

# Baltic Navigation in Ice in the Twenty First Century

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**ABSTRACT:** The Baltic Sea, even though not large in the global scale, is an important shipping lane. In winter, especially in the region of the Gulf of Bothnia, navigation is seriously obstructed by ice. The aim of this work was investigation of changes in the intensity of the obstruction by ice, caused by climate change in coming 90 years of the twenty first century. It was one of the first attempts of technical application of the global climate scenarios effects. It should be stressed, that the presented work results (as application of the climate scenarios), couldn't be treated as forecast, as it is only the changes tendency assessment.

The climate changes were examined as the changes in air temperature (adaptation of global emission models to regional scale) and atmospheric pressure gradient (model ECHAM5), according to three global scenarios B, A2 and A1B. The number of cases, in which Swedish and Finnish icebreakers assisted the ships, was assumed as the indicator of navigation obstruction by ice "K".

The severity of sea ice conditions was presented by the indicator "S", calculated as the mean value of regional indices. The "S" is the function of the number of days with sea ice, observed at the stations in the particular regions and probability of the sea ice appearances.

Relations between sea ice severity index "S" and regional climate parameters (monthly and annual air temperature and atmospheric pressure gradient) were calculated for the calibration period of 1956-2004. Three models were build: model 1a. "thermal" (the dependence on the mean monthly temperature of July and December); model 1b. thermal "B" (the function of average annual air temperature and of the mean monthly December temperature) and model 2 "thermal zonal" (the dependence on the mean temperature of July and December and zonal component of air pressure gradient). The level of approximation was similar for the analyzed models (over 0,6). Calculation of the future (in XXI century) changes of indicator "K" was done according to three scenarios B, A1B and A2. The number of icebreakers' assistance events should be lower than the one in the twentieth century. The lowest intensity of this decrease is estimated by model 2 and scenario A1Br1, the highest one – for model M1b and scenario B r1.

Otherwise, the minimum value, calculated for the scenarios, is higher than in a period of 1956-2004. It means, that probably, the period with obstruction for navigation in ice could be longer, but not as severe as in the period of 1956-2004. The obstruction intensity could increase during the 21 century according to scenario B1r1, the same for empirical model 2. The similar tendency has been shown by scenario A1Br1 and by model 1a. Other models and scenarios estimated the decreasing trend up to 2100

## 1 INTRODUCTION

The Baltic Sea, even though not large in the global scale, is an important shipping lane. In winter, especially in the region of the Gulf of Bothnia, navigation is seriously obstructed by ice. Operation

of icebreakers to support maritime trade is usually included in the infrastructure offered by the port states. Only in Russia private icebreaker services are operating, as, for example, the Gazprom icebreakers. On the area of the Gulf of Bothnia – the severe

region of the Baltic Sea, in general, Swedish and Finnish icebreakers are in charge.

The aim of this work was investigation of changes in the intensity of navigation obstruction by ice, occurring in effect of climate changes in coming 90 years of the twenty first century.

The observed in XX century changes of climate, especially a rise of the mean air temperature induced more intensive interest in climate modeling and forecasting future changes thereof within a long lasting time period, e.g. by the end of XXI century. From among many scientific research institutions engaged in this subject, the most spectacular achievements (Nobel prize) were gained by IPCC (Intergovernmental Panel on Climate Change). The works of IPCC have been published in a form of reports. According to the reports, it seems to be the most likely, that a cause of the observed climate changes in XX century was the anthropogenic growth of greenhouse gas concentration. The Special Report on Emissions Scenarios (SRES) has presented probable scenarios of greenhouse gas emissions in XXI century. Thus, the predicted gas emission and a rise of air temperature, calculated on the grounds of the scenarios, were used as the input data to the global climate models – the global circulation models - (among the others: ECHAM model for Europe and the North Atlantic).

