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Bayes Estimates of Variations of the Duration of the Navigation Period Along the Northern Sea Route in the XXI Century from Simulations with Ensemble of Climate Models

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Abstract. In the 21st century, a significant increase in the duration of the navigation period on the Northern Sea Route is expected. This is due to the stronger warming of the climate in the Arctic. Current climate models are characterized by considerable uncertainty in the sensitivity of the characteristics of sea ice in the Arctic Ocean to current climate changes. In order to take into account, the uncertainty of the results of numerical calculations for models, together with the uncertainty of the observational data, Bayesian analysis methods are used. This paper analyzes the changes in the duration of the navigation period (NPD) on the Northern Sea Route (NSR) for the Coupled Models Intercomparison Project, phase 5 (CMIP5) climate model ensemble under Representative Concentration Pathways (RCP) anthropogenic scenarios using Bayesian statistics. For various scenarios of anthropogenic impact, it was found that the expected duration of the navigation period on the Northern Sea Route will be 2–3 months by the middle of the XXI century and 3–6 months by its end.

Keywords: Climate changes · The arctic · Sea ice · North sea route · Satellite data · Climate models · Bayesian statistics · CMIP5

1 Introduction

Variations in the sea-surface temperature in the arctic latitudes in recent decades were lager then the global mean changes by a factor of two. At the same time, the area of sea ice in the Arctic is rapidly decreasing. The area of the Arctic sea ice in 1979–2014 in September it decreased at a rate of 1.3% per year [1]. With the continuation of modern climate warming in the 21st century, the Arctic Ocean can be free of sea ice in the

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summer-autumn seasons. This tendency contributes to an increase in the duration of the navigation period on the Northern Sea Route [2–4].

Climate models, in particular the models included in the CMIP5 ensemble, are characterized by considerable uncertainty in the reproduction of the characteristics of sea ice in the Arctic Ocean compared to the observed climate changes, both from the results of numerical calculations of the climate reproduction of the XX century and calculations of climate change in the 21st century [5]. In order to obtain more reliable estimates of changes in the PNP on the SMP in the 21st century, it is necessary to use analysis methods that take into account the uncertainties in the results of climate model estimates and uncertainties in the observational data. For this, in particular, one can use Bayes averaging [6–8].

In our work, we analyze changes in the duration of the navigation period using calculations of the Coupled Models Intercomparison Project, phase 5 (CMIP5) climate model ensemble for Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios of anthropogenic impact using Bayesian statistical methods.

2 Data and Methods

For the analysis, model calculations of sea ice compactness in the Arctic Ocean of the CMIP5 ensemble for the period 1979–2100 were used. The initial year of this period was chosen as the beginning of satellite observations. We use numerical calculations of the "historical" scenario for the period 1979–2005. and the results of numerical calculations with the CMIP5 climate model ensemble under the scenarios of anthropogenic and natural impacts of the RCP family for the period 2006–2100. Of the four anthropogenic RCP scenarios, we select the moderate (RCP 4.5) and more "aggressive" (RCP 8.5) anthropogenic scenarios. To find the duration of the navigation path, we considered that the model cell was free of sea ice, if it had an average monthly ice concentration of no more than 15%. In addition, the duration of the navigation period was determined by taking into account how much Z of the route of the Northern Sea Route was ice-free (for Z, values of 80% and 90% were used).

We highlight some of the characteristics in order to take into account both the quality of the reproduction of the current climate models, and climate change at different time scales. These characteristics are (1) the average long-term NPD duration $T_{Z,m}$, (2) the linear trend for a series of NPD data $T_Z^{'}$, and (3) the standard deviation of the short-period interannual variability σ_Z. Bayesian weights are calculated as the likelihood functions of these quantities for the measured data. To obtain observational data, we use the Scanning Multichannel Microwave Radiometer instrument on the Nimbus-7 satellite (SMMR) for the period 1980–2014. We assume that all variables are normally distributed and their means and standard deviations can be found from observational data. Thus, weights are calculated as:

$$w_j^{(k)} = N\left(X_j^{(k)}, X_j^{(0)}, \sigma_j^{(0)}\right), \tag{1}$$

where $j = 1-3$, k is mmodel index, $N(x, x_0, \sigma)$ is the normal distribution of variable x with the mean value x_0 and standard deviation σ. The weights taking into account traits 1–3 and $X_j^{(k)} = T_{Z,m}$ if $j = 1$, $X_j^{(k)} = T_Z^{'}$, if $j = 2$, $X_j^{(k)} = \sigma_Z$, if $j = 3$. Here, $X_j^{(0)}, \sigma_j^{(0)}$ indicates that these are the data of observations. In addition, we assume that each trait contributes to the result independently of the others, and the resulting contribution of this model will be the product of the weights:

$$w_4^{(k)} \sim w_1^{(k)} w_2^{(k)} w_3^{(k)}$$

An additional condition is required for all weights:

$$\sum w^{(k)} = 1$$

In addition, combinations of weighting factors are used that take into account all three time scales. Using the calculated weight factors, the ensemble averaging $E(T_Z|D)$ and calculation of the intermodel (intraensemble) standard deviation $\sigma(T_Z|D)$ is performed:

$$E(T_Z|D) = \sum T_Z^{(k)} w^{(k)}$$

$$\sigma(T_Z|D) = \left\{ \sum \left\{ \left[\sigma(T_Z|D)^2 + T_Z^{(k)2} w^{(k)} \right] - E(T_Z|D, T_Z^{(k)})^2 \right\} \right\}^{1/2}$$

Where $T_Z^{(k)}$ are array of variable T_Z of traits 1–3.

3 Results

Weights for scenarios of anthropogenic impacts RCP4.5 and RCP8.5 and Z = 80% are illustrated on Fig. 1. Weights w_1 (characterizing the average multiannual value of the NPD) are distributed relatively uniformly between the models. A more non-uniform intermodal distribution of weights is noted for w_2, w_3 and w_4. The degree of this non-uniformity can be characterized using the information entropy normalized to a value corresponding to the weights $w_0 = 1/K$:

$$H_j = -(\sum w_j^{(k)} \log_2 w_j^{(k)}) / \log_2 K$$

The values of this entropy are: $H_1 = 0.98, H_2 = 0.93, H_3 = 0.72$ and $H_4 = 0.66$. They decrease with increasing weights numbers. The greatest contribution to the inter-model differences in estimating the change in the NSR is due to the reproduction of the short-period interannual variability of sea ice compactness on the NSR. In addition, the pairwise correlation coefficients between weights are not statistically significant. This allows us to use the combined weighting factor in the form w_4.

