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Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century

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Abstract The ability of modern climate models to simulate ice season length in the Arctic, its recent changes and navigation season on Arctic marine routes along the Eurasian and the North American coastlines is evaluated using satellite ice cover observations for 1979–2007. Simulated mean sea ice season duration fits remarkably well to satellite observations and so do the simulated 20th century changes using historical forcing. This provides confidence to extend the analysis to projections for the twenty-first century. The navigation season for the Northern Sea Route (NSR) and Northwest Passage (NWP), alternative sea routes from the North Atlantic to Asia, will considerably increase during this century. The models predict prolongation of the season with a free passage from 3 to 6 months for the NSR and from 2 to 4 months for the NWP by the end of twenty-first century according to A1B scenario of the IPCC. This suggests that transit through the NSR from Western Europe to the Far East may be up to 15% more profitable in comparison to Suez Canal transit by the end of the twenty-first century.

1 Introduction

Rapid Arctic sea ice retreat during the last decades is one of the most noticeable manifestations of global warming (Arctic Climate Impact Assessment (ACIA) 2005)

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and has major impacts on Arctic marine transport systems development and shelf exploration (Granberg 1998). Satellite observations show a rapid reduction of Arctic ice cover in all seasons, with strongest changes in summer. The decline accelerated recently, which resulted in record low sea ice extent of only 4.3 million km^2 in September 2007 (e.g. Comiso et al. 2008; Stroeve et al. 2007), corresponding to a 40% reduction relative to 7.5 million km^2 in 1979. These changes lead to prolonged open water conditions in the marginal Arctic Seas and new perspectives for the Arctic transport systems. Northern Sea Route (NSR) follows the northern Eurasian coast from Novaya Zemlya to the Bering Strait. NSR is presently open for about a month and half per year for ice-strengthened ships navigation at the end of summer and shortens the transport distance from northern Europe to northeast Asia and northwest North America by up to 50% relative to the southern routes through Suez or Panama Canal (e.g. Mulherin 1996). Northwest Passage (NWP) extends along the northern North American coast and through the Canadian Arctic archipelago. This shortens the transit distance from western Europe to the Far East by 9,000 km in comparison to the conventional Panama Canal transit route (e.g. Howell and Yackel 2004). It was completely free of ice for the first time in recorded modern history in September 2007 allowing unhindered ship navigation (e.g. Cressey 2007).

Climatic changes should be taken into account in future projections of socioeconomics development in the Arctic and marine transportation. Global climate models simulate a further decrease of Arctic sea ice cover in the twenty-first century if atmospheric greenhouse gas concentrations continue to rise (Arzel et al. 2006; Zhang and Walsh 2006; Kattsov et al. 2007; Stroeve et al. 2007). A considerable increase in the length of navigation season (Mokhov et al. 2007) for both northern passages can be foreseen, which makes them a real alternative to the current conventional ship transport routes.

Modern climate models are able to reproduce the present spatial distribution and seasonal cycle of Arctic sea ice (e.g. Parkinson et al. 2006; Zhang and Walsh 2006), but only some of them adequately simulate the recent downward trend (e.g. Stroeve et al. 2007). However, the unprecedented reduction of Arctic sea ice in recent years may also be due to natural factors, such as anomalous atmospheric circulation (e.g. Zhang et al. 2008).

In order to get further insight into the perspectives of Arctic ship transport during this century, climate change integrations with an ensemble of state-of-the-art climate models are analyzed. Model estimates of sea ice conditions affecting the duration of the summer Arctic navigation are compared to satellite data. We estimate benefits for Arctic transportation, which by the middle of the twenty-first century may become competitive to the traditional Europe–Asia routes through the Suez or Panama Canals.