In the research there have been used scenarios B1, A2 and A1B of greenhouse gases emission, worked out by IPCC for XXI century. The differences between the scenarios result from varying assumptions of the world evolution in XXI century, due to globalization, economic development, predicted changes of population and also abiding by the sustainable development principles.

Thus, in B1 scenario, an very integrated global development with simultaneous implementation of the sustainable development was assumed. It would cause a rapid economic growth focused on services and informatics sciences. By 2050 a growth of population and next its drop are expected.

According to A2 scenario the much less integrated development was assumed (the independently developing regions /nations will be more significant). It will result in fast and continuous growth of people, free economic development focused on regional benefits, less and more diversified development, differentiated abiding by sustainable development (to the total denial) and minor changes in technology.

Furthermore, in A1B scenario there was assumed a rapid economic growth with the balanced exploitation of all accessible power supply sources (fossil and non fossil ones) with introducing the

new, more productive technologies as well. It has to be emphasized that the European Union accepted A1B scenario as a basis for shaping the energy policy.

Adaptation of the emission scenarios (A2, B1 and A1B) results, also the results of the global climate model ECHAM to the Baltic and Poland conditions was carried out within the framework of KLIMAT Project ([www.klimat.imgw.pl](http://www.klimat.imgw.pl)) by two IMGW-PIB Departments : Zakład Modelowania Klimatycznego i Prognoz Sezonowych oraz Centrum Monitoringu Klimatu Polski

The basis included re-analyzing and downscaling performed for the selected reference period (1955-2004) between the global driving factor (the same climate elements and the same spatial grid as in SRES and ECHAM models) and the regional one. The obtained relations between the global and the regional driving factor were used to create the regional scenarios for the Baltic Sea and Poland in XXI century; the global driving factor was represented by SRES and ECHAM models' results. Adaptation of the global models to the Baltic and Poland conditions and working out the regional driving factor field are results of the works carried out by the IMGW PIB and were described, among the others, in the work by Jakusik (Jakusik at al. 2010a, Jakusik at al. 2010b), also in the reports of Klimat project presented on the web page [klimat.imgw.pl](http://klimat.imgw.pl).

Two elements of the regional driving factor field were adopted for purposes of the research: monthly air temperature and the component indicators (meridian and zonal) of the atmospheric circulation (monthly, annual). In this case as well, for the calibration period there were constructed statistic and empiric models, displaying relationship between the selected parameters (Baltic sea-ice severity index and implicit a number of icebreakers assistance events) and the predictors, which are characteristic for the regional driving factor field i.e. the monthly and annual air temperature and the component indicators (meridian and zonal) of the atmospheric circulation (monthly, annual). The obtained statistic and empiric relations and results of the scenarios for the regional driving factor have been used for assessment of changes in the XXI century.

The algorithmic description of methodical actions performed during work realization is shown in Fig. (1)

## 2 DATA

In the calculations 3 types of data were applied: results of the regional driving factor field, sea-ice

severity index and a number of the icebreakers assistance events occurred in the Baltic Sea.

### Regional driving factors

The following elements were subject to analyzing: monthly air temperatures ( global greenhouse gases emission scenarios downscaling – SRES models) and the atmospheric circulation (result of ECHAM model downscaling) - component indicators (meridian and zonal) of the atmospheric circulation (monthly, annual).

2008) . The index is based on the probability of ice occurrence and the number of days with sea ice observed in the analyzed period in the selected basins. The ice severity index is given by the relation

