Biannual Report 2022-2023

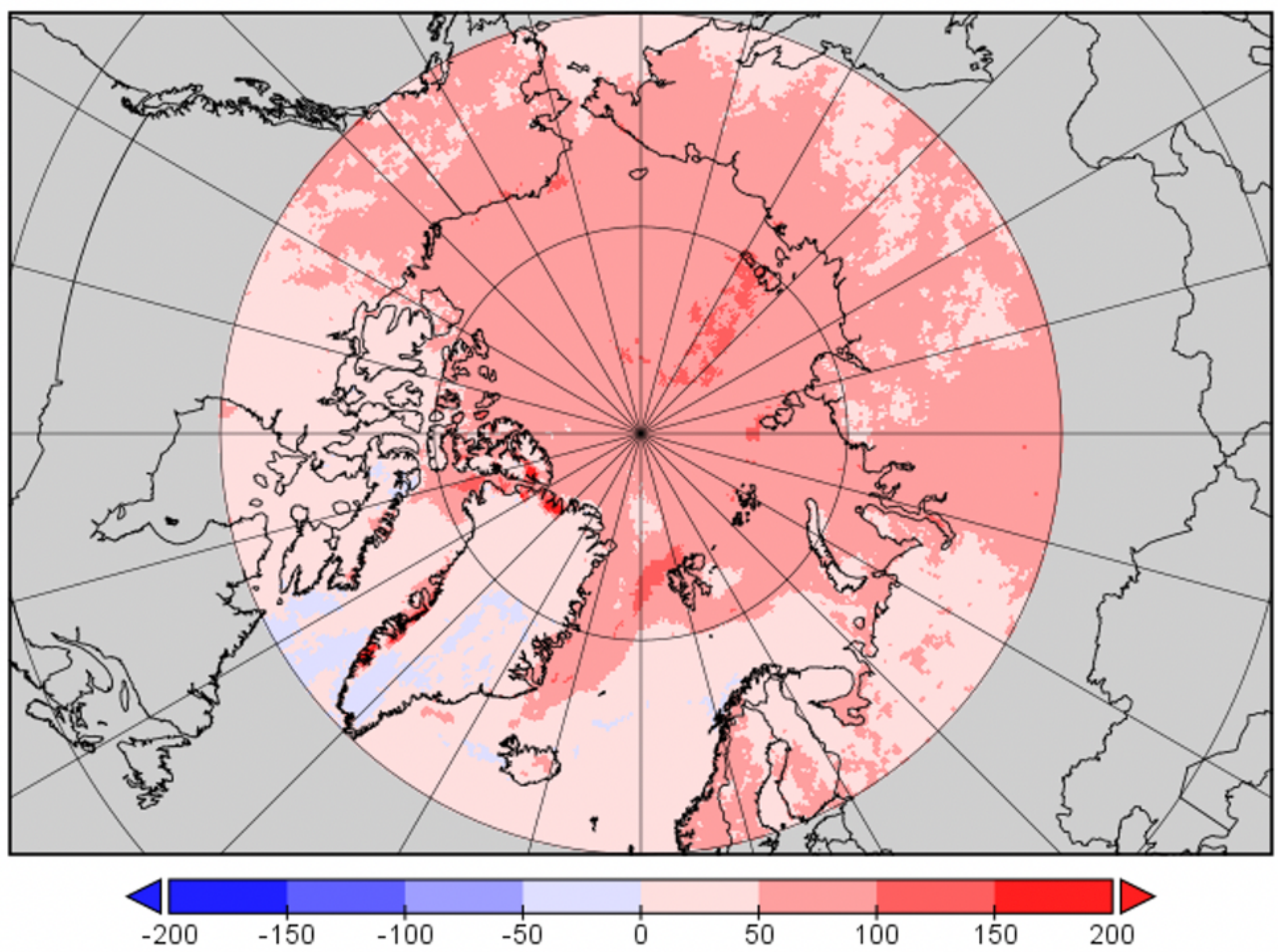
Nansen International Environmental and Remote Sensing Centre

St. Petersburg, Russia

Non-profit international centre for environmental and climate research

Founded in 1992

Increasing heat waves in the Arctic



Difference in the number of heat waves between 1991-2020 and 1951-1980

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Cover page: *Spatial distribution of difference in the number of heat waves in the Arctic between 1991–2020 and 1951–1980 derived from ERA5 reanalysis indicating significant increase in heat waves over the past 30 years.*

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Vision

The Scientific Foundation "Nansen International Environmental and Remote Sensing Centre" (Nansen Centre, NIERSC) vision is to understand, monitor and predict climate and environmental changes in the high northern latitudes for serving the Society.

