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GEOPHYSICS

Variations in the Ice Cover of the Arctic Basin in the 21st Century Based on Model Simulations: Estimates of the Perspectives of the Northern Sea Route

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Trends in variations of the ice cover of the Arctic Basin were analyzed based on the daily data of simulations for the 21st century to estimate possible perspectives of the Northern Sea Route. Numerical simulations using the coupled atmosphere–ocean general circulation model (AOGCM) ECHAM5/MPI-OM were used in the analysis [1, 2] under a sufficiently aggressive SRES-A2 scenario [3] of anthropogenic emission of greenhouse gases into the atmosphere.

Variation in the sea ice area in the Arctic Ocean is one of the key factors and indicators of climatic changes in the Arctic. The processes of ice formation and melting are related to a number of physical factors. Ice formation depends not only on the meteorological factors that influence cooling of the ocean, but also on the characteristics of the upper ocean layer, in particular its temperature, salinity, and thickness. A transition from the ice-free regime to the ice regime is related to the reconstruction of the vertical structure of the oceanic layer with the formation of a halocline, which limits significantly the vertical exchange [4].

According to the satellite data (see, for example, http://nsidc.org), since the end of the 1970s, the minimal area of sea ice in the Arctic basin in September decreased annually by 60 000 km^2, on average [5]. The sea ice area in the Arctic Ocean was minimal (approximately 5.5 mln km^2) in September 2005 was significantly greater (approximately 7.5 mln km^2) at the end of the 1970s. According to [6], the thickness of sea ice in the 1990s decreased relative to the terminal 1950s–mid-1970s period (see also [7]).

The simulations point to the decrease in the sea ice area in the 21st century with account for interannual and long-term variations and spatial inhomogeneity of the variations. The sea ice regime in the Arctic is very important for Russia in connection with problems of the Northern Sea Route and development of the shelf. According to the estimates in [8] based on a set of five models, a decrease in the sea ice area by the end of the 21st century in the Northern Hemisphere under the anthropogenic SRES-B2 scenario is approximately 2.5 mln km^2, on average, in March (when the ice cover is maximal) and in September (when the ice cover is minimal). Modern climate models yield a large scatter in simulations of the sea ice regime and its variation in the Arctic [9]. According to some estimates, the Arctic basin can be completely free of ice at the end of summer beginning from the second half of the 21st century.

The AOGCM ECHAM5/MPI-OM model is one of the best global climate models in terms of reproduction of the modern regime of sea ice in the Northern and Southern hemispheres [10, 11]. Figure 1 characterizes the spatial distributions of the variations in $\Delta\tau_{ni}$ (relative to 1961–1990) of the period τ_{ni} with a potential navigation regime based on the simulations using this model under scenario SRES-A2 in (a) 2001–2030, (b) 2031–2060, and (c) 2061–2090. The regime was considered navigable if the proportion of sea ice δ_i did not exceed 15% of the area of the model cell ($\delta_i \le \delta_{i,cr} = 0.15$). Regimes with $\delta_{i,cr} = 0.5$ were also analyzed.

According to Fig. 1, in the first 30 years of the 21st century, the maximal increase in the navigation period in the Arctic latitudes would be manifested in the influence sector of the Atlantic. In the Barents, Kara, and Greenland seas, the $\Delta\tau_{ni}$ values would reach 2–3 months or more.

According to the simulations using the ECHAM5/MPI-OM model, increase in τ_{ni} during all three 30-yr intervals in the 21st century on the Northern Sea Route along the Arctic coast of Eurasia would be the smallest in the East Siberian Sea. The $\Delta\tau_{ni}$ value would be no more than 10 days in 2001–2030, approximately one month in 2031–2060, and approximately one season in 2061–2090. In 2061–2090, the maximal