$$S = 0.05 \times \frac{1}{i} \sum_j \left( \frac{N}{p} \right)_j$$

where

**S** - severity index,

**N** - number of days with ice observed during the winter season at the particular station,

**p** - probability of ice occurrence at the particular station, calculated for the analyzed period and

**i** - number of stations taken into account.

To calculate the Baltic Sea Ice Severity there were applied the data referring to numbers of days with ice and its occurrence probability taken from 34 stations from 1955 to 2004 (Western Baltic Sea, with: Unterwarnow, Warnemünde, Kiel LH; Southern Baltic Sea, with: Zalew Szczeciński, Świnoujście, Kołobrzeg, Gdańsk, Zalew Wiślany; Gulf of Finland, with: Hanko, Russarö, Helsinki. Harmaja, Helsinki LH, Loviisa, Oerengrund, Hogland; Sea of Aland and the Archipelago, with: Maarianhamina, Koppaklinter, Långskär, Turku, Bogskär (Kihti), Utö Sea of Bothnia, with: Rauma, Kylmäpihlaja, Raumanmatala , Norra Kvarken, with: Haasa, Ensten, Norrskär, Bay of Bothnia, with: Ajos, Mutkanmatala, Kemi One, Ykspihlaja, Repskär, Tankar). Variability of sea ice severity index and possibility of application thereof in prediction and modeling of influence of sea ice conditions on navigation, including also icebreakers activity were presented in 2009 at TRANSNAV conference (Sztobryn and others 2009).

### Icebreakers activity – navigation in sea ice

In this work it was assumed that the indicator of difficulties “K” in the navigation related to the occurrence of ice phenomena is the number of assistance events with Swedish and Finnish icebreakers, during the ice season. The data including a number of icebreakers assistance events in specific seasons come from the annual SMHI Works: Report of sea ice condition and icebreakers’ activity.

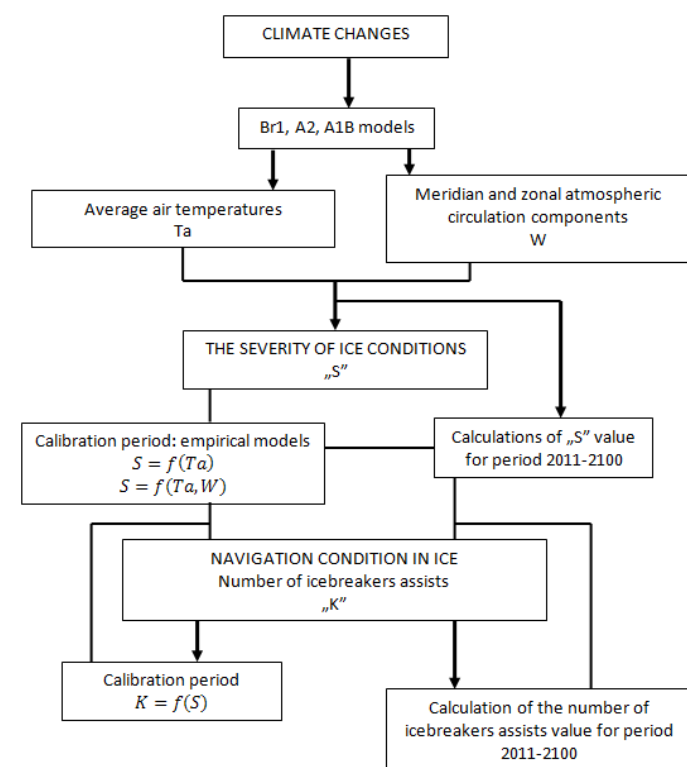


Figure 1. The algorithmic description of methodical actions performed during work realization.

In the following part of the work, dedicated to modeling of sea-ice conditions for various scenarios, an applied scenario summary was presented together with the model name. Thus for example, a name of model M1 A2 designates M1 model, where the original source of driving factors had been A2 scenario.

### Sea Ice Severity index

Sea ice severity index „S” originally was constructed for Polish Coastal zone (Southern Baltic) in 2006 (Sztobryn M. 2006) and next, in 2009, was applied to determine conditions of the whole Baltic sea ice condition (Sztobryn and others

### 3 RELATION BETWEEN THE ICEBREAKERS ASSISTANCE EVENTS NUMBER (K) AND SEA ICE SEVERITY INDEX (S)

Obstructions in navigation on the Baltic Sea while ice cover occurrence were represented with the indicator of difficulties in navigation, which was equal to a number of Swedish and Finnish icebreakers assistance events within a specific ice season. There has been analyzed and next constructed the mathematic model.

