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GEOPHYSICS

New Model Estimates of Changes in the Duration of the Navigation Period for the Northern Sea Route in the 21st Century

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Abstract—New estimates of changes in the duration of the navigation period for the Northern Sea Route (NSR) are obtained based on calculations with the current generation of global climate models under moderate anthropogenic impacts in the 21st century. In order to obtain more reliable estimates, it was analyzed whether or not the present climate models can simulate both the average conditions of sea ice and their interannual variation and tendencies to change in the Arctic basin, in particular on the NSR, as compared to the satellite data for recent decades.

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The Arctic regions are characterized by the strongest and fastest climate changes up to and greater than 0.8 K/10 years for the average annual surface temperature and up to and greater than 1 K/10 years for the average seasonal temperature in recent decades. The current rate of surface warming in the Arctic is considerably higher than the global and hemisphere rates, which is the so-called Arctic amplification. The most impressive changes are related to the fast decrease in ice cover of the Arctic Basin, especially at the end of summer and the beginning of fall. This indicates that as early as the first half of the 21st century sea ice will not be likely to occur in the Arctic basin during summer and fall months. The change in the conditions of the extent of sea ice in the Arctic has great importance due to the potential development of the Arctic Sea transport systems and the shelf [1–15].

The strong and fast changes in the climate at the Arctic latitudes require comprehensive studies of their causes and the estimation of the role played by natural and anthropogenic factors. The significant uncertainty concerning the estimates of climate changes in the Arctic regions is determined by the strong climate variability at high latitudes. The considerable interannual and interdecadal variations in the temperature and ice conditions are exhibited against the background of the long-term tendencies.

The expected increase in the availability of ship navigation in the Arctic Ocean and the growing potential of using the Arctic regions in economics makes it necessary to estimate the ability of the modern climate models to simulate sufficiently the changes in the sea ice conditions, in particular for the NMR. It is natural that the estimates of possible changes have to depend on the possible scenarios of natural and anthropogenic impacts and the requirements for the maximum degree of ice cover in the water area, which are different for ships with different ice classes.

In [4, 6, 7], we obtained the estimates of a possible increase in the duration of the navigation period (NPD) for the NSR because of a decrease in the sea ice extent in the Arctic in the 21st century by calculations with the ensemble of climate models as part of the international CMIP3 project for the scenario of moderate anthropogenic impact. According to the model estimates that were obtained in [6, 7], transit to the Southeast Asia from Western Europe through the NSP may become more promising than through the Suez Canal, even during winter months if the warming tendency continues in the 21st century.

This work presents estimates of the possible changes in the NPD on the NSR in the 21st century by calculations based on an ensemble of the new generation of climate models [10].

To estimate the changes in the area of sea ice in the Arctic basin, the results of numerical calculations based on the ensemble of modern global climate models were analyzed as part of the international CMIP5 project under the scenarios of natural and anthropogenic impacts of the RCP set. In particular, we used the scenario of moderate anthropogenic impacts RCP 4.5 for the 21st century. The navigation period duration for the NSR was calculated similarly [6, 7]. For this purpose we used the results of calculations with the ensemble of the global climate models CMIP3 of the previous generation under the scenarios of the SRES set [10].

The ability of the global models to simulate the present-day fast changes in the Arctic climate was assessed as compared to the satellite data [12].To do this, we used the daily data on the sea ice concentra-

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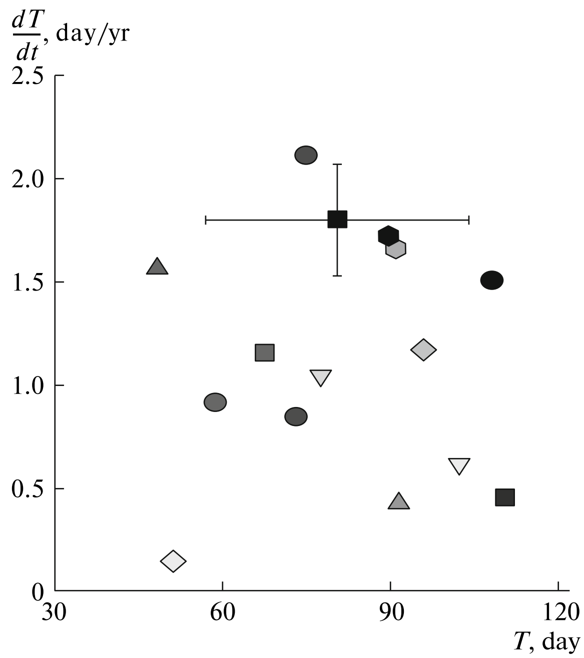

