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Ice-free period duration changes in the coastal zone of the Kara Sea and the Laptev Sea using satellite data

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ABSTRACT

Rapid sea ice extent reduction in the Arctic in XXI leads also to an ice-free period duration increase. The ice-free period duration is an important climate indicator of the coastal dynamics in the Russian Arctic. Ice-free period changes (start/end dates shifts, total duration increase) significantly influence coastal infrastructure, navigation, and coastal ecosystems. Modern satellite datasets allow analyzing the long-term means and sea ice cover dynamics in the Arctic coastal zone. Based on the original advanced threshold approach, which is adapted for the coastal data, the annual estimates of ice-free period characteristics for the Kara Sea and the Laptev Sea coastal zones were obtained from the sea ice concentration satellite observations (JASMES, OSI SAF, and NSIDC) for 1979-2019 period. According to analyzed satellite data, the ice-free period duration in the coastal zone of the Kara Sea and the Laptev Sea has increased significantly over the last decades. The linear trend in the duration of the ice-free period was estimated Sea ice retreat/advance dates trends analysis highlight the areas with the most intense changes in the Russian Arctic coastal zone: Ugra Peninsula, Baydaratskaya Bay, the western coast of Yamal Peninsula, as well as the western and eastern coasts of Taimyr Peninsula.

KEY WORDS: Ice-free period; Sea ice concentration; Sea ice; Arctic coastal zone; Climate change

INTRODUCTION

The Russian Arctic coastal zone is a territory of active interaction between natural processes and anthropogenic activities. The assessment of the coastal dynamics rates is an essential condition for sustainable development of the Russian Federation Arctic territories, for the effective oil and gas industries management, for the transport administration as well as the harmless coastal infrastructure operation.

The rapid sea ice reduction of in the Arctic in XXI century is a clear evidence of the global warming process (Cavalieri & Parkinson, 2012). Sea ice conditions play an important role in the circumpolar Arctic coastal dynamics (Ogorodov et al., 2016). Most of the coastal erosion occurs during a relatively short summer season – the ice-free period (IFP). Sea ice area decline influences the IFP duration, it becomes longer in the Arctic Ocean seas (Bliss et al., 2019). An increase in the IFP duration will leads to an intensification of thermal abrasion processes and, ultimately, to more rapid changes in the coast position (Overeem et al., 2011). Statistically significant changes in the IFP characteristics (start dates, end dates, and total duration) affect coastal infrastructure, navigation, and coastal ecosystems. IFP is an effective climate indicator, which is especially important to monitor the coastal dynamics.

Satellite microwave observations are used more than 40 years' time period to investigate sea ice in the Arctic. It opens up great opportunities for monitoring of the sea ice conditions. Satellite datasets, devoted to sea ice characteristics (extent, area and concentration), are widely used for the Arctic Ocean seas (Stroeve et al., 2006), but are rarely used for coastal zones studies (Barnhart et al., 2014). The difference in brightness temperatures observed over open water and land combined with the satellite pixel size of several kilometers can cause spurious sea ice concentrations to appear along coasts (Lavergne et al., 2019). Despite the so called "spillover correction" implementation, there are still data problems within sea ice concentration climate datasets. This is the reason why the coastal data analysis requires taking into account such features and using methods that allow the correct data interpretation.

Sea ice concentration (SIC) data can be used to estimate the ice-free period characteristics (Shabanov & Shabanova, 2019). In the research, the advanced threshold approach (Shabanov & Shabanova, 2020) is used to determine the key dates of SIC change during its annual melt/freeze cycle in the coastal zone of the Russian Arctic. The study was carried out for the coastal zones of the Kara Sea (from 60°E to 105°E) and the Laptev Sea (from 105°E to 140°E).

DATA & METHODS

The following satellite sea ice concentration datasets were used to define the key dates, which determine the IFP characteristics (start date «S», end date «E» and its total duration «D») along the coastal zone of the Kara Sea and the Laptev Sea: satellite monitoring program for Environmental Studies of the Japan Aerospace Exploration Agency (JASMES; JASMES JAXA, 2019); US National Snow and Ice Data Center (NSIDC; Peng et al., 2013; Meier et al., 2017); center for the application of satellite systems to ocean and sea ice research of the European organization for satellite meteorology (OSI SAF; EUMETSAT, 2017; EUMETSAT, 2019; Lavergne et al., 2019). All satellite datasets cover 1979-2019 period and have a declared spatial resolution 25 km. The temporary resolution of all datasets is daily or sub daily (from1980-s). All sea ice concentration data were converted to percentages (0-100% range).

Ice-free period determine method

The threshold method is a state-of-the-art procedure to define the number of open water days using SIC data (Comiso & Zwally, 1984; Meier & Stroeve, 2008; Farquharson et al., 2018). A number of open water days are very close to ice-free period duration. In the threshold approach, all involved pixels or grid cells with values less than the threshold (usually the threshold is set to 15%) are marked as "open water" (Peng et al., 2018; Howell et al., 2009; Khon et al., 2010).