The relationship between ice condition (represented by "S" index) and navigation condition in ice (by number of icebreakers' assists) was formulated by the exponential regression method.

The number of icebreakers assists, recorded in 1956-2004 period, was given by the formula 1 :

$$K = a * \exp(b * S) \quad (1)$$

where:

- K – calculated number of assistance events,
- S – indicator of the Baltic sea ice severity (mean),
- a,b, - numerical coefficients

Comparison of the course of the calculated number of icebreakers assistance events and the real number thereof in 1956-2004 is shown on Fig. (2). The black, thin line stands for the real number of icebreakers assistance events, whereas the grey thick one represents the number of events calculated using the formula.

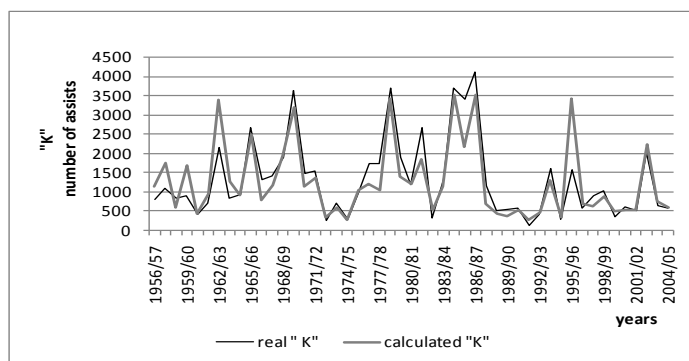


Figure 2. Comparison of the calculated and the real numbers of icebreakers assistance events in 1956-2004 period.

Differences between the "K" indicator real value (a number of assistance events) and the one calculated using formula 1, - are specially visible for calculations performed for 1995/96 season. However it is characteristic for the mentioned season that then the ice conditions were very differentiated in various water areas. The south and west Baltic ice severity was similar to the Gulf of Bothnia; in this area

neither Finnish nor Swedish icebreakers operated. Moreover, in March, meteorological conditions in the Gulf of Bothnia proved to be highly changeable (drift ice in several hours displaced between the coastal zones of Sweden and Finland).

The correlation coefficient between the real number of icebreakers assistance events and the one calculated on the basis of the formula equals to 0,88.

### 4 "S" AND "K" INDICATORS DEPENDENCE ON CLIMATE CONDITIONS

Functional dependencies between "S" ice index and the regional driving factor (the data from re-analysis for the same climate conditions – the parameters and spatial location – as the greenhouse gases emission scenarios results and ECHAM model for the XXI century) were analyzed and processed for the calibration period of 1956-2004.

Primary, the influence of climate was represented by 129 parameters, affecting formation of sea ice in the Baltic Sea; these parameters were taken into account for the calibration period of 1956-2004. They were mainly the annual and monthly average air temperatures and their combinations, also the component indicators (meridian and zonal) of the atmospheric circulation (monthly, annual).

The next step of this work was to formulate the relationship (as the function) between ice severity indicator "S" and climate parameters. Construction of the optimal predictors set has been made on the basis of the carried out analysis results: correlation (statistically significant at 95%; level: the highest value of the correlation coefficient between the predictors and response variable and the lowest between predictors), genetic algorithm (the longest "survival" of the predictors) and model sensitivity tests (better/worse work of the model with/without analyzed predictor). The researches proved that the sea-ice severity indicator "S" is the most sensitive to the mean monthly air temperatures in July and December and the mean annual air temperature as well as the zonal component of the atmospheric circulation. Therefore these parameters were used in constructing the models.

Relations between the parameters were calculated for the calibration period of 1955-2004 by multiplying linear regression for 3 types of the models.