Scientific Research Groups

- Climate of High Northern Latitudes (*Head Dr. Igor Bashmachnikov)*
- Aquatic Ecosystems Under Global Warming (*Head Prof. Dmitry Pozdnyakov)*
- Applied Meteorological and Oceanographic Research (*Head Dr. Vladimir Volkov*)

Organization

NIERSC is an independent non-profit international research foundation established by Russian, Norwegian and German research organizations. NIERSC conducts basic and applied environmental and climate research funded by the Russian research agencies and industry.

NIERSC was established in 1992 and re-registered at the St. Petersburg Administration Registration Chamber into a non-profit scientific foundation in 2001. The Centre got accreditation at the Ministry of Industry, Science and Technology of the Russian Federation as a scientific institution in 2002 and was re-registered in 2006 according to a new legislation on Non-Commercial Organizations of the Russian Federation.

NIERSC got a license for conducting meteorological and oceanographic observations from Roshydromet in 2006. In 2008 NIERSC received also license from Roscosmos for conducting space-related research activities.

Staff

At the end of 2023 NIERSC staff incorporated 32 employees, 17 full-time and 15 part-time, comprising research and administrative personnel. Research personnel included two full Doctors of Science and 16 PhDs. One PhD-student and two Master students were supervised and supported financially through the Nansen Fellowship Programme, all holding also positions of Junior Scientists at NIERSC.

Scientific Production

In 2022-2023, totally 34 publications were published including 18 papers in peer reviewed journals, 2 papers in other journals and 14 abstracts and brief papers in conference proceedings (see the list of main publications at the end of the report).

Research Cooperation

NIERSC has a long-lasting cooperation with Russian organisations including St. Petersburg State University and institutions of the Russian Academy of Sciences, Federal Space Agency, Federal Service for Hydrometeorology and Environmental Monitoring, among which are the Northern Water Problems Institute, Murmansk Marine Biological Institute, Scientific Research Centre for Ecological Safety, Obukhov Institute of Atmospheric Physics, Arctic and Antarctic Research Institute, Russian State Hydrometeorological University, Voeikov Main Geophysical Observatory and others.

Fruitful relations are established also with a number of foreign and international organizations, universities and institutions including Global Climate Forum, Climate Service Centre Germany (HZG-GERICS), Max-Planck Institute for Meteorology, Friedrich-Schiller-University (all Germany), Finnish Meteorological Institute and University of Helsinki (Finland), University of Sheffield (UK), Stockholm University (Sweden), Johanneum Research (Austria), Iskenderun Technical University (Turkey), Vlaamse Instelling voor Technologisch Onderzoek (VITO) & Royal Meteorological Institute of Belgium, Gent University (all Belgium), Latvian Environment, Geology and Meteorology Centre, Norwegian Research Centre (NORCE), Institute of Atmospheric Physics of Chinese Academy of Science, National Centre for Polar and Ocean Research of India, and especially with the NIERSC founders. Close cooperation is established with the Nansen Centre and the Nansen Scientific Society in Bergen, Norway.

Nansen Fellowship Programme

The main goal of the Nansen Fellowship Program (NFP) at NIERSC is to support PhD-students at the Russian educational and research institutions including Russian State Hydrometeorological University, St. Petersburg State University, Arctic and Antarctic Research Institute, Institute of Atmospheric Physics of the Russian Academy of Science and others. The preferred research areas include current and future climate and environmental changes in the high northern latitudes, as well as methods and techniques of satellite remote sensing with the focus on sea ice in the Arctic. NFP provides PhD-students with the Russian and international scientific supervision, financial fellowship, efficient working conditions at NIERSC, involvement into international and national research projects. All NFP PhD-students obliged to publish their scientific results in the national and international refereed journals and make presentations at the national and international scientific symposia and conferences.