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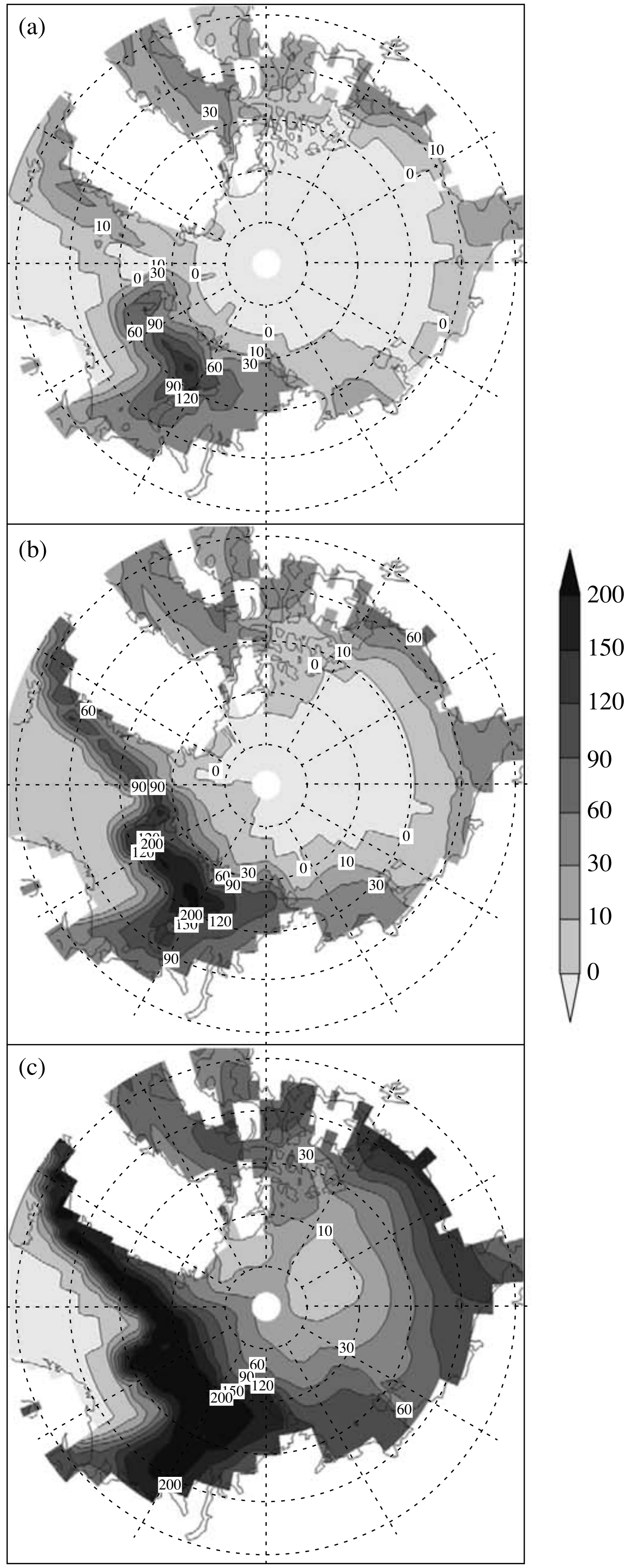

Fig. 1. Spatial distribution of variations in the τ_{ni} period with a potential navigation regime relative to 1961–1990 based on the simulations using the AOGCM ECHAM5/MPI-OM model under SRES-A2 scenario: (a) 2001–2030, (b) 2031–2060, and (c) 2061–2090.

$\Delta\tau_{ni}$ value in the Atlantic sector would reach 200 days or more.

Long-period trends of τ_{ni} are related to different variations in the annual cycle in different Arctic seas. Figure 2 shows annual cycles of the navigation time share $\delta_{ni} = 1 - \delta_i$ of the area of the (a) Barents and (b) Kara seas and (c) the Laptev Sea during different 20-yr intervals of the 21st century based on the simulations using the ECHAM5/MPI-OM model. One can see that the annual cycle of δ_{ni} and its long-period variations differ significantly in the three seas.