Unfortunately, the threshold approach is very sensitive to absolute data values. In the coastal zone the sea ice concentration time series before 1987 perform complicated behavior and spurious values, which are usually not confirmed by observations. Despite the applied correction procedures during OSI SAF post-processing (correction step is quite efficient at reducing land spillover contamination), questionable values are still part of the satellite SIC time series. In these cases, sea ice concentrations always exceed 30-40%, even in summer, while alternative observations show close to zero values. Also, the ice motion and polynyas significantly complicate the automated processing using only SIC absolute values (Reimnitz et al., 1994; Dmitrienko et al., 2005). All these circumstances limit the threshold method usage. To overcome the threshold method limitations, the new approach to determine the ice-free period in the coastal zone was developed – the advanced threshold approach (Shabanov & Shabanova, 2020).

The advanced threshold approach (ATA) is based on the annual sea ice concentration time series analysis and allows us to define the ice-free period key dates. To determine the IFP duration (D), the start date (S) and the end date (E) of the period should be calculated.

The smoothed time series of daily SIC for the ice year 1 March through 1 March of the following year are used to derive the dates and the IFP duration. IFP start date is searched within the period from the 1st of March till the 15th of September. Two sub-periods are investigated: from 1 March to 15 September for IFP start date (S) search and from 15 September through 1 March of the following year for IFP end date (E) search.

SIC time series within each sub-period (for S and E separately) are normalized to avoid problems with the threshold absolute values. Then the SIC gradients are calculated for a 28-day rolling window. The gradient is calculated as a difference between the last and the first day of the 28-days period. Only non-empty slices, with values lower/greater (start date/end date) than the threshold, are considered. Following (Peng et al., 2018), the threshold was set to 15%. The slice with the maximum gradient is chosen. The last/first slice element is interpreted as the ice-free period start/end date respectively. Rolling window width could be perceived as a representative melting/freezing period, or as a period, when significant changes (melt or freeze) are observed in sea ice concentrations data. The tests show that the optimal (in terms of root mean squared error) window width is near 28 days.

RESULTS

Along the coastline of the Kara Sea and the Laptev Sea, 113 points were chosen. Using three satellite sea ice concentration datasets (JASMES, NSIDC, OSI SAF), annual IFP characteristics estimates for 1979-2019 were obtained for each point using the advanced threshold approach: start/end dates (in units "day of the year", DoY) and period's total duration (in days). Three satellite data sources were combined into a median ensemble estimate (ensemble). Such estimates are more robust due to result consistency and are less sensitive to the systematic inaccuracies, specific to an individual dataset.

IFP long-term means

Using the annual ensemble estimates, standard statistics were calculated for IFP characteristics for the Kara Sea (63 points) and the Laptev Sea (50 points) coastal zones. The results are presented in Table 1 and in Figure 1 (left column).

A comparison between the two seas shows obvious higher variability in the Kara Sea for IFP long-term means (LTMs). This variability is presented not only in comparison with the Laptev

Sea LTMs, but also within the Kara Sea coastal zone.

The averaged IFP duration in the considered region is close to 78 days. In the Laptev Sea this parameter (on average) is 10 days less (68 days), and in the Kara Sea – 10 days longer (88 days). IFP LTM duration minimums do not differ significantly from point to point, from sea to sea, and are in the 53-56 day's range. At the same time, the IFP LTM duration maximums differ significantly over the region. While for the coastal zone of the Laptev Sea this parameter does not exceed 80 days, in the Kara Sea it reaches more than 140 days. IFP LTM duration standard deviation for the Kara Sea exceeds three weeks, 24 days (the standard error of the mean is 3.02 days). This indicates a significant heterogeneity of the ice conditions in the coastal zone of the Kara Sea according to satellite SIC data. For parameters in the Laptev Sea more uniform distribution is typical: the IFP duration standard deviation (SD) is only 6 days, the standard error of the mean is 0.84 days.

Table 1. IFP long-term statistics averaged for the coastal zones of the Kara and Laptev Seas: S – IFP start date (DoY); E – IFP end date (DoY); D – IFP duration (days)

	The Kara Sea			The Laptev Sea		
	S	**E**	**D**	**S**	**E**	**D**
MEAN	204	291	88	211	277	68
SD, σ	12	14	24	6	2	6
MIN	181	277	53	200	274	56
25%	193	282	72	208	276	63
50%	207	284	82	210	278	68
75%	211	300	106	216	279	73
MAX	227	326	144	220	281	78

IFP characteristics long-term trends

In addition to IFP long-terms means, linear trends were also calculated using annual ensemble estimates of the IFP characteristics for 1979-2019 period. For each of the 113 points over the Kara and Laptev seas the linear trend coefficients were estimated with an assessment of their statistical significance at the 95% confidence level. The linear trends statistics of IFP characteristics for the Kara Sea and the Laptev Sea are presented in Table 2 and in Figure 1 (right column).