2 Data and models

The model simulations included in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) (Meehl et al. 2007) were analyzed (Table 1). These simulations were used in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). The models were driven with increasing concentrations of greenhouse gases and

Table 1 List of analyzed models

Model	Country	Atmosphere resolution	Ocean resolution
BCM2	Norway	T63 L31	0.5–1.5° × 1.5° L35
CCSM3	USA	T85 L26	0.3–1° × 1° L40
CGCM3-T47	Canada	T47 L31	1.9° × 1.9° L29
CGCM3-T63		T63 L31	0.9° × 1.4° L29
CNRM	France	T63 L45	0.5–2° × 2° L31
CSIRO3.0	Australia	T63 L18	0.8° × 1.9° L31
CSIRO3.5			
ECHAM5/MPI-OM	Germany	T63 L31	1.5° × 1.5° L40
ECHO-G	Germany/Korea	T30 L19	0.5–2.8° × 2.8° L20
GFDL2.0	USA	2.0° × 2.5° L24	0.3–1° × 1° L50
GFDL2.1			
GISS-AOM	USA	3° × 4° L12	3° × 4° L16
GISS-ER	USA	4° × 5° L20	4° × 5° L13
HADCM3	UK	2.5° × 3.8° L19	1.5° × 1.5° L20
HADGEM1	UK	∼1.3° × 1.9° L38	0.3–1.0° × 1.0° L40
INM	Russia	4° × 5° L21	2° × 2.5° L33
IPSL	France	2.5° × 3.75° L19	1–2° × 2° L31
KCM	Germany	T31 L19	0.5–2° × 2° L31
MIROC-HR	Japan	T106 L56	0.2° × 0.3° L47
MIROC-MR		T42 L20	0.5–1.4° × 1.4° L43
MRI	Japan	T42 L30	0.5–2.0° × 2.5° L23

Selected models are indicated in bold. T/L labeling specifies horizontal/vertical model resolution
T triangular spectral truancation, *L* number of vertical levels

aerosols according to the moderate scenario A1B which is one of the IPCC scenario characterized by rapid economic growth, growth of global population up to nine billion in 2050 and balanced emphasis on all energy sources. Another model was also included in the analysis. This is the recently developed Kiel Climate Model (KCM) (Park et al. 2009), which was found to be in a good agreement with observations. Original monthly sea ice concentration fields were linearly interpolated into the 1°× 1° latitude–longitude grid in order to enable intercomparison of simulated geographical distributions and to permit comparisons with observational data.

The daily sea ice concentration data from satellite observations (Cavalieri et al. 1999) for 1979–2007 at 25 × 25 km resolution were used for the comparison. These data are derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) -F8, -F11 and -F13 Special Sensor Microwave/Imager (SSM/I) radiances using the NASA team algorithm (Cavalieri et al. 1999). The length of the ice season was calculated as number of days with sea ice concentrations exceeding 15% (e.g. Parkinson 1992, 2000) for each model cell. Correspondingly, the length of navigation season in the model cells was defined as the number of days with open water (ice concentration less then 15%). We used 15% sea ice concentration as threshold for the possible navigation of light ice-class ships without icebreaker escort. "Route weighed" length of navigation season was calculated as an averaged along the routes (Fig. 2i). Therefore, "route weighed" navigation season length does not require entirely open passage at the same time. This definition is a simplified approach caused by coarse model resolution, which does not allow representing many details and important sub-grid features such as flow and deformation of sea ice through narrow passages. However, this method was justified by reasonable correspondence to present-day data on navigation season length for the NSR.

NWP (Fig. 2i) is a sea passage running east to west through the Canadian Arctic Archipelago along Parry Channel. It begins at Lancaster Sound, passes through Barrow Strait and Viscount-Melville Sound, finally reaching the Beaufort Sea through McClure Strait. An analysis of sea ice conditions along the NWP demands using sufficiently high resolution observations and model simulations. Satellite data have quite high spatial resolution (25 × 25 km) for resolving ice conditions within Canadian Arctic Archipelago. The best modern climate models are also able to adequately represent the major part of the NWP passing along the Parry Channel (see Fig. 2). Therefore, in case of the NWP we selected only those models that are able to resolve the major part of the Parry Channel from Lancaster Sound to McClure Strait.

