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CRYOGENIC PHENOMENA IN SEAS AND OCEANS

INTERANNUAL VARIATIONS OF MAXIMAL FAST ICE EXTENT IN THE EAST SIBERIAN SEA

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The paper presents the data on maximal extent of the East Siberian Sea fast ice and its variability based on the Arctic and Antarctic Research Institute operational sea ice chart for the period from 1999 to 2019. The maximal fast ice extents were compared to the ERA5 reanalysis local winds. The analysis of the maximal fast ice variability showed no statistically significant changes between 1999 and 2019. Two typical configurations of fast ice edge were revealed for the winter month characterized by the maximal fast ice extent. In some seasons fast ice development stops, once the edge reaches 20 m depths, while in other season the fast ice edge advances to 30 m depths. The maximal fast ice extent is reached during the seasons with prevailing onshore northerly and north-easterly wind. The onshore wind favors sea ice deformation and grounding at the seaward fast ice edge.

Keywords: *landfast sea ice, sea ice, stamukhas.*

INTRODUCTION

The East Siberian Sea is located in the zone affected by the Atlantic and Pacific Ocean atmospheric interactions. The region is characterized by the shortest summer and the coldest winter among the Russian Arctic shelf seas. In winter the atmospheric wind regime is mainly defined by the Siberian High with a less effect of the Polar High. This results in the domination of south-easterly and southerly winds with a mean speed of 6–7 m/s. Atlantic cyclones, prevailing in the western part of the sea, and Pacific cyclones, prevailing in the southeastern part of the sea, cause an increase in the winds in the north and northeast directions [*Dobrovol'skij, Zalogin, 1982*]. The northerly and north-easterly wind favor formation of rafted and ridged sea ice in the region. The formation and development of sea ice cover take place during the entire winter period and ends in the end of May [*Yulin et al., 2018*]. The western part of the East Siberian Sea is characterized by the presence of favorable factors for the formation of fast ice: a rugged coastline, the presence of islands and shallow waters that allow the formation of stamukhas and the absence of strong tidal currents [*Zubov, 1945*]. The fast ice extent around the New Siberian Islands at its maximal development comprises more than a half of the total fast ice area in the Russian Arctic [*Karklin et al., 2013*]. The water depth and the underwater relief are the main factors limiting maximal fast ice extent. Commonly, the seaward fast ice edge follows the contours of 20 to 25 m isobaths [*Gudkovich, 1974; Mahoney et al., 2014*]. The fast ice regime in the region is described in details in [*Karklin, Karelin, 2009*].

Currently, due to observed climate changes and developing economic activity in the Arctic, the sea ice state and regime have been actively observed and investigated. Based on the sea ice charts produced by Arctic and Antarctic Research Institute (AARI) and National Oceanic and Atmospheric Administration (NOAA) trends in the duration of fast ice season were derived [*Divine et al., 2004; Yu et al., 2014; Selyuzhenok et al., 2015*]. The analysis of NOAA data revealed a negative trend in fast ice area for all Russian Arctic shelf seas, while the total fast ice area in the Northen hemisphere decreases with a speed of $12.27 \cdot 10^3$ km^2 (7 ± 1.5 %) per decade [*Yu et al., 2014*]. The aim of this study is to evaluate the interannual variability of the maximal fast ice extent in the East Siberian Sea from 1999 to 2019.

DATA

The data on fast ice extent and the location of fast ice edge in the East Siberian Sea were retrieved from the regional sea ice charts produced at AARI for the period 1999–2019. The sea ice charts are freely available in SIGRID-3 format [*http://wdc.aari.ru/*]. Since 1998 the charts are mainly based on the information form the satellite remote sensing, which is analyzed by an expert. The charts are drawn at a scale 1:500 000 and issued on a weekly basis. Thus, the sequence of sea ice charts allows to create the most accurate homogeneous series of observation on the fast ice state.

