤ S ≤ −0.4 σ); extremely soft (ES ≤ −1.2 σ) winters.

2. Results
The average value of ice cover of the Tatar Strait for the standard reference period was 31 % or 32.7 thousand km². The maximum value was observed in 1985, and the minimum – in 1974, 56 and 18 %, respectively. The range of fluctuations in its values was 38 % (figure 2). The analysis of the long-term variability of ice cover in the standard reference period revealed a general tendency of its increase by 3 % for every 10 years (a significant linear trend at the 95 % level), which corresponds to an increase in the ice area by ~10 thousand km² over a 30-year period. At the same time, for the entire reconstructed series of observations in the Tatar Strait from 1882 to 2018 [12], a general tendency for a decrease in the area of ice extent at a rate of 0.7% over 10 years was established.

The average value of ice cover in the standard climate normal 1991–2020 was 29 % or 30.9 thousand km² (figure 3). The difference between the mean values of ice cover for both normals...
was less than the accuracy of calculations. The range of fluctuations in ice cover was 24 %, which was 1.6 times less than the same value in the standard reference period. There was no linear trend slope. The maximum ice cover was recorded in 2001, when its value was 43 %. The minimum ice cover of 14 % was recorded in 1991, which corresponded to the absolute minimum in the entire history of observations [12].

It was established that long-term fluctuations in the ice cover's seasonal variability in the Tatar Strait and the Sea of Okhotsk were in phase only in two isolated periods: 1894–1920 and 1985–2009. In the current warming period, the general downward trend of the ice cover in the Tatar Strait commenced in 1985, five years later than in the Sea of Okhotsk [12]. Those discrepancies happened due to the morphometry of the studied water areas (the wind tunnel effect in the strait) and the particular conditions of destruction of the ice cover in southern latitudes south of 48°N. In the Tatar Strait, the ice cover was destroyed due to the active thermal effect of the western flow of the warm Tsushima Current, while in the southern part of the Sea of Okhotsk, the processes of ice accumulation in the "ultimate ice trap of the Sea of Okhotsk" prevailed over the processes of ice destruction under the influence of the eastern branch of Tsushima Current flowing through the La Perouse Strait.

Figure 4 and figure 5 show the integral curves of ice cover anomalies calculated for the Tatar Strait relative to the standard reference period 1961–1990 and the standard climate normal 1991–2020. The configurations of the integral curves of ice cover anomalies in the periods corresponding to the considered climate normals characterize the tendencies of changes in the direction of ice processes. There was no dependency of the course of the integral curve on the normal selected for the calculation, which indicates the relative stability of ice formation processes in the strait over the past sixty years.

**Figure 4.** Integral curve of ice cover anomalies in the Tatar Strait relative to the standard reference period 1961–1990.

**Figure 5.** Integral curve of ice cover anomalies in the Tatar Strait relative to the standard climate normal 1991–2020.
The typification of winters according to the anomalies of the average ice cover values for a season in the Tatar Strait was carried out relative to the average value of ice cover for a season in the period 1961–2020 (figure 6, 7 and 8). The results of the analysis for the selected gradations of winter types showed that in the 60-year period (figure 6), the moderate (M) type of winters prevails – 33%. The next most frequent type was the soft (S) type (28%). The ratio of severe (Sv) winters accounted for 20%. Extreme types accounted for 8% in the category of extremely soft (ES) and 10% in the category of extremely severe (ESv) winters. Comparative analysis of 30-year consecutive periods (figure 7 and figure 8) allowed us to ascertain a decrease in the frequency of ESv winters by 6% in 1991–2020. The ratio of ES and S ice cover anomalies taken together in the standard reference period 1961–1990 and in the period of the standard climate normal 1991–2020 was the same – 18%. The frequency of Sv winters remained at the same level. The proportion of M winters in 1991–2020 increased by 7%.

Table 1. Typification of winters based on anomaly of ice conditions in the Tatar Strait from 1961 to 2020.

![Figure 6. Frequency of occurrence of winter types in the Tatar Strait for the period from 1961 to 2020.]