HadISST1 sea ice concentrations (Rayner et al. 2003) were used to evaluate the potential impact of ice cover on NSR transit cost for the period 1957–1990.

3 Model evaluation

We evaluate the models' ability to reproduce long-term means and changes of the sea ice conditions along NSR and NWP. Figure 1 shows mean (1980–1999) length of sea

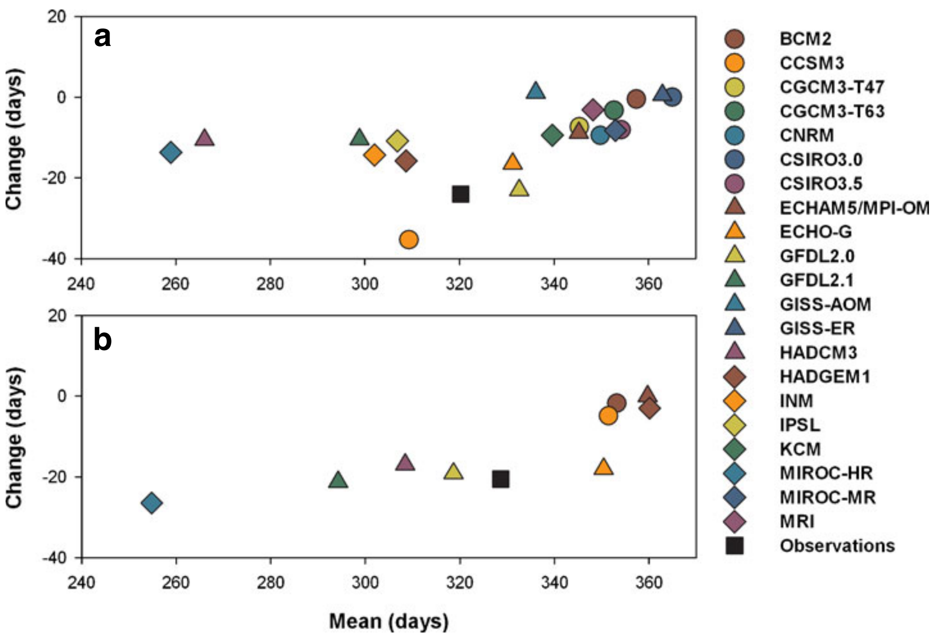

Fig. 1 Validation of the present ice season length averaged along the Northern Sea Route from Kara Strait to Bering Strait (**a**) and along the Northwest Passage from Lancaster Sound to Bering Strait (**b**): long-term (1980–1999) mean length of ice season (days) and its changes from 1979–1988 to 1998–2007 as observed (Cavalieri et al. 1999) and simulated (Table 1)

ice season averaged along the NSR (from Kara Strait to Bering Strait, (a) and NWP (from Lancaster Sound to Bering Strait, (b) and its change for 1998–2007 relative to 1979–1988 from observations and the climate models. In case of NWP analysis we selected only those models that are able to resolve the major part of pathway along the Parry Channel. Thus, only the nine best resolution models were selected for the further analysis of the NWP conditions. Most models overestimate length of ice season and underestimate its decrease in recent decades (see also Stroeve et al. 2007). Student's *t*-test was applied to select the most realistic models. Five models (CCSM3