Figure 1 shows the mean seasonal changes in fast ice extent in the East Siberian Sea. The average fast ice extent in February–May was used as the maxi-

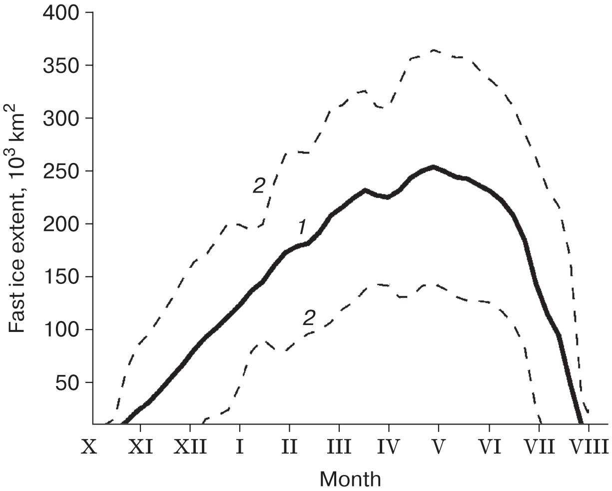

Fig. 1. Mean seasonal changes in fast ice extent in the East Siberian Sea for 1999–2019.

1 – mean value; *2* – two standard deviation from the mean.

mum fast ice extent. From October to May, the fast ice extent increases, and from June it begins to decrease (Fig. 1). Due to gap in sea ice charts in winter period 2002–2003, this period was excluded from the analyses.

The ERA5 reanalysis data [*Hersbach et al., 2020*] were used to obtain wind speed and direction in the region. Compared to other reanalysis models (ERA-Interim, Japanese 55-year Reanalysis, Modern Era Retrospective Analysis for Research and Applications-2, National Centers for Environmental Prediction / National Center for Atmospheric Research Reanalysis 1), ERA5 reproduces wind speed and direction with high accuracy [*Ramon et al., 2019*]. The mean daily wind speed and direction for the marine part of the region were derived from hourly meridional and zonal wind components at 10-m level. Next, we calculated the frequency of wind in eight directions and the number of calms (the number of days with an average wind speed of less than 0.5 m/s) from the beginning of November to the end of May, which covers the period from the beginning of fast ice formation to the beginning of its decay.

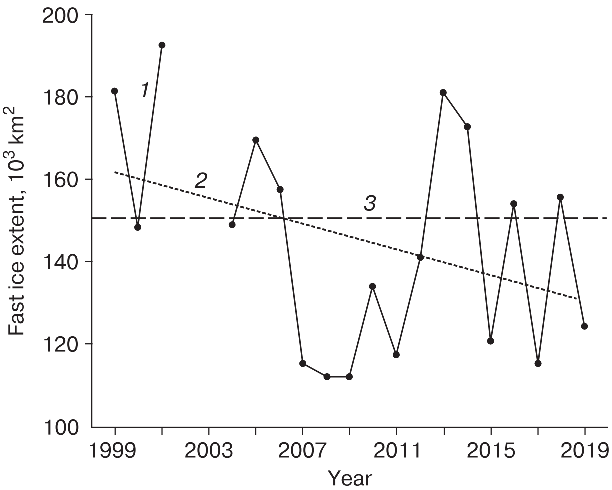

Fig. 2. Variations in maximal fast ice extent in the East Siberian Sea for 1999–2019.

1 – mean fast ice extent in February–May; *2* – linear trend; *3* – multi-annual average value of fast ice extent in February–May (1999–2019).

RESULTS AND DISCUSSION

Figure 2 shows interannual variability of the maximal fast ice extent (February–May) for 1999–2019. The mean interannual fluctuations of fast ice extent comprises 15 %, but in some season can exceed 30 % from multi-annual mean. The minimal fast ice extent was observed from 2007 to 2012. This period coincides with the seasons of record low summer sea ice extent in the eastern Arctic. The maximal retreat of sea ice edge in summer in the East Siberian Sea was observed in 2007 [*Egorov, 2020*]. The linear trend for fast ice extent comprises $-1.6 \cdot 10^3$ km^2 for 1999–2007, but it is not statistically significant (p-level <90 %).

In the seasons with negative fast ice extent anomaly in February–May, the location of fast ice edge coincides with the contours of 20–25 m isobaths (Fig. 3). In the seasons with positive extent anomaly, in the central part of the region fast ice edge shifts to the north and reaches 30-m isobath. The main differences in the average position of the edge are observed between the 155° E and 170° E.