Anna Vesman and Mikhail Latonin, supported by the Nansen Fellowship Programme, successfully defended their theses in 2022 in St. Petersburg State University:

- Anna Vesman – 03.06.2022 on the topic "Features of the manifestation of global warming in the 20th-21st centuries in the waters washing the archipelago Spitzbergen";
- Mikhail Latonin – 08.06.2022 on the topic "Arctic amplification and meridional oceanic and atmospheric heat transports into the Arctic".

Thus, totally 33 Russian PhD-students have got their doctoral degrees under NFP since 1994.

Scientific Report

Main Projects

Polar Regions in the Earth System (PolarRES) is the European Union's project funded by Horizon 2020 Research and Innovation Programme for a period of 4 years beginning in September 2021. The PolarRES consortium consists of 17 partners from 11 different countries (Belgium, China, Denmark, Finland, Germany, Netherlands, Norway, Russia, Sweden, Ukraine, and the United Kingdom). The Polar regions play a crucial role in the global climate system with the poles heating up much faster than the rest of the world. However, future climate projections for the Polar regions still have significant uncertainties. PolarRES will advance our understanding of how the climate of the Arctic and Antarctic will respond to future changes in the global circulation. PolarRES will also deliver new insights into how physical and chemical processes, crucial for atmosphere-ocean-ice interactions, can shape the global climate system. A key outcome from the PolarRES project will be more confident climate change projections for the Polar regions. This will enable better mitigation and adaptation actions in the polar regions. NIERSC is involved in this project in its Arctic part.

Arctic Region in the Earth Climate System and its transformation under global warming (MON-PolarRES) is the "mirror" project complemented to the European Union's Horizon 2020 project PolarRES (Polar Regions in the Earth System, see above). MON-PolarRES is funded by the Ministry of Science and Higher Education of the Russian Federation (Unique Project Identifier RF----225121X0006, 2021-2023). The project is assessing the main parameters of the future Arctic climate, its impact on the regional environment and economic activity including shipping in the Northern Sea Route, as well as on the midlatitude weather and climate on the base of (1) new higher level of understanding of the key physical and chemical processes involved in the atmosphere-ocean-ice interaction in the Arctic, their response to- and impact on the future projected changes in the global atmospheric and oceanic circulation, and (2) producing innovative, more confident future climate projections for the Arctic region based on the future greenhouse gas emission scenarios and circulation storylines. NIERSC foreign partners in this "mirror" project are Norwegian Research Centre (NORCE), Bergen, Norway, and Finnish Meteorological Institute (FMI), Helsinki, Finland.

Antarctic polar lows and their role in the ocean-ice-atmosphere system is the joint Russia-Iran bilateral project aimed at the large-scale meteorological and oceanographic study of the polar lows in the Antarcic region over the period 2002-2020. The foreign partner is the Iranian National Institute for Oceanography and Atmospheric Science (INIOAS). In Russia this project is funded by the Russian Fund for Basic Research (RFBR), Grant No. 20-55-56051, 2021-2023.

Modelled dynamics of wind waves generated by polar lows is the project funded by the Russian Science Foundation (RSF), Grant No. 22-27-00701, 2022-2023. The aim of the project is to use numerical models (i.e., the atmosphere model WRF and the wave model WAVEWATCH III) to analyze wind and wave fields within polar lows, their dynamics during cyclone lifetime and dependence of their characteristics on the cyclone formation mechanisms.