![Figure 7. The frequency of occurrence of winter types in the Tatar Strait for the period from 1961 to 1990.]

![Figure 8. The frequency of occurrence of winter types in the Tatar Strait for the period from 1991 to 2020.]

The analysis of temporal distribution and frequency of ice cover anomalies performed using the created calendar of ice cover anomalies (Table 1) allowed us to detect the fact that the vast majority of ESv and Sv anomalies in ice cover were observed at the end of the standard reference period 1961–1990. The period corresponding to the standard climate normal 1991–2020 was characterized by a predominance of moderate winters, evenly represented throughout the entire 30-year series.

Figure 9 shows the intra-seasonal variation of the average ice cover values corresponding to different climate normals. At the stage of ice formation, no significant differences in the course of the curves were observed. Relative to the standard reference period 1961–1990, during the period of the
In the standard climate normal 1991–2020 there was a 5-day delay of the onset of the maximum ice cover, and the stage of destruction of ice cover occurred 10 days earlier.

The first appearance of ice extent in the strait was observed on average on November 13, the average date for stable ice formation was November 15. The early dates and late dates of the first and the stable appearance of ice were scattered from 15 to 20 days. The first ice clearing of the strait on average was recorded on April 25. The difference between the dates of the earliest and the latest initial clearing of the water area from sea ice was 45 days (April 5 and May 20, respectively). The average date for final clearing of ice was April 27. In moderate types of winters, the earliest final clearing of the studied water area from ice occurred on April 5, and the latest – on May 20. The accuracy of calculating the onset of ice phases using pentad maps was +/- 2.5 days.

The average duration of the ice season was 159 days for soft winters, 164 days for severe winters and 165 days for moderate winters (average duration – 163 days). The shortest ice season in the last 30 years was recorded in the winter of 1992/93, when its duration was 141 days. The longest one was 1998/1999 ice season, when ice remained in the studied water area for 181 days.

The dates of the beginning of ice formation and the final clearing of the strait in the reference climate normal were established according to the data of marine hydro-meteorological stations. According to long-term average data, in 1961–1990 the duration of the ice period was 190 days. Analysis of the available data allowed us to conclude that the duration of ice season in the period corresponding to the standard climate normal 1991–2020 decreased by almost a month, namely by 27 days, from 190 to 163 days. The difference in the duration of ice season, as function of the types of winters, became less substantial and was only 5 days. At the same time, in the period corresponding to the reference normal, it could increase or decrease by a month compared to the average long-term dates, depending on the severity of winter [2].

3. Conclusion

Based on the analysis of variations in long-term ice cover fluctuations in the Tatar Strait in the periods corresponding to the standard reference period 1961–1990 and the standard climate normal 1991–2020 the following was established:

1. A reduction in the average ice cover over the past 30 years by 2% (from 31% to 29%), which was within the accuracy of the calculations. Linear trend of sea ice cover in the Tatar Strait during the standard reference period 1961–1990 had a positive trend. The slope of the linear trend during the period of the standard climate normal 1991–2020 was close to zero.
2. The range of fluctuations in the value of ice cover in the standard climate normal 1991–2020 amounted to 24%, which was 1.6 times less than the same value in the standard reference period 1961–1990.
3. Relative to the standard reference period 1961–1990, during the period of the standard climate normal 1991–2020, there was a 5-day delay in the stage of the onset of the maximum ice cover, and the stage of destruction of ice cover occurred 10 days earlier. The duration of ice season during the period of the standard climate normal 1991–2020 decreased by almost a month from 190 to 163 days.
4. The ratio of soft and extremely soft ice cover anomalies in aggregate in the standard reference period 1961–1990 and during the period of the standard climate normal 1991–2020 remained at
the level of 18%. In 1991–2020, the proportion of moderate winters increased by 7%, and the frequency of extremely severe winters decreased by 6%. The period corresponding to the standard climate normal 1991–2020 was characterized with predominance of moderate winters, evenly represented throughout the entire 30-year series.

5. The nature of the course of the integral curves testified to the relative stability of ice formation processes in the strait over the past sixty years.

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