Describing the IFP changes for more than 40-year period of satellite observations, we should first note the total IFP duration increase for 1979-2019 period along the coastal zone of the region: the average increase rate is 10.9 days/decade. It is important that all calculated trends are positive and statistically significant. With the vast majority (100 out of 11se3 points) statistically significant trends are indicated even at 99% confidence level. Negative IFP duration trends are determined only occasionally (mainly in the north of the Taimyr Peninsula) and have no pronounced statistical significance. The IFP duration trend maximums reach 23.29 days/10 years in the west of the Ugra Peninsula (the Kara Sea), and 14.14 days/10 years in the Laptev Sea (eastern coast of the Taimyr Peninsula).

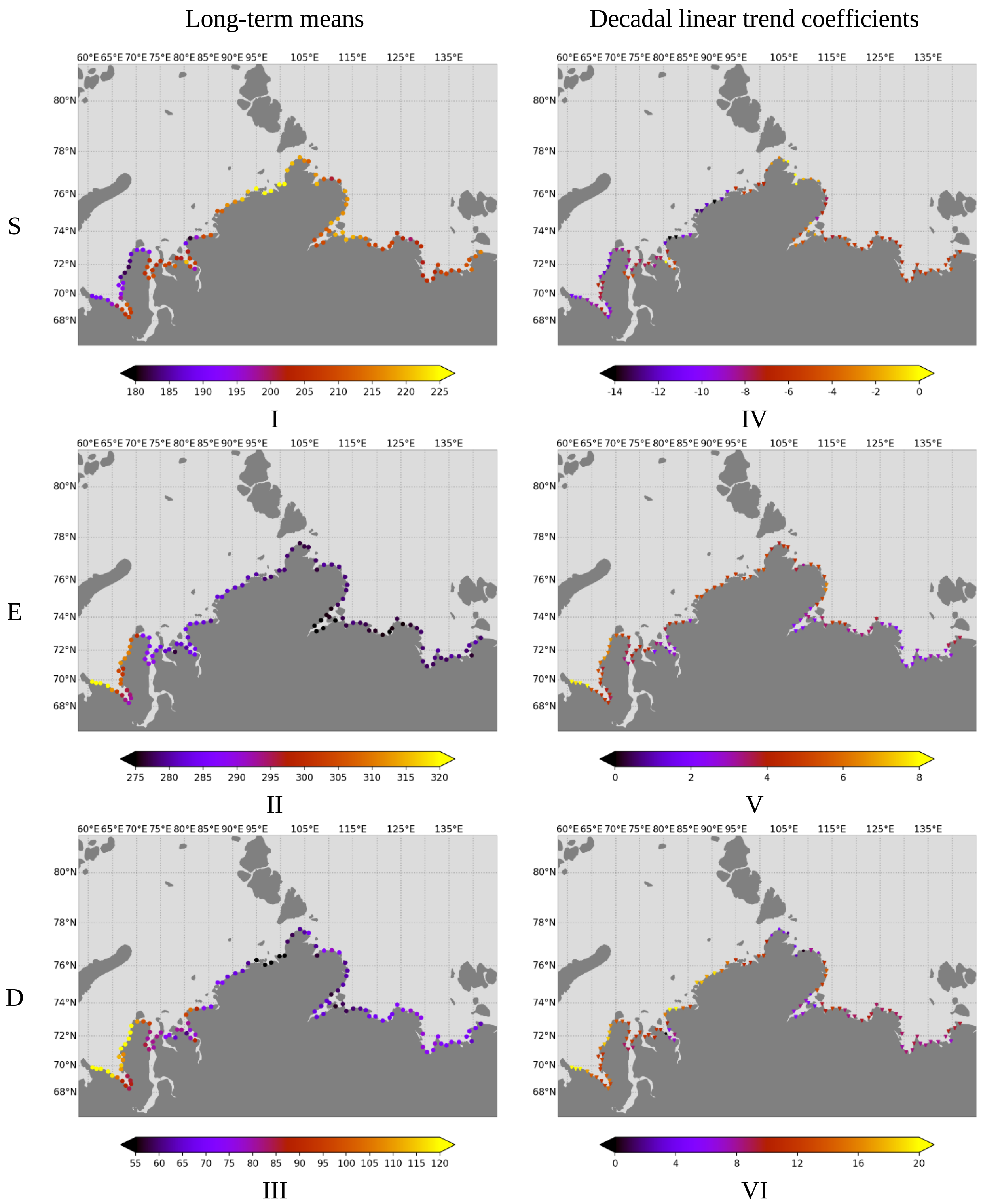

Figure 1. Regional IFP long-term means (left column, I-III) and decadal trends of dates (days/decade; right column, IV-VI; triangle markers indicate statistical significance at the 95% confidence level) for 1979-2019 period. S – IFP start dates (DoY or DoY/decade); E –

IFP end dates (DoY or DoY/decade); D – total duration (days or days/decade).