In the first 20-yr period of the 21st century, in the Barents Sea sector located in the zone of strong influence of the Atlantic and Gulf Stream, the δ_{ni} value varies from 1/4 in spring to 1/2 in autumn (at $\delta_{i,\,cr} = 0.5$, δ_{ni} increases from 1/3 in spring to 2/3 in autumn). In the two subsequent 20-yr periods, the proportion of δ_{ni} changed comparatively uniformly with relatively slight differences in different seasons. In the second half of the 21st century during the transition to the fourth 20-yr period, the ice cover of the Barents Sea was characterized by a more significant decrease compared to the previous periods. Slightly greater changes were observed in the winter–spring months. In the period 2061–2080, sea ice in September is practically absent in this sector. Transition to the last 20-yr period is characterized in the model by a sharp attenuation in the decrease of the ice cover area.

In the Kara Sea sector, the range of variations in δ_{ni} during the annual cycle in the first 20-yr period of the 21st century is greater than in the Barents Sea sector. It is close to zero in spring and winter and reaches 2/5 (up to 2/3 at $\delta_{i,\,cr} = 0.5$) in September. Up to the middle of the 21st century, variation in the proportion of δ_{ni} is minimal in spring and winter. However, the amplitude of the annual cycle increases unlike in the Barents Sea. In the second half of the 21st century, similarly to the Barents Sea sector, the Kara Sea sector is characterized by a notably greater decrease in the ice cover area compared to the previous periods. At the end of the century, the differences in the variation rate of ice cover area in this sector are more prominent: the area of ice-free water increases more significantly in winter than in summer. In the last 20-yr period of the 21st century, the Kara Sea sector in the model becomes almost ice-free by September (at $\delta_{i,\,cr} = 0.5$, sea ice is not observed in the end of summer–beginning of autumn during a period of approximately two months). At the end of the 21st century, the minimal values of δ_{ni} in summer are approximately equal to 1/6 (in spring at the end of the 21st century, at $\delta_{i,\,cr} = 0.5$, the minimal δ_{ni} value is only slightly higher than 1/4 in the Kara Sea sector and approximately equal to 3/4 in the Barents Sea sector).

In the 21st century, significantly weaker changes are recorded in the ice cover area of the Laptev Sea sector. Up to the end of the century, the ice-free water area in this model basin remains almost zero in spring and the early summer. At the same time, autumnal changes in the ice cover area of the Laptev Sea sector are significantly stronger than in the Barents and Kara sea sectors. In the last 20-yr period of the 21st century, the Laptev Sea sector in the model becomes ice-free by September