Fig. 1. Average duration T and rate of change (trend) $\frac{dT}{dt}$ of the navigation period (at a sea ice concentration of no more than 15%) on the NSR in 1980–2013 according to the satellite data and the calculations by using the different climate models under the CMIP5 project. The horizontal and vertical segments show the respective MSDs according to the satellite data.

tion that were obtained based on passive microwave sounding by SMMR–SSM/I radiometers (Scanning Multichannel Microwave Radiometer-Special Sensor Microwave/Imager) under the space Nimbus-7 program and the DMSP (Defense Meteorological Satellite Program) for the period of 1980–2013. The satellite data with a spatial resolution of 25 × 25 km were under analysis.

Table 1. The average NPD T on the NSR (at a sea ice concentration of no more than 15%) and the rate of its change $\frac{dT}{dt}$ in 1980–2013 according to the satellite data and the calculations by using the climate models CNRM–CM5, MPI–ESM–LR, and MPI–ESM–MR

Data	$\frac{dT}{dt}$, day/yr	T, day
Satellite	1.8 (±0.3)	80 (±24)
CNRM–CM5	2.1 (±0.2)	75 (±25)
MPI–ESM–LR	1.7 (±0.3)	91 (±24)
MPI–ESM–MR	1.7 (±0.4)	90 (±28)
Average	1.8 (±0.2)	85 (±21)

The respective MSDs are given in brackets here and in Table 2.

To determine the NPD, we used different values of the limit concentration (the share of the area) of the sea ice in the ocean model cells. We also estimated the number of days per year when the sea ice concentration n_i did not exceed 15% (or 85% of the area with open water) and 25% (75% of the area with open water). The different criteria correspond to the conditions of safe passage of ships with different ice classes.

Figure 1 presents the numerical estimates for the NPD T and the rate of its change (trend) $\frac{dT}{dt}$ that are average for the period of 1980–2013 according to the satellite data (SMMR) and the calculations with the ensemble of climate models at n_i not exceeding 15% that were obtained in a similar way [10]. The horizontal and vertical segments mark the respective mean-square deviations (MSD) for the satellite data. The regional estimates of the average duration of the navigation period for the NSR in the Arctic basin were greatly scattered in the different model calculations.

According to Fig. 1, in general the models underestimate the rate of changes in the NPD. The CNRM–CM5, MPI–ESM–LR, and MPI–ESM–MR are the three climate models that conform best to the average values of the duration T and the rate of changes $\frac{dT}{dt}$ (of the trend) of the navigation period on the NSR with deviation values that are close to or less than the MSD. CNRM–CM5 was the only model among the ensemble of the models CMIP5 that showed a greater $\frac{dT}{dt}$ than by the satellite data. The average value of the NPD T was smaller in half of the models analyzed as compared to the satellite data; the other half of the models had this value as greater.

Table 1 presents the average NPD values on the NSR at a sea ice concentration no greater than 15% and the rates of its change in 1980–2013 according to the satellite data and the calculations made by using the three selected ("best") climate models CNRM–CM5, MPI–ESM–LR, and MPI–ESM–MR. The average NPD value was 80 days by the satellite data for the period of 1980–2013 with a considerable interannual variation and the MSD equal to approximately a month (24 days). The rate of the NPD decrease was 18 days for the decade at the MSD equal to 3 days.

According to Table 1, the climate models are able to present sufficiently not only the NPD on the NSR, on average, but also the rate of its change. We note that the typical interannual variations that are characterized by the MSD are also quite consistent in the best models with those that are recorded based on the satellite data. This indicates that, in general, the modern climate models can also sufficiently simulate climate variability, including the interannual variability in the area of sea ice in the Arctic Ocean. It is noteworthy that despite that, in general, the estimates that were averaged for the ensemble of the model calculations