Influence of meridional atmospheric heat and moisture transport on climate feedbacks in the Arctic and formation of Arctic amplification is the project funded by the Russian Science Foundation (RSF), Grant No. 23-77-01046, 2023-2025. The project is devoted to the extremely relevant topic of present climate change in the Arctic and is aimed at studying the internal mechanisms of the Arctic climate system. The main goal of the project is to assess how the interaction of meridional atmospheric heat and moisture fluxes with climate feedbacks in the Arctic might influence the formation of the Arctic amplification. Thus, the main scientific novelty lies in the assessment of the ability of meridional atmospheric heat and moisture fluxes to act as a trigger of climate feedbacks in the Arctic, which in turn lead to the formation of the Arctic amplification. The study employs the latest data from the ERA5 climate reanalysis, as well as the Russian climate models of the general circulation of the atmosphere and ocean INM-CM4-8 and INM-CM5-0 participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6).

Arctic amplification and extremely cold winters in Siberia is the project aimed at studying the phenomenon of Arctic amplification (AA), which extends over the Arctic region and significant part of the polar territories of the Russian Federation, and its potential relationships with the frequency and intensity of anomalously cold winters in Siberia. The magnitude of AA and its regionalization will be investigated using the latest versions of GISTEMPv4, HadCRUT4 observational datasets, ERA5 climatic reanalysis and CMIP6 model simulations, which will allow to obtain with the maximum validity to date estimates of AA magnitude, future trends in the development of this phenomenon and the frequency dynamics of cold winters in Siberia. This project is funded by the Russian Science Foundation (RSF), Grant No. 23-77-01106, 2023-2025.

Climate of High Northern Latitudes

The coherence of the oceanic heat transport through the Nordic Seas

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Igor Bashmachnikov, St. Petersburg State University (SPbSU)/ Nansen Centre (NIERSC), St. Petersburg, Russia

Pavel Golubkin, NIERSC, St. Petersburg, Russia

Atlantic waters are the main source of oceanic heat in the Arctic Ocean. The intensity of the Atlantic water transport into the Arctic affects such important climatic parameters as sea ice extent and air temperature. We studied the Atlantic oceanic heat transport into the Arctic using dataset ARMOR-3D (1993-2016), which represents a set of 3D fields of monthly water temperature, salinity and geostrophic currents obtained using in-situ and satellite data.

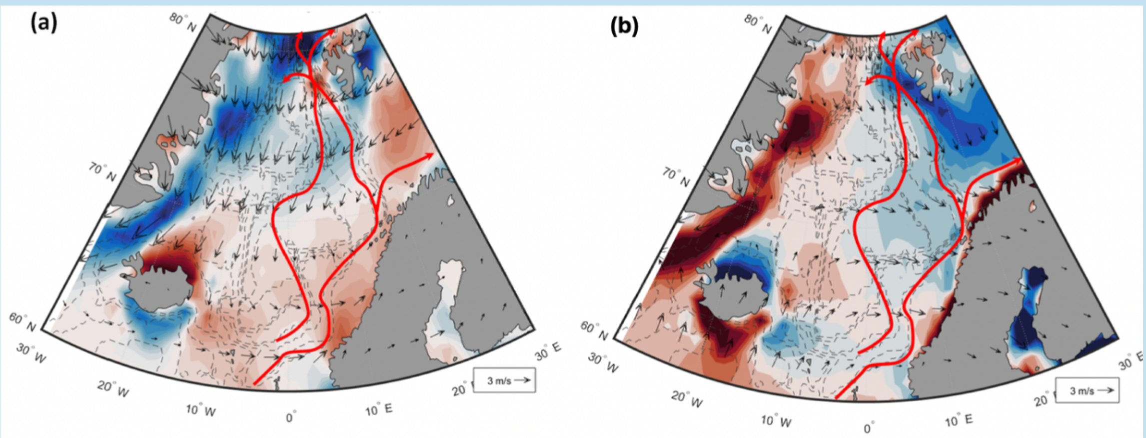

Figure 1. *Wind velocity anomalies over the Norwegian and Greenland seas (arrows) associated with two types of atmospheric circulation: (a) type W, (b) type C. The colour shows the areas of sea level rise (red) and drop (blue) caused by the wind. Dotted lines represent the bathymetry contours; branches of the Norwegian current are shown as red lines.*