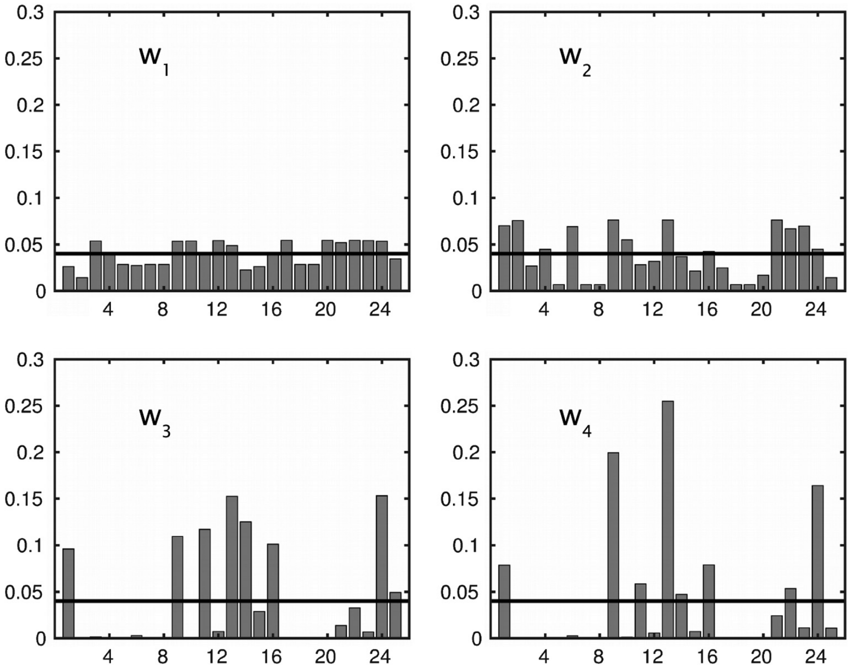

Fig. 1. Bayesian weight factors for the NPD on the Northern Sea Route (a case where 80% of the route is ice-free). For simplicity, an index indicating the climate model is omitted in the drawings. In determining the weights for 2006–2014. used the results of calculations with the script RCP 4.5. The number of the climatic model is indicated on the abscissa axis. The horizontal line shows the weight w (0) = 1 / K (K is the number of models in the ensemble).

It was found that the models of the CMIP5 ensemble are consistent with each other in an overall significant increase in the NPD at the NSR in the 21st century. This increase is more for the RCP 8.5 scenario than for the RCP 4.5, which is associated with a large increase in greenhouse gas concentrations in the atmosphere in the first scenario than in the second. In the case when 80% of the NSR route is free of sea ice, the change in the NPD under anthropogenic impact on the climate is slightly larger than in the case of 90%, the uncertainty intervals overlap for these values. Thus, the results of the work are not very sensitive to the choice of the value of Z (Fig. 2).

Models that best reproduce the current multi-year value of the NPD (models whose weights w_1 are greatest) are characterized by a small change in T_Z during warming caused by anthropogenic impact. In addition, the sensitivity of the NPD in the models that best reproduce the linear trend T_Z over the past decades (which is characterized by weights w_2) is maximum. The response of T_Z in models with the best reproduction σ_Z (i.e. with maximum weights w_Z) is greater than the response of models that best reproduce $T_{Z,m}$, but smaller than the corresponding response in models that best reproduce $T_Z^{'}$. The response of models with the largest weights w_4 is similar response models with relatively large w_3 weights.

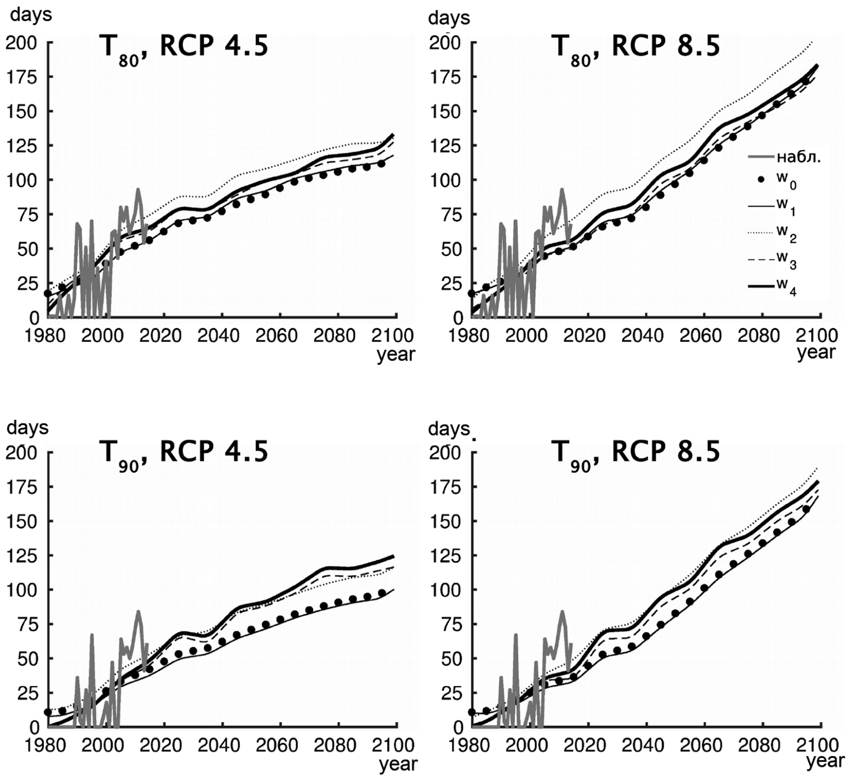

Fig. 2. The ensemble average value of the NPD on the Northern Sea Route for scenarios of anthropogenic impacts on the climate system RCP 4.5 and RCP 8.5, for different values of the Z parameter and for different options for calculating Bayesian weights.