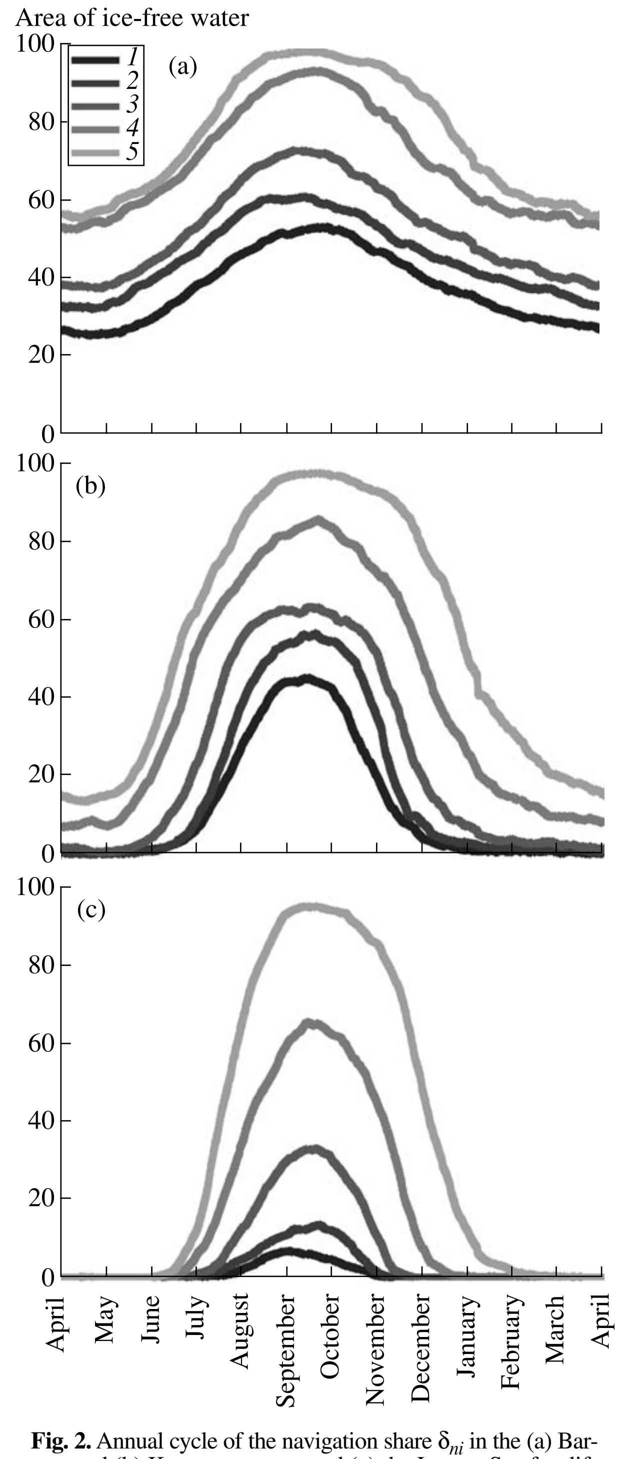

Fig. 2. Annual cycle of the navigation share δ_{ni} in the (a) Barents and (b) Kara sea sectors and (c) the Laptev Sea for different 20-yr intervals in the 21st century based on simulations using the AOGCM ECHAM5/MPI-OM model under scenario SRES-A2: (*1*) 2001–2020; (*2*) 2021–2040; (*3*) 2041–2060; (*4*) 2061–2080; (*5*) 2080–2100.

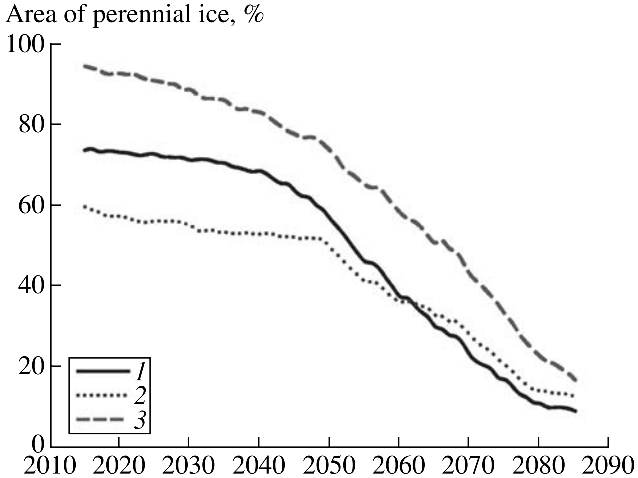

Fig. 3. Variations in the annual mean proportion (in %) of perennial ice (at 30-yr averaging) based on the simulations using the AOGCM ECHAM5/MPI-OM model under scenario SRES-A2 for the (*1*) Barents and (*2*) Kara sea sectors and (*3*) the Laptev Sea.

(at $\delta_{ni, cr} = 0.5$, the amplitude of the annual cycle δ_{ni} reaches 100% in this basin by the end of the 21st century, as compared to 20% at the beginning of the century). Variations in the ice cover area show a distinct asymmetry for different seasons, in particular, for the seasons of the formation of complete ice cover and the reverse process. Widening of the interval with nonzero δ_{ni} values in the annual cycle of the 21st century in the model is related to the corresponding variations in winter.

The seasonal asymmetry of trends revealed in the model of the ice cover area in the 21st century can be related to the trend of thinning of the sea ice cover and the replacement of perennial ice by seasonal ice (Fig. 3, see also [9]). As a result, the rate of decrease in the sea ice area in summer should increase. Figure 3 shows variations in the share of perennial ice in three sectors of the Arctic basin. The annual mean proportion of perennial ice was estimated as the ratio of the minimal area of sea ice in the annual cycle (in September) to the annual mean area of ice. The model simulations indicate the appearance of regimes with different rates of decrease in the share of perennial ice in the 21st century (Fig. 3). A notably stronger increase in the rate of ice melting in the middle of the 21st century compared to the previous periods (Fig. 3) is related to this fact.