- "thermal" (the dependence on the mean monthly temperature of July and December further called M1a model ;
- thermal "B" (function of the average annual air temperature and of the mean monthly December temperature)- further called M1b model

- c “thermal-zonal” (dependence on the mean air temperature of July and December and the zonal component of the atmospheric circulation) - further called M2 model

Comparison of the data from the period of observation (1956-2004) with the calculation results proved a statistic consistency, characterized by the following correlation coefficients: 0,6 (model 1a); 0,64 – model 1b and model 2.

To enable potential changes of navigation conditions in ice (represented with “K” indicator) in the XXI century there have been used combinations of formula 1 and processed dependencies between “S” and the climate parameters (items a, b and c)

## 5 RESULTS

To predict changes of the sea ice severity “S” indicator value in the XXI century the processed and presented in the section 3 models have been used; also to settle a number of assistance events “K” – formula1.

The climate parameters, which the models were based on, have been taken from calculations of the IMGW PIB Climate Departments and they are an effect of adaptation of three global climate scenarios B, A1B and A2 run1 and also ECHAM-5 to the regional conditions.

It means that each of the models (M1a, M1b and M2) was calculated for 3 scenarios (B, A1B and A2 run1 and also ECHAM-5). To differentiate particular models and scenarios the following concept of designation was adopted:

- M1a Br1 – stands for the model based on the dependence “S” on the mean monthly temperature of July and December) reckoned using the data taken from the scenario B run 1,
- M1a A1Br1 – the model based on the dependence “S” on the mean monthly temperature of July and December) calculated using the data taken from the scenario A1B run 1,
- M1a A2r1 – the model based on the dependence “S” on the mean monthly temperature of July and December) calculated using the data taken from the scenario A2 run 1,
- M1b Br1 is a model based on dependence between S and the average annual air temperature and of mean monthly December temperature calculated using the data from the scenario B run 1,
- M1b A1Br1 is a model based on dependence between S and the average annual air temperature and of mean monthly December temperature calculated using the data from the scenario A1B run 1,
- M1b A2r1 is a model based on dependence between S and the average annual air temperature

- and of mean monthly December temperature calculated using the data from the scenario A2 run 1,
- M2 Br1 designates a model based on dependence between S on the mean air temperature of July and December and the zonal component of atmospheric circulation, calculated using the data from the scenario B run 1,
- M2 A1B designates a model based on dependence between S on the mean air temperature of July and December and the zonal component of atmospheric circulation, calculated using the data from the scenario A1B run 1,
- M2 A2 designates a model based on dependence between S on the mean air temperature of July and December and the zonal component of atmospheric circulation, calculated using the data from the scenario A2 run 1,

The results of calculation carried out for these types of models (3 models for 3 different scenarios) for a period of next 20 years (2011-2030) are presented in Table 1 with comparison thereof with the values obtained for 20 years of 1971-1990 period.

Values of the following parameters: standard error, standard deviation and range, are significantly lower in 2011-2030 period than in the reference period. However, the mean, median and minimum values are in 2011-2030 period higher than in the reference period. The Kurtosis value for M2 A1Br1 model is very close to the value calculated for the reference period, as is the skewness, calculated on the basis of M1b A2r1 and M2B1 models. A maximum value calculated on the basis of M1b A2r1 model is close to the maximal value of the reference period (4,28 and 4,79).

It means that concentrations of „S” values around the mean value are similar for the both periods under consideration (model M2 A1Br1), as well as asymmetry of calculations of M1b A2 r1 and M2 B1 models are. The values of the mean, median and minimum are higher while the maximum value is comparable, what indicates that in coming years there are expected (according to the assumed scenarios) more winters with a small number of days with ice (but still with ice) than in the reference period.

The course of “S” indicator in period 2011-2030, calculated on the basis of scenario A2r1, together with comparison with the last climate reference period is shown on Figure 3.

Process variation of “S” indicator in the twenty first century was estimated on the basis of three models, each for three scenarios. Results of these calculations for scenario A1B are presented in Figure (4).

Table 1. Statistical parameters of „S” indicator for 2011-2030 and the reference period 1971-1990.