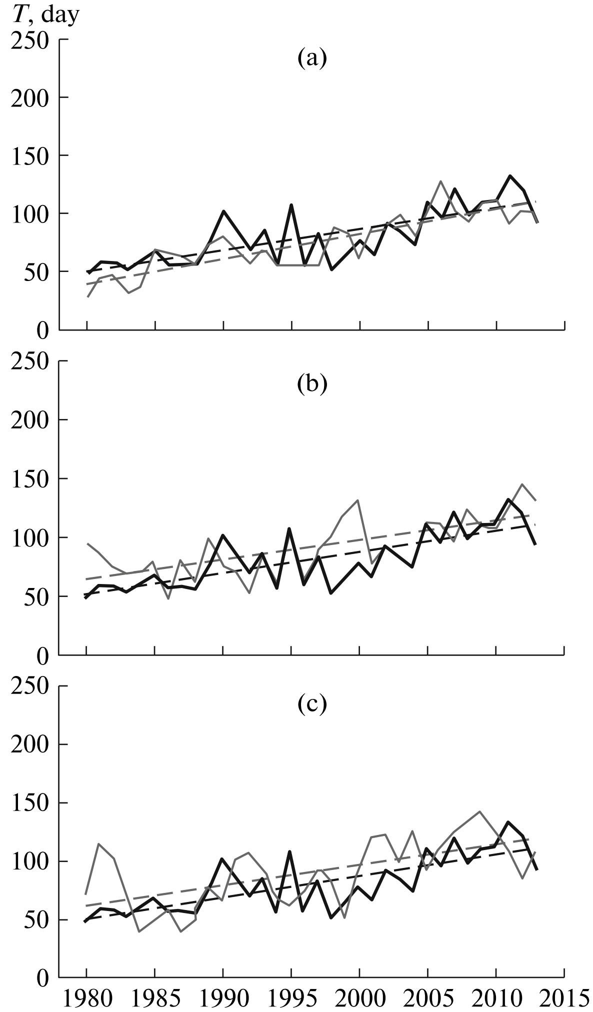

Fig. 2. Interannual variations in the NPD *T* (day) at a sea ice concentration of no more than 15% in 1980–2013 according to the model calculations CNRM–CM5 (a), MPI–ESM–LR (b), and MPI–ESM–MR (c), as compared to the satellite data (thick lines). The straight lines denote the corresponding linear trends.

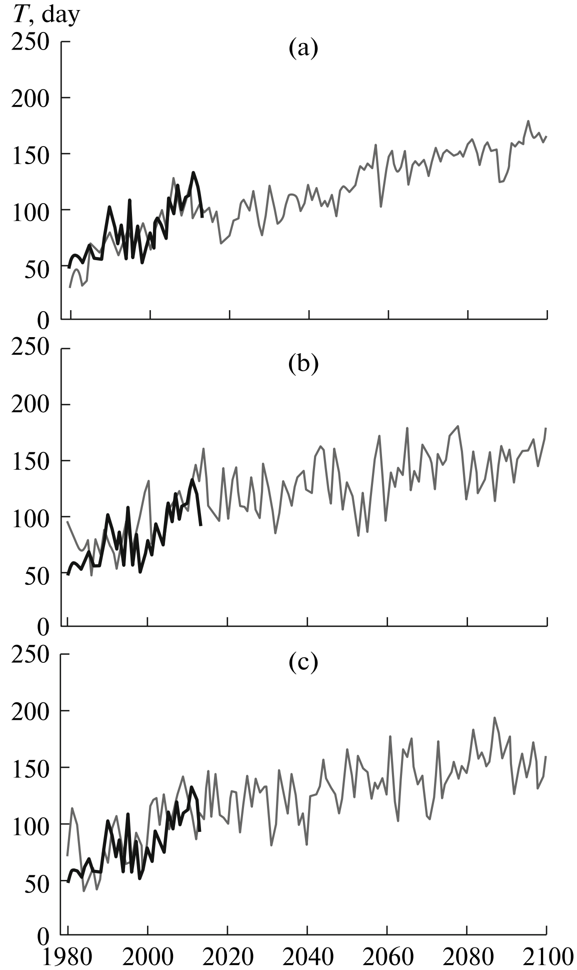

Fig. 3. Interannual variations in the NPD *T* (day) at a sea ice concentration of no more than 15% in 1980–2100 according to the model calculations CNRM–CM5 (a), MPI–ESM–LR (b), and MPI–ESM–MR (c) under the scenario of moderate anthropogenic impact RCP 4.5, as compared to the satellite data (thick lines).

are more consistent with the average values of climate variables and the tendencies to their change from the observational data, the variation level, in particular the interannual level, is underestimated when the averaging is done using the ensemble calculation.

Figure 2 presents the interannual variations in the NPD at a sea ice concentration of no more than 15% in 1980–2013 according to the model calculations as compared to the satellite data. The respective trends are shown by dashed lines. With very good consistency among the average values of the NPD for the NSR, their trends, and the MSD, there are significant differences from the satellite results for certain time intervals.