As was noted in [4], meteorological factors have a crucial influence on the variation in the sea ice area in summer and autumn. In other seasons, the development of the ice cover depends strongly on the oceanic regime, in particular, on the degree of development of the Arctic halocline. The vertical structure of the Arctic Ocean is characterized by a sharp halocline with the upper freshened layer and the underlying layer of more saline and warmer Atlantic waters. The halocline limits strongly the vertical heat exchange.

The heat content in the active layer of the ocean is important for the shift of the ice formation time. The heat content has a negative correlation with the onset of the ice regime in the annual cycle. It should be noted that the heat content of the active layer is important for cold seasons with decreased vertical stability of oceanic layers and stronger heat fluxes to the surface. The regime of sea ice melting is characterized by the formation of the freshened layer barrier that decreases heat fluxes. This effect can be responsible for the relatively weak sensitivity of the transition from the regime of ice-covered ocean to the regime of ice cover reduction, in particular, for the Laptev Sea sector in Fig. 2c.

The obtained model results evidence that ice conditions along the Northern Seas Route would improve significantly in the 21st century. According to the simulations performed using the ECHAM5/MPI-OM model under anthropogenic scenario SRES-A2, it is possible to expect that the period of potential navigation along the entire Northern Seas Route would be prolonged approximately one season or even more by the end of the 21st century with respect to the end of the 20th century. The duration of the potential navigation regime estimated from the total area of sea ice cover can increase even more under a less strict condition, in particular, if ice not thicker than 6 cm is permissible for navigation (see, for example, [1]). More precise specification of the distribution of sea ice in the eastern Arctic basin in summer months should favor additional prolongation of the navigation period. We should note that the model used in the present work is based on a very aggressive version of the anthropogenic scenario of variations in the content of greenhouse gases in the atmosphere. The variations should be lower for less aggressive scenarios. However, we cannot exclude regional peculiarities.

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REFERENCES

1. E. Roeckner, G. Bäuml, L. Bonaventura, et al., *The Atmospheric General Circulation Model ECHAM 5. Part 1: Model Description*, (MPI Rept. 349) (Max Planck Inst. Meteorol., Hamburg, 2003).
2. S. J. Marsland, H. Haak, J. H. Jungclaus, et al., Ocean Model. **5**, 91 (2003).
3. *Climate Change 2001: The Scientific Basis*, Intergovernmental Panel on Climate Change, Ed. by J.T. Houghton,

Y. Ding, D.J. Griggs, et al. (Cambridge Univ. Press, Cambridge, 2001).

4. V. F. Zakharov, *Sea Ices in Climatic System* (Gidrometeoizdat, St. Petersburg, 1996) [in Russian].
5. I. I. Mokhov, Zemlya Vselennaya, No. 2, 34 (2006).
6. D. A. Rothrock, Y. Yu, and G. A. Maykut, Geophys. Res. Lett. **26** (23), 3469 (1999).
7. *Formation and Dynamics of Modern Arctic Climate*, Ed. by G.V. Alekseev (Gidrometeoizdat, St. Petersburg, 2004) [in Russian].
8. V. P. Meleshko, G. S. Golitsyn, V. A. Govorkova, et al., Meteorol. Gidrol., No. 4, 38 (2004).
9. X. Zhang and J. E. Walsh, J. Climate **19**, 1730 (2006).
10. C. L. Parkinson, K. Y. Vinnikov, and D. J. Cavalieri, J. Geophys. Res. **111**, C07012 (2006), doi: 10.1029/2005JC003408.
11. K. Y. Vinnikov, D. J. Cavalieri, and C. L. Parkinson, Geophys. Res. Lett. **33**, L05704 (2006), doi: 10.1029/2005GL025282.