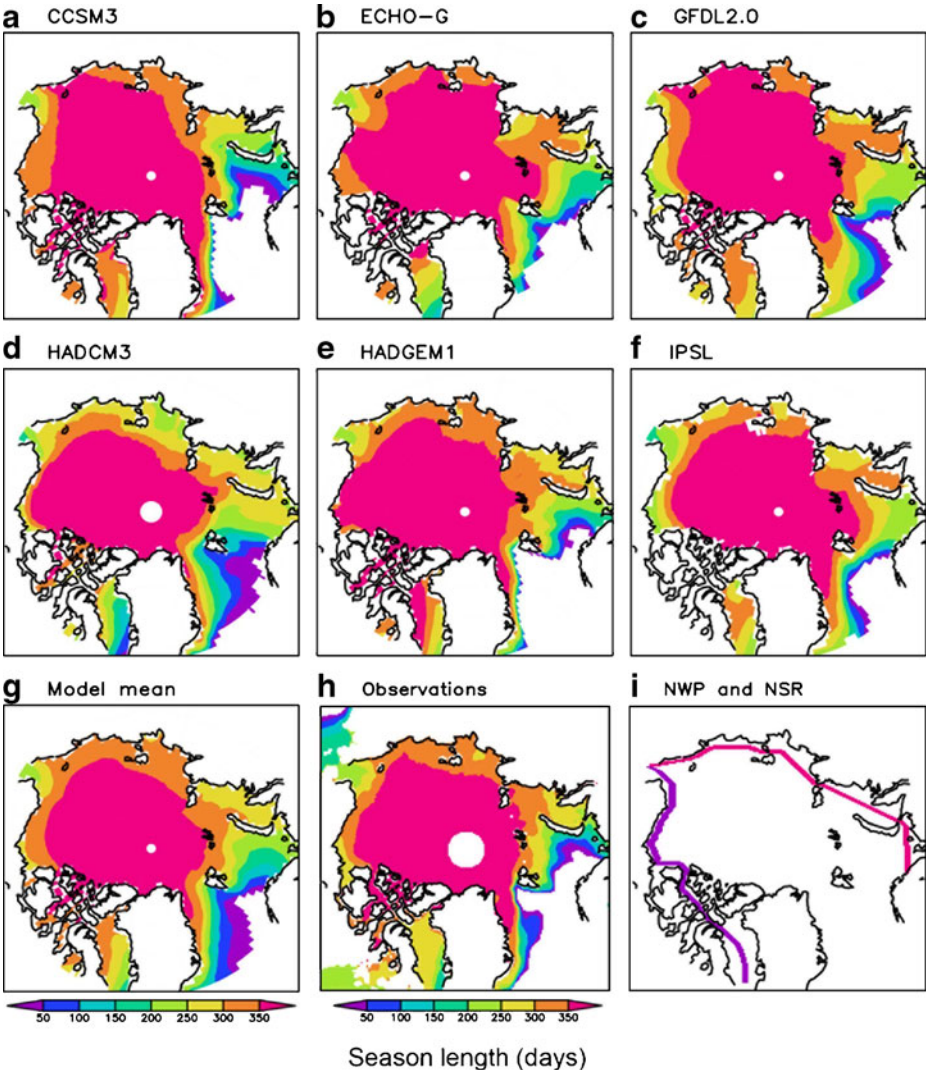

Fig. 2 Length of ice season (days) simulated by selected global climate models (**a**–**f**), the mean over all selected models (**g**) in comparison to observations (**h**) for 1980–1999; Northern Sea Route and Northwest Passage (**i**)

(Collins et al. 2006), ECHO-G (Min et al. 2005), GFDL2.0 (Delworth et al. 2006), HadGEM1 (Johns et al. 2006) and IPSL-CM4 (Marti et al. 2005)) were selected for NSR route analysis, as they yield the most successful representation of the NSR ice season length. Observed and simulated NSR ice season length is not different at the 5% significance level for these models. The most realistic reproduction of the NWP ice season length was found for ECHO-G, GFDL2.0 and HadCM3 (Johns et al. 2003) models, which are used for NWP analysis. It should be noted that the selected models successfully reproduce the seasonal cycle and spatial sea ice distribution (Parkinson et al. 2006; Zhang and Walsh 2006) for the present climate.

Figure 2 displays the spatial distribution of the sea ice season length during 1980–1999 simulated by the selected models (Fig. 2a–f), the ensemble mean (average over six selected models) (Fig. 2g), and as derived from the satellite data (Fig. 2h). The models reasonably well reproduce the mean pattern of the ice season length, with the multi-model mean being closest to the observed pattern. It should be noted that most of analyzed models do not properly simulate the observed ice-free area north of Norway that may be related to underestimation of the warm inflow from the Gulf Stream and North Atlantic and Norwegian currents.