Figure 3 presents the model estimates of the interannual variations in the NPD at a sea ice concentration of no more than 15% in 1980–2100 according to the calculations under the scenario of moderate anthropogenic impacts RCP4.5 as compared to the satellite data. Against the background of the general tendency to an increase in the NPD, there is a great interannual and interdecade variability, including the periods of a noticeable decrease in the NPD in the 21st century.

The features of the nonlinear changes in the NPD for the NSR that are recorded in Fig. 3 appear in Table 2, which presents the quantitative estimates of the average NPD at a sea ice concentration of no more than 15% on the NSR and the rate of its change according to the calculations based on the three climate models CNRM–CM5, MPI–ESM–LR, and MPI–ESM–MR for the different 10-year periods in the 21st century under the scenario of moderate anthropogenic impacts RCP4.5. With a general tendency of the NPD to increase in connection with the significant inter-

Table 2. Average NPD T on the NSR (at a sea ice concentration of no more than 15%) and the rate of its change $\frac{dT}{dt}$ according to the calculations by using the climate models CN–RM–CM5, MPI–ESM–LR, and MPI–ESM–MR for the different ten-year periods in the 21st century under the scenario of moderate anthropogenic impacts RCP 4.5

Data Period, years	$\frac{dT}{dt}$, day/yr	T, day
CNRM–CM5		
2016–2025	2.6 (±1.3)	89 (±14)
2046–2055	4.0 (±0.8)	121 (±14)
2091–2100	0.8 (±0.7)	163 (±7)
MPI–ESM–LR		
2016–2025	0.9 (±2.1)	114 (±18)
2046–2055	−4.7 (±2.2)	116 (±23)
2091–2100	2.4 (±1.3)	157 (±13)
MPI–ESM–MR		
2016–2025	1.0 (±2.1)	117 (±18)
2046–2055	3.2 (±1.8)	139 (±18)
2091–2100	−0.7 (±2.0)	150 (±17)
Average		
2016–2025	1.5 (±1.1)	107 (±11)
2046–2055	0.8 (±0.8)	125 (±7)
2091–2100	0.9 (±1.1)	157 (±10)

decadal variation, a few decades show negative NPD trends, including the most significant ones, for example, according to the calculations for the middle of the 21st century by the MPI–ESM–LR model. We note a general tendency to a decrease in the MSD values of the NPD by the end of the 21st century as compared to its beginning.

Figure 4 illustrates the interannual variations in the NPD on the NSR at a ice sea concentration of no more than 15% for the 21st century according to the different model calculations under the scenario of moderate anthropogenic impacts (fine lines) with the added average variations for the ensemble of models as compared to the satellite data for 1980 (thick line). The range of variations according to the model calculations is cross-hatched. The model estimates show that a great variation in the NPD causes us to expect a general deceleration of the NPD growth rate and even a tendency to its decrease in the coming decades despite global warming in the 21st century.

The estimates in the changes in the NPD depend on the requirements for the maximum concentration of sea ice (the degree of ice cover in the water area), which are different for ships with different ice classes. For comparison, we presented the estimates of the average NPD when the ice extent on the NSR is less than 25% according to the calculations using the ensemble of climate models for different 10 year periods in the 21st century under the scenario of moderate anthropogenic impacts RCP4.5 [10]. The estimates depend considerably on the possible scenarios of anthropogenic impacts. In particular, as was noted in [10], the calculations with the comparatively highly sensitive climate model show that if the scenario of the anthropogenic impacts is more aggressive (RCP6.0), the NPD for the NSR could reach eight months by the end of the 21st century at a threshold (maximum) value of the sea ice concentration $n_i = 30\%$. With a threshold value of the sea ice concentration $n_i = 50\%$, the NPD rises even more for ships with greater ice classes.

In general, the estimates obtained indicate that the modern models can simulate key features of the conditions of the Arctic sea ice and changes in it, in particular on the NSR. Both the model calculations and the satellite data showed that the NPD was 80 days, on average, for the NSR from 1980, when the sea ice concentration was less than 15%, and the rate of the NPD growth was approximately 18 days, on average, for the decade. We note that the significant level of interannual variation in the NPD is about one month (24 days for the MSD of the NPD according to the satellite data and from 24 to 28 days according to the different model estimates).