Period	1971-1990			2011-2030						
Input Scenario	<i>real</i>	<i>M1a Br1</i>	<i>M1b B1r1</i>	<i>M2 B1r1</i>	<i>M1a A1Br1</i>	<i>M1b A1Br1</i>	<i>M2 A1Br1</i>	<i>M1a A2r1</i>	<i>M1b A2r1</i>	<i>M2 A2r1</i>
Mean	1,92	2,34	2,53	2,14	2,45	2,50	2,17	2,53	2,91	2,51
Median	1,52	2,26	2,48	2,13	2,54	2,59	2,14	2,54	2,83	2,62
Standard deviation	1,45	0,54	0,76	0,55	0,50	0,58	0,45	0,47	0,64	0,54
Kurtosis	-0,46	0,32	-0,76	1,18	-0,24	1,21	-0,43	0,68	0,14	-1,09
Skew/skewness	0,82	0,29	0,10	0,79	-0,45	-1,04	0,17	0,61	0,72	-0,27
Minimum	0,11	1,20	1,34	1,19	1,41	1,05	1,28	1,65	1,86	1,60
Maximum	4,79	3,53	3,78	3,60	3,35	3,43	3,01	3,60	4,28	3,35

In the course of the ice severity indicator, calculated for the twenty first century using three scenarios, one can see the similar characteristics, recognized for period of 2011-2030.

The estimated number of icebreakers’ assistance events was calculated using formula 1 for each of 3 models of “S” for 3 climate scenarios. Numbers of the estimated occurrence of obstruction for navigation in ice are shown in figures 5-7. Model 1a is represented by thick, black line, model 1b by drops and model 2 by thin dark line.

According to all three scenarios, a number of icebreakers assistance cases should be lower than in the twentieth century. The lowest intensity of such decrease is estimated using model 2 and scenario A1Br1, the highest one – using model M1b and scenario B r1.

Otherwise, the minimum value, calculated for the scenarios, is higher than in 1956-2004 period. It means that probably the period, when obstructions for navigation in ice occur, could be longer, but not so severe as it happened in the period of 1956-2004. According to scenario B1r1 as well as the empirical model 2, intensity of such obstruction could increase during the 21 century. The same tendency is shown in scenario A1Br1 and using model 1a. The other models and scenarios have proved a decreasing trend up to 2100.

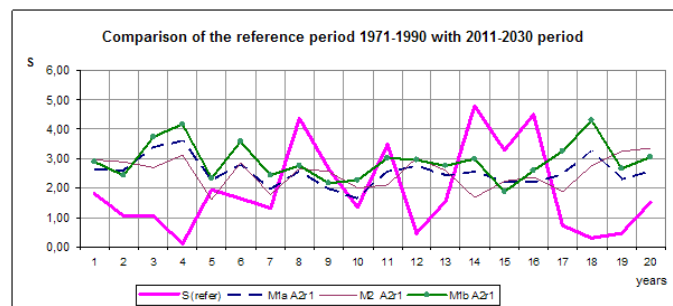


Figure 3. Comparison of the sea ice severity indicator calculated for the reference period and estimated for 2011-2030 period according to A2r1 scenario.