Acknowledgment: *The research was supported by the grant from the Saint-Petersburg State University No 93016972.*

Relevant publication: *Vesman, A.V., I.L. Bashmachnikov, P.A. Golubkin, and R.P. Raj (2023). The Coherence of the Oceanic Heat Transport Through the Nordic Seas: Oceanic Heat Budget and Interannual Variability. Russ. J. Earth. Sci., 23, ES3006*

The results show that the interannual variability of heat transport with the Norwegian current rapidly loses its coherence with the oceanic heat inflow at the entrance to the Norwegian Sea (section at 65°N): the correlations decrease to insignificant towards the Fram Strait (75-79°N). This is a result of the different nature of the inter-decadal variability, as well as differentiated attenuation of amplitudes at different periods of variability (the amplitude of 5-6-year fluctuations decreases much faster than of 2-3-year ones). It is shown that although none of the types of regional variability of atmospheric circulation determines the intensity of heat transfer by the Norwegian current, there is a simultaneous increase in the heat transport along the entire length of the current during the weather type W and a decrease during the weather type C (Fig. 1). These links are explained by the nature of the sea level changes associated with the corresponding wind field anomalies.

The role of coupled ocean-atmosphere heat transport in the decadal variability of the Arctic amplification

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Dr. Igor Bashmachnikov, SPbSU/ NIERSC, St. Petersburg, Russia
Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia

One of the triggers of the Arctic amplification is the poleward heat transport, however, the relative contribution of its oceanic and atmospheric components remains poorly understood. In this study, we investigate the role of the Atlantic meridional oceanic and atmospheric heat transports into the Arctic for the emergence of the Arctic amplification. The meridional heat fluxes were computed using ORAS4 and ERA5 reanalyses for the Atlantic Water layer and over the lower troposphere. Mean annual values for the period 1958–2017 were studied. The horizontal and vertical boundaries of the sections in the ocean and atmosphere were selected to include only the areas, where the time mean heat transport is directed into the Arctic. It is found that the meridional heat fluxes and the regional