The models that best reproduce the modern climate are not sensitive to anthropogenic warming. The models that best reproduce the linear trend over the past decades are the most sensitive to anthropogenic warming. Combining criteria in the form of a weight w_4 leads to an average response of the NPD to anthropogenic warming.

With all the choice of weighting factors used, the intermodel standard deviation $\sigma(T_Z|D)$ as a whole increases with time. As the weight number increases, the intermodel standard deviation decreases (Fig. 3). It can be observed that the intermodel variation for different scenarios of anthropogenic impact and Z values is very significant. But this does not mean that changes over time in the NPD are statistically insignificant. The change in $E(T_Z|D)$ for time variations should be compared not with $\sigma(T_Z|D)$, but with T_Z (standard deviation of interannual variability). The values of this standard deviation for different scenarios of anthropogenic influences, Z values and time points range from 1 to 2 weeks. Thus, the increase in the NPD on the Northern Sea Route becomes statistically significant even for the beginning of the XXI century.

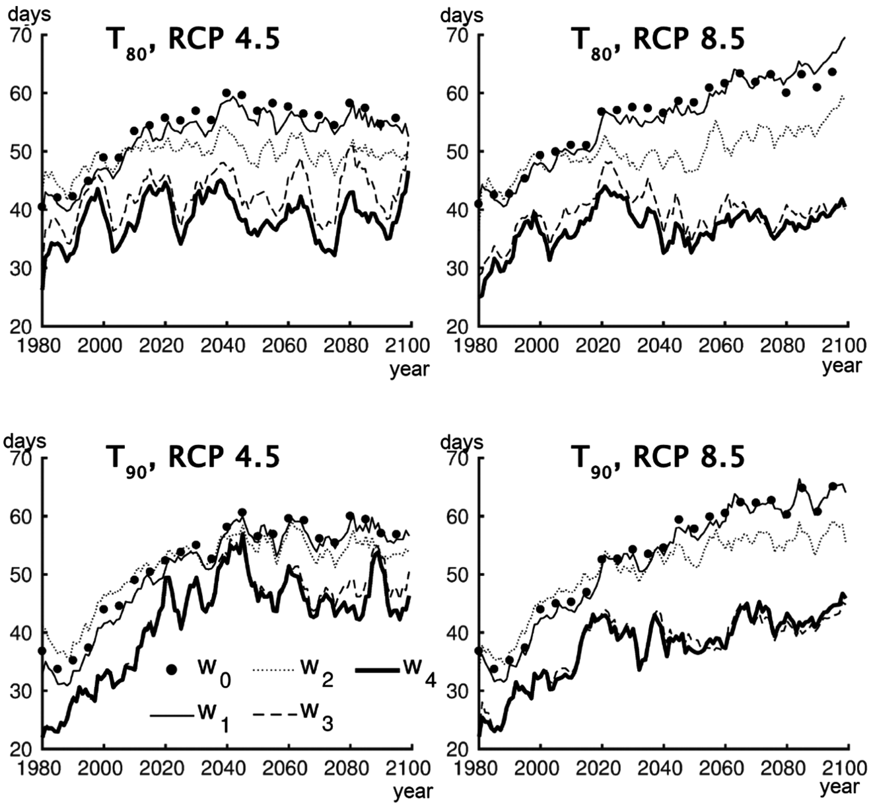

Fig. 3. The inter-model standard deviation of the NPD on the Northern Sea Route for scenarios of anthropogenic impacts on the climate system RCP 4.5 and RCP 8.5, for different values of the Z parameter and for various options for calculating Bayes weights.

Thus, the estimated duration of the navigation period on the Northern Sea Route for the scenarios of anthropogenic impacts of RCP is expected to be 2–3 months according to the ensemble model estimates. in the middle of the XXI century. At the end of the XXI century, the duration is expected to be 3–6 months.

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