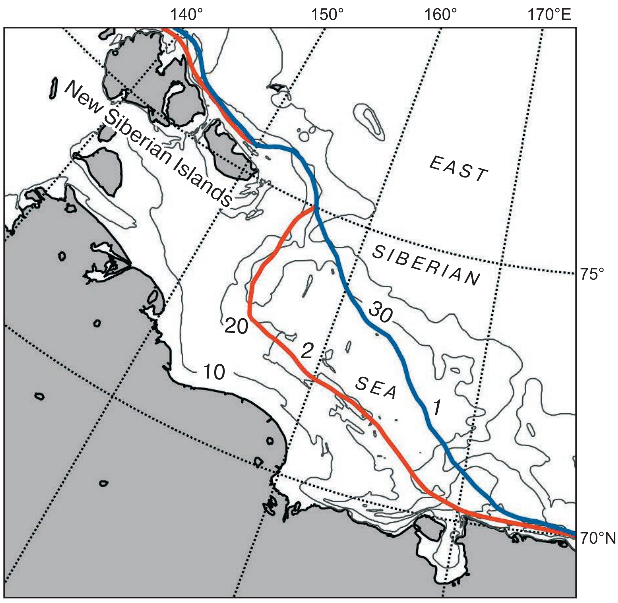

Fig. 3. Mean location of fast ice edge in February–May:

1 – in seasons with positive fast ice extent anomaly; *2* – in seasons with negative fast ice extent anomaly.

Table 1. **Frequency of wind occurrence in directions; number of calms**

Years	Frequency of wind occurrence in directions , %								Number of calms
	N	NE	E	SE	E	SW	W	NW	
With positive fast ice extent anomaly	18.8	26.2	12.1	9.2	6.2	6.0	10.0	11.5	4
With negative fast ice extent anomaly	14.9	7.0	10.7	10.7	20.3	13.3	10.1	13.0	11

An analysis of the surface wind frequency shows that seasons with a positive fast ice extent anomaly are characterized by onshore northerly and northeasterly winds (Table 1). The total frequency of winds of these directions in seasons with a negative extent anomaly is 2 times lower. For the seasons with negative fast ice extent anomaly, the southerly winds, which push the sea ice away from the shore, are the most frequent. The occurrence of calms from November to May for seasons with both positive and negative anomalies of the fast ice extent is less than in 15 days (9 %).

The correspondence between the fast ice extent variations and predominant wind directions indicate a close relationship between the processes. The role of onshore winds in the seasonal formation of fast ice was first described in [*Zubov, 1945*]. The mechanism of interaction between the wind direction and fast ice extent is clear: under the influence of pressure winds, drifting ice fields are shifted to the fast ice boundary. As a result of strong compression, they freeze to the previously formed fast ice. Such a mechanism of an abrupt increase in the fast ice extent in the adjacent to the East Siberian Sea, Laptev Sea is described in modern works (for example, [*Karklin et al., 2013*]). When changing the mode of the prevailing wind direction from onshore to offshore, the sea ice is held in place and freezes in the fast ice cover. The location of fast ice edge the period of its maximum development in the eastern part of the Laptev Sea coincides with the contour of 20–25 m isobaths and shows no interannual variations. The variations of fast ice maximal extent there do not ice in the sea do not exceed 15 % [*Selyuzhenok et al., 2015*]. According to [*Gudkovich, 1974*], 1.5–2 m thick fast ice [*Karklin et al., 2013*] cannot withstand the combined effect of tangential wind forces and tidal phenomena acting at the fast ice edge at 20–25 m depths. At greater water depth stamukhas provide additional additional support 25 m [*Gorbunov et al., 2008*]. The absence of stamukhas is another factor which might limit the development of fast ice to 20–25 m depth. In the East Siberian Sea, the distribution of fast ice up to the 30 m isobath (the position of the edge *1* in Fig. 3) is observed only in seasons with a predominance of onshore winds. It is likely that with the predominance of the offshore wind directions, a sufficient number of stamukhas capable of holding the fast ice of a large area in place are not formed.

CONCLUSIONS

The fast ice extent in the East Siberian Sea shows a large long-term interannual variability. The mean variations of fast ice extent are 15 %, but in some years they can exceed 30 % of the long-term average. Depending on the prevailing wind directions, the fast ice edge in the period of maximum development occupies one of two characteristic positions: 1) the seaward edge of the fast ice coincides with location of the 20 m isobath; 2) the seaward edge of the fast ice in the central part of the water area protrudes to the north and approaches the 30 m isobath. Fast ice reaches its maximum extent in winters with prevailing onshore winds, which likely contribute to ice hummocking and the formation of stamukhas. Stamukhas are additional support points for fast ice, due to which fast ice is able to withstand the forces of wind and tidal phenomena at depths of more than 25 m. The analysis of fast ice extent time series shows no statistically significant trend during the period between 1999 and 2019.

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