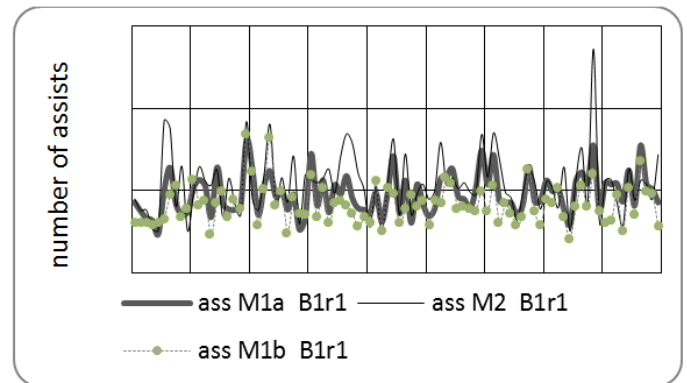
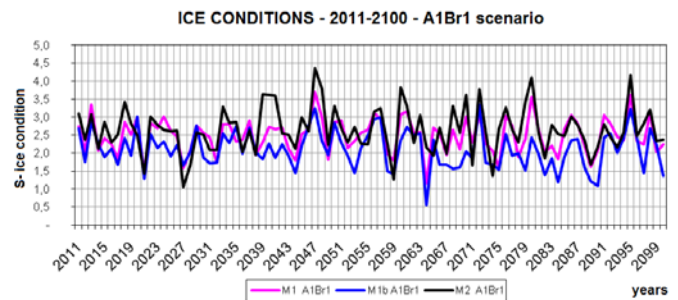


Figure 5. The changes of the estimated number of icebreakers’ assistances in the twenty first century, calculated using B1 scenario and three empirical models (M1a B1r1, M1b B1r1, M2 B1r1)

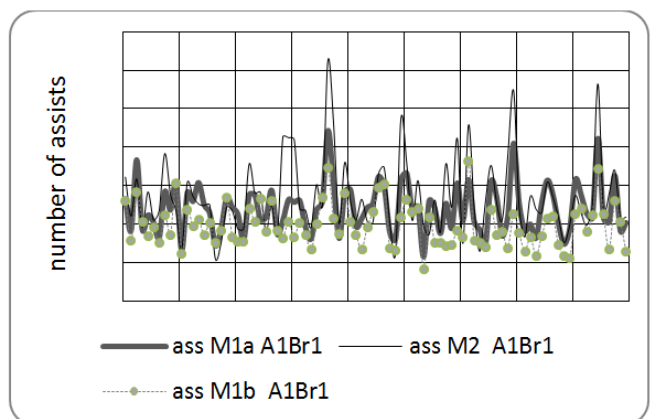


Figure 6. Changes of the estimated number of icebreakers’ assistance events in the twenty first century, calculated using A1B scenario and three empirical models (M1a A1Br1, M1b A1Br1, M2 A1Br1)

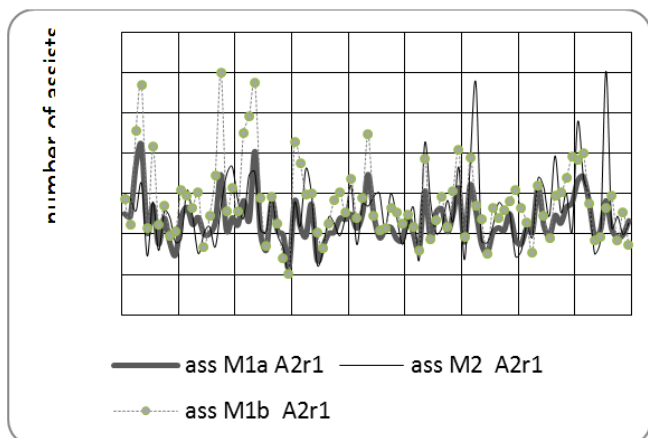


Figure 7. Changes of the estimated number of icebreakers' assistance events in the twenty first century, calculated using A2 scenario and three empirical models (M1a A2r1 M1bA2r1, M2A2r1)

## 6 REMARKS

The aim of this work was investigation of changes in intensity of obstruction by ice occurrence (represented by the number of Swedish and Finnish icebreakers' assistance events, forced in effect of the climate change in coming 90 years of the twenty first century. The estimation was made under a hidden assumption that technical parameters of icebreakers and merchant ships would not change in the twenty first century, the same as intensity of Baltic navigation in ice.

It has been one of the first probes of technical application of the global climate scenarios changes. It should be stressed, that the presented work results (as application of climate scenarios), cannot be treated as a forecast, as they are only used to estimate the changes tendency.

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