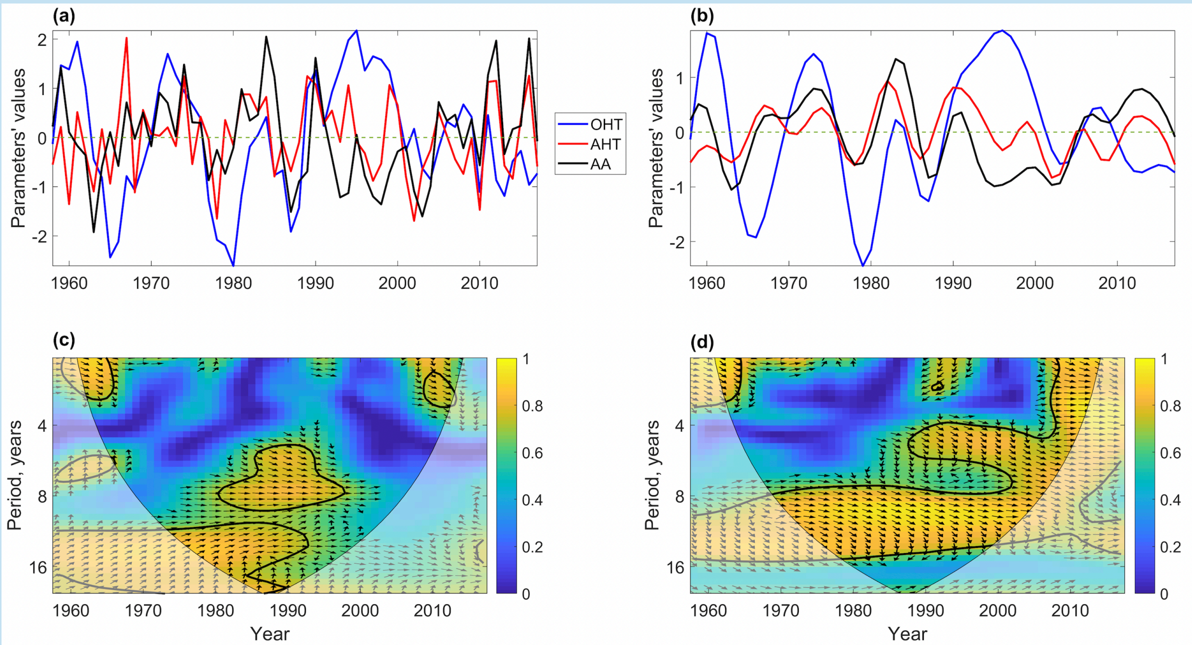

Figure 2. *Time series of the oceanic heat transport (OHT), atmospheric heat transport (AHT) and regional Arctic amplification (AA) with linear trends removed (a) and after an application of the low-pass Butterworth filter with a threshold period of six years (b); wavelet coherences between the oceanic heat transport and AA (c) and between the atmospheric heat transport and AA (d). The mean annual values of the parameters of the panel (a) were used for the panels (c) and (d). Yellow areas, confined by the black curves, show significant coherences relative to the red noise spectrum at the 5% significance level. Black arrows show the phase angle: directed to the right means in-phase and directed vertically upward means that the AA leads the oceanic/atmospheric heat transport by 90° in the given frequency band. Lighter shade areas on the panels (c) and (d) show the cones of influence, where oscillations' amplitudes might be distorted by edge effects.*

Arctic amplification in the Eurasian Arctic are strongly coupled on the decadal time scales (10–15 years). The reliability of this relationship is confirmed by the wavelet analysis (Fig. 2).

Acknowledgment: This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).

Relevant publication: Latonin, M.M., Bashmachnikov, I.L., Bobylev, L.P. (2022). Bjerknes compensation mechanism as a possible trigger of the low-frequency variability of Arctic amplification. Russian Journal of Earth Sciences, 22, ES6001.

We argue that the low-frequency variability of the Arctic amplification is regulated via a feedback, which elements include the oceanic heat transport, atmospheric heat transport and Arctic amplification. An increase (decrease) in the oceanic heat transport leads to a decrease (increase) in the atmospheric heat transport and to a decrease (increase) in the Arctic amplification. The atmospheric response to the ocean forcing occurs with a delay of three years and is attributed to the Bjerknes compensation mechanism. In turn, the atmospheric heat and moisture transport directly affects the magnitude of the Arctic amplification, with the latter lagging by one year. This chain of relationships was identified based on the wavelet analysis and cross-correlation analysis according to the data in Fig. 2.

Thus, the variability of the oceanic heat transport at the southern boundary of the Nordic seas might be a predictor of the magnitude of the Arctic amplification over the Eurasian Basin of the Arctic Ocean with a lead time of four years. The decadal variability of the Arctic climate, expressed in terms of the Arctic Ocean Oscillation index, supports the results obtained in this study.

Impact of Atlantic Meridional Overturning Circulation on the upper water temperature of the North Atlantic and Atlantic sector of the Arctic Ocean

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Daria Kuznetsova, SPbSU/ NIERSC, St. Petersburg, Russia

In this study, we investigate the impact of variability of the Atlantic Meridional Overturning Circulation (AMOC) on the water temperature of the upper 100-m layer of the North Atlantic and Arctic Ocean. For this we use three datasets (ARMOR-3D, SODA3.4.2, and ORAS4) with different spatial resolutions and coverage of different time periods.

The temperature variability is decomposed into its natural modes using Empirical Orthogonal Function analysis (EOF). The second EOF, which accounts for 20–27% of variance of water temperature in the upper ocean, is associated with a change in the AMOC intensity. The time variability of the principal component of this mode has a high correlation with the AMOC (0.6–0.9) depending on the dataset and AMOC index used. The spatial distributions of temperature anomalies associated with the AMOC dynamics are similar for all three datasets. The strengthening of the AMOC leads to an increase in water temperature in most of the North Atlantic and the Norwegian Sea, and to a decrease in the temperature over most of the Greenland Sea, the Barents Sea and in the area north of Spitsbergen (Fig. 3). An absence of the cold anomalies in the Nordic seas forced by an increase of the AMOC in the ARMOR-3D array may be related to a relatively short length of the data series.