The models can reproduce not only the mean ice season characteristics, but also capture remarkably well the changes since 1979. Figure 3 presents changes of the ice season length between the two decades 1998–2007 and 1979–1988 as observed (Fig. 3a) and simulated (Fig. 3b) by the selected model ensemble. A decrease of the ice season length is seen for the major part of the Arctic basin with exception of the central part with persistent multi-year ice cover. The strongest decrease with changes of the order of 100 days is found in the Atlantic (Barents and Kara Seas) and eastern part of the Arctic basin close to the Bering Strait. A good qualitative agreement between model results and observations can be stated with some underestimation of the changes in the eastern part of the Arctic (Fig. 3b).

4 Projections for the twenty-first century

Ice season length changes by the end of the twenty-first century (2080–2099 mean relative to the 1980–1999 mean) as expressed by the multi-model average are shown in the Fig. 3c. The simulated pattern of future changes projects well on the trend pattern observed during the recent decades. The most pronounced decrease of ice season length can be expected in Atlantic Sector (Barents and Kara Seas) and eastern part of Arctic (Chukchi Sea), consistent with the trend pattern over the past decades (Fig. 3a, b). In the Atlantic Sector, the models show decrease of ice length throughout the year, while ice melting in the inner Arctic takes place mainly during the warm season (not shown).

The simulated fields of sea ice concentration were used to assess the potential changes in the duration of the navigation season for the NSR and NWP. Figure 4 presents the temporal evolution of navigation season length (10-year running means) averaged along the NSR (Fig. 4a) and NWP (Fig. 4b) from satellite data (black line) and as simulated by the climate models. Blue lines display multi-model mean (solid line) and its standard deviation (dotted line) for the selected 'best' models. Navigation season averaged over all models and the corresponding standard deviation are shown by the orange line and the yellow shading. The ensemble mean of