The total IFP duration increase in the coastal zone of the Kara Sea and the Laptev Sea is influenced by both factors: an earlier onset of the start dates (S) and a later onset of the end dates (E). Moreover, the overwhelming number of estimated points show simultaneous statistical significance (95% confidence level) for start and end dates trends: 85%, 98%, and 91% for the S, E, and D parameters, respectively.

Comparing the averaged trend rates in the coastal zones of the two Arctic seas, the similarity is found for IFP end dates (E) trends (4.57 and 3.41 days/10 years in the Kara and Laptev seas) and a significant difference is detected for estimates of IFP start date (S) trends: -8.35 and -4.94 days/10 years in the Kara and Laptev seas (Table 2). In the coastal zone of the Laptev Sea, the averaged trends of S and E parameters are quite comparable, while in the Kara Sea the IFP start date trend is almost twice as high as IFP end date trend (Table 2). The extremes of IFP start date trends in the Kara Sea reach -17.81 days/decade and a quarter of considered points show trends less than -10 days/decade. In the Laptev Sea IFP start and end dates trends are almost twice as low as in the Kara Sea

In general, the annual means spatial distribution of the IFP characteristics and their tendencies has inter-meridian trend: from the west to east, the mean IFP durations and the «D» trends decrease; the mean IFP start dates and the «S» trends increase (in the west the trends are stronger, but they are negative); the mean IFP end dates and the «E» trends decrease (in the west the trends are stronger, positive trends). The coastal zones of the Yugorsky Peninsula, the west of the Yamal Peninsula, and the Taimyr Peninsula are the most affected by the ice-free period duration changes over 1979-2019 according to the satellite sea ice concentration data.

Table 2. Averaged over the coastal zone of the Kara and Laptev seas IFP linear trends for 1979-2019 period. S – IFP start dates (DoY/decade); E – IFP end dates (DoY/decade); D – IFP duration (days/decade)

	The Kara Sea			The Laptev Sea		
	S	**E**	**D**	**S**	**E**	**D**
MEAN	-8,35	4,57	13,00	-4,94	3,41	8,22
SD, σ	3,26	1,47	4,43	2,21	1,07	2,73
MIN	-17,81	1,00	-0,96	-8,61	2,11	0,35
25%	-10,14	3,73	10,76	-6,25	2,53	7,17
50%	-7,96	4,45	12,03	-5,75	3,23	8,61
75%	-6,67	5,19	15,27	-4,41	4,04	9,45
MAX	1,95	9,11	23,29	0,94	6,33	14,14

CONCLUSIONS

Long-term means and trends analysis of the ice-free period characteristics along the coastal zones of the Kara Sea and the Laptev Sea for the period 1979-2019 according to satellite SIC data, showed that:

1. the ice-free period duration in the coastal zone of the Kara Sea and the Laptev Sea has increased in the recent decades. Average rate is +11 days/10 years over a period of years 1979-2019;
2. the IFP duration increase occurs due to both processes: earlier sea ice melting (the average is negative, statistically significant, 95% confidence level, -7 days/decade), and later freezing (positive, statistically significant, 95% confidence level, +4 days/decade);
3. the change rates in the dates of retreat (S) are almost twice as high as the rates for the dates of advance (E) for the Kara Sea. Such a difference in the Laptev Sea is not so great.

The Kara Sea coastal zone is characterized by a wide variety of both IFP long-term means and trends. The coastal zone of the Laptev Sea has a noticeably higher regional uniformity and less variability (especially in the IFP end dates).

The study allowed estimate IFP long-term means and tendencies with focus on the coastal zone of the Kara and Laptev Seas. Unlike with the results (Bliss et al., 2019), where similar key dates were considered, this study specializes on the coastal zone assessment. During a preprocessing stage the initial satellite SIC data were smoothed, and instead of the threshold method, a specially developed advanced threshold approach was used to determine the ice-free period key dates. Also, three satellite datasets were processed into ensemble estimates: JASMES, NSIDC, and OSI SAF.

The research results illustrate the difference of the IFP duration change along the coastline of two neighboring seas of the Russian Arctic according to satellite passive microwave observations. Showed regional estimates allow identifying the most intensively changing coastal areas of the Russian Arctic. One of these areas is the Yamal Peninsula, the region of active hydrocarbon production (oil and gas industry). Monitoring, studying the ice-free period changes, and understanding the coastal dynamics are indispensable conditions for the sustainable development of the Russian Arctic regions.

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