According to the calculations with the climate models under the scenario of moderate anthropogenic impacts, the average values of the NPD can be expected to increase at a sea ice concentration (the degree of ice cover in the water area) less than 15% up to 3–4 months in the coming decade, to 4–5 months by the middle of the 21st century, and to about 5 or more months by the end of this century. Against the background of the long-period tendencies, there are significant interannual and interdecadal variations in the temperature and ice conditions. Here, we present the average rates of changes in the NPD on the NSR $\frac{dT}{dt}$, day/yr by the model calculations for the period of 2016–2100 for the scenario of moderate anthropogenic impacts RCP4.5: CNRM–CM5 is 9.6 (±0.5), MPI–ESM–LR is 5.5 (±0.9), and MPI–ESM–MR is 5.7 (±0.9), the average is 6.9 (±0.4). The respective MSDs are given in the brackets. According to the model calculations, the average rate of the increase in the NPD till the end of the 21st century was determined to be equal to 7 days/yr at a sufficiently high MSD of 4 days/yr.

In this case the respective changes are expected in the wind and cyclonic conditions of the atmosphere and in the wind disturbance and the iceberg activity in the Arctic basin. The estimates of possible changes in the wind–wave activity in the Arctic basin in the 21st century that we obtained by using the models of wind disturbance and the regional climate changes with

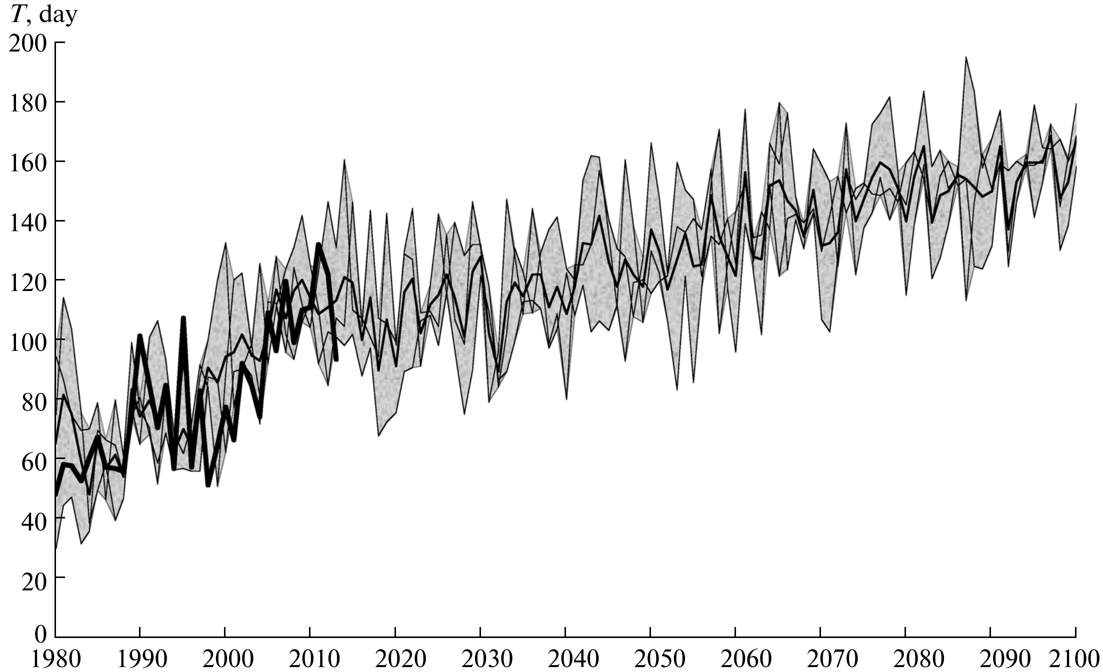

Fig. 4. Interannual variations in the NPD at a sea ice concentration of no more than 15% according to the ensemble of model calculations (fine lines, the average variations for the ensemble of the models are also identified) under the scenario of moderate anthropogenic impacts in the 21st century, as compared to the satellite data in 1980 (thick line). The variation range for the different model calculations is cross-hatched.

respect to the moderate anthropogenic impacts indicate new potential risks with total amplification of wave activity in the Arctic Ocean. There is an expected increase in the recurrence of hazardous phenomena accompanied by strong winds and extreme sea waves along the NSR. This is caused by the increase in the length of the wave roll and the regional strengthening of the surface wind [13–15]. The growth in the sea disturbance contributes to coastal erosion in the Arctic, which currently reaches several meters per year [3]. The high rate of coastal erosion is also caused by the permafrost and its degradation.

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