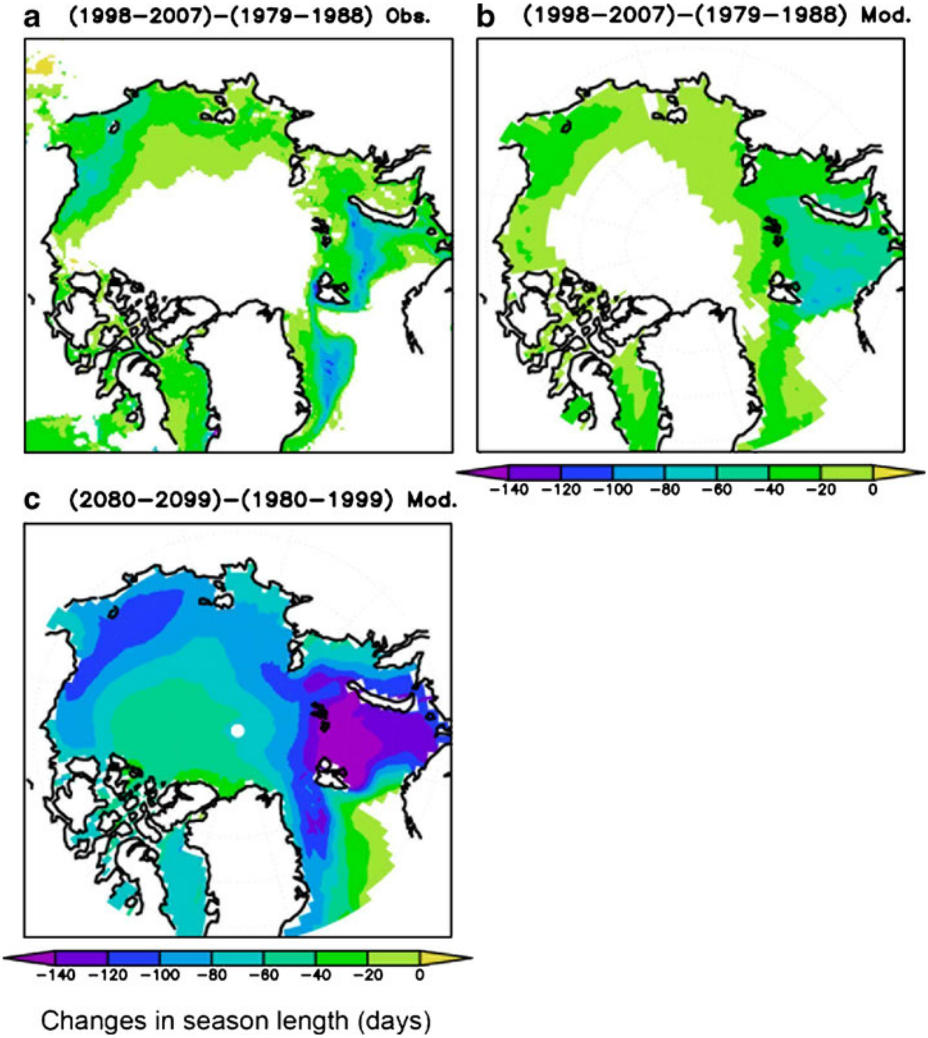

Fig. 3 Changes of ice season length (days) from 1979–1988 to 1998–2007. Satellite observations (**a**) and multi-model mean (**b**); multi-model mean change from 1980–1999 to 2080–2099 (**c**)

the ‘best’ models realistically describes NSR and NWP changes during the recent decades as inferred by the satellite observations. Observed and simulated long-term mean navigation season length along the NSR and NWP are shown in Table 2. The satellite data demonstrate a growth of the NSR and NWP navigation length during last decades with linear trends about 40 and 30 days (per 30 years) for the NSR and NWP, respectively. In the twenty-first century, models show steady increase in the NSR navigation length of about 4.5 ($\pm$1.3) and 3.6 ($\pm$1.7) months averaged over the ‘best’ and all models, respectively. This is not the case for the NWP. Model results show a small and statistically insignificant increase in the NWP navigation season for the 2010–2030. A considerable increase in the length of the navigation season,

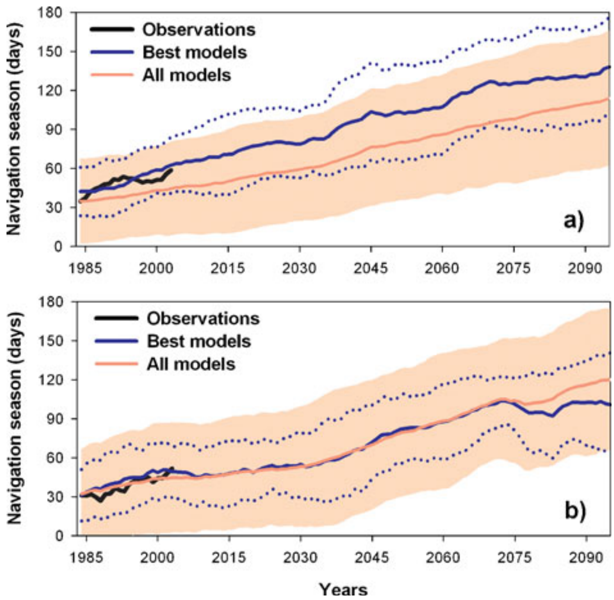

Fig. 4 Length of the navigation season (days) along the Northern Sea Route from Kara Strait to Bering Strait (**a**) and along the Northwest Passage from Lancaster Sound to Bering Strait (**b**) from satellite data (*black line*) and model simulations using A1B scenario. *Blue lines* show means (*solid line*) of the selected best models and the inter-model standard deviation (*dotted lines*). *Orange line* and *shaded area* show all model-ensemble mean and the inter-model standard deviation

however, is seen thereafter. To the end of the twenty-first century the prolongation of the season with a free passage along the NWP may be increased from 2 to 4 months according to A1B scenario. However, the projected navigation along the NWP may be less feasible due to penetrating thick multi-year ice through the McClure Strait and Queen Elizabeth Islands channels (e.g. Stewart et al. 2007).

5 Economical aspects

Development of the Arctic marine navigation in the coming decades will be mainly driven by exploration of offshore oil and gas fields in the Arctic Shelf (e.g. Granberg 1998; Peresypkin 2006). Melting Arctic ice will facilitate transit traffic through the two Northern Passages (Arctic Marine Transport Workshop (AMTW) 2004). The

Table 2 Long-term annual mean length (in days) of navigation season along Northern Sea Route (from Kara Strait to Bering Strait) and Northwest Passage (from Lancaster Sound to Bering Strait)

Arctic route	Satellite data (1979–2008)	'Best' models[a] (1979–2008)	'Best' models (2080–2099)
NSR	49 (±18)	51 (±20)	134 (±38)
NWP	39 (±21)	41 (±22)	100 (±35)

Standard deviations of model ensemble are shown in brackets
[a]The 'best' models are CCSM3, ECHO-G, GFDL2.0, HadGEM1 and IPSL-CM4 for Northern Sea Route, and ECHO-G, GFDL2.0 and HadCM3 for Northwest Passage

increase of marine navigation season (Fig. 4) may significantly reduce expenses for icebreaker escort and ice reinforcement for cargo ships, shorten mean shipping time and diminish the accompanied risks. This will result in increased reliability and decreased cost of transit traffic, which may significantly raise a commercial attraction of the Arctic transportation systems compared to the southern marine routes (through the Suez or Panama Canals). Moreover, given the current growth rate of marine freight transport (6% per year AMTW 2004), capacity limits for both the Suez and Panama Canals may be reached by the middle of the century (AMTW 2004). Economical profit of Europe–Asia transit through NSR relative to the Suez Canal is estimated (Granberg and Peresypkin 2006) as up to 500,000USD per passage.

To assess potential economic benefits, we used estimates of the seasonal freight rates F_{NSR} obtained by Kitagawa (2001) for the NSR using developed transport-economic model and observational data for the second half of twenty-first century. The relation between the ice conditions and the ship speed was obtained from the experimental voyage of the Kandalaksha (Kitagawa 2001).

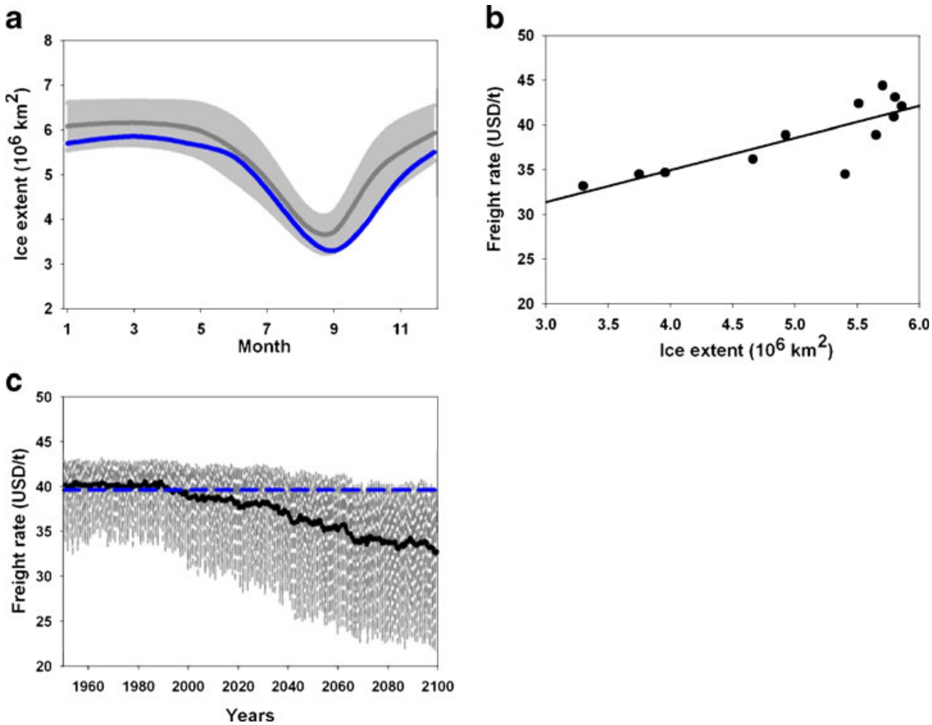

Fig. 5 **a** Seasonal cycle of observed (*blue line*) and simulated (*dark gray line* and *shaded area* for model spread) ice extent in the Northern Sea Route sector (30°–190° E; 60°–90° N) for 1957–1990 (Rayner et al. 2003); **b** freight rate (USD/t) for the Northern Sea Route (Europe–Asia transit, icebreaking bulk/container ship) as a function of the observed sea ice extent (**b**, *blue line*); **c** monthly (*dashed line*) and annual (*solid line*) mean freight rates for the Northern Sea Route estimated from the five 'best' models. The Suez Canal transit rate (Kitagawa 2001) is shown by the *horizontal dashed line*

Estimates of observed (Rayner et al. 2003) and simulated (5-model mean) sea ice extent S_{NSR} (Fig. 5a) for the NSR sector (30°–190° E; 60°–90° N) were used to assess a seasonal dependence of the F_{NSR} on the observed sea ice extent S_{NSR} (Fig. 5b). The data for the second half of the twentieth century yield a linear dependence $\Delta F_{NSR}/\Delta S_{NSR} \approx 3.5\text{USD}/(\text{t}\ 10^6\ \text{km}^2)$. Simulated ice cover extent (dark grey line for model mean and shaded area for model spread on Fig. 5a) agree well with observations, which justifies estimation of the NSR transit cost during the twenty-first century.

This suggests 15% less annual mean costs (Fig. 5c) compared to the transit through the Suez Canal by the end of the twenty-first century according to the model projections analyzed in this study. According to the model simulations the intra-annual variability will be substantially increased during twenty-first century in response to strong reduction of summer sea ice. It should be noted that the NSR may become more profitable than the Suez Canal transit even in winter by the end of the twenty-first century (Fig. 5c).

6 Summary and conclusions

The sea ice observations show accelerated sea ice decrease in the Arctic, which falls beyond the model estimates and could imply a faster sea ice melt in the future suggesting models' underestimation of the sea ice changes. This Arctic sea ice decline could be caused by increasing anthropogenic forcing as well as by natural variability as indicated by several recent studies (persistent atmospheric circulation pattern) (e.g. Zhang et al. 2008). Only additional future observational data on sea ice evolution will make it possible to attribute the recent sea ice drop to either of mechanisms or their combination.

This paper provides an analysis of the simulations of the Arctic sea ice characteristics affecting the navigation along the NSR and NWP performed by global climate models in comparison with observations. This work aims at validating models in the representation of sea ice season length for the present-day climate. Multi-model means over selected 'best' models are in a good agreement with observations. Some underestimations of the simulated ice season changes are found in the eastern Arctic. Multi-model simulations show prolongation of the season with a free passage from 3 to 6 months for the NSR and from 2 to 4 months for the NWP by the end of twenty-first century according to A1B scenario. These estimates were performed for the light ice-class ships navigation without taking into account the icebreaker escort.

More ship transportation in the Arctic will, however, increase emission of aerosols and ozone precursors in this region, which may have noticeable environmental impact. Due to increased Arctic ship transportation, concentration of surface ozone in the Arctic is estimated to be comparable to the level currently observed in many industrialized regions (up to 40–60 ppbv) of the Northern Hemisphere (Granier et al. 2006).

Given that global greenhouse gas emissions increased exponentially during the last decades and further taking into account the large inertia of the climate system we must assign a rather high probability to our scenario. According to the model estimates, the year-round transit cost from Western Europe to the Far East through NSR may be lower by 15% in comparison with transit through the Suez Canal by the end of twenty-first century. To realize the NSR potential, however, it's required a substantial modernization of the Arctic transport system and construction of new ice reinforced container ships.

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