Acknowledgment: This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).

Relevant publication: Iakovleva, D.A., Bashmachnikov, I.L., Kuznetsova, D.A. (2023). Impact of the Atlantic Meridional Overturning Circulation on the Water Temperature of the North Atlantic and the Atlantic Sector of the Arctic Ocean. Oceanology, 63, 2, 149-156.

The AMOC has the highest impact on water temperature of the Irminger Sea, in the central part of which the amplitude of the associated temperature fluctuations reaches 1.5–2°C. EOF-analysis of the Irminger Sea area only (black rectangle in Fig. 3) showed that in this region the percentage of water temperature dispersion of the upper 100-meter layer associated with the variability of AMOC was 61% in ORAS4, 78% in SODA3.4.2 and 85% in ARMOR-3D.

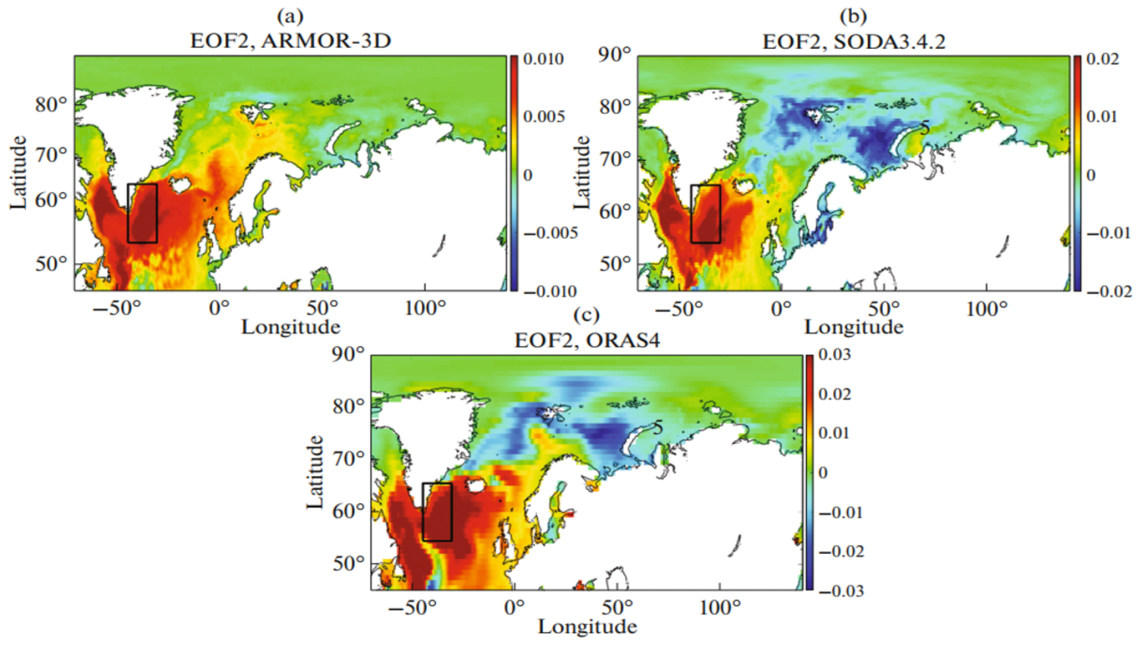

Figure 3. *Spatial distribution of amplitude of second EOF of water temperature in 0–100-m layer, which is associated with AMOC variability: (a) ARMOR-3D data; (b) SODA3.4.2 data; (c) ORAS4 data. Area of frequent deep convection in the Irminger Sea is delimited by the black rectangle.*

Mechanisms for the formation of density inversions in areas of regular deep convection in the Greenland Sea

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Dr. Igor Bashmachnikov, SPbSU/ NIERSC, St. Petersburg, Russia

This work identifies density inversions in the Greenland Sea that precede the development of deep convection. The mechanisms of their formation are considered using data from the oceanic reanalysis GLORYS12V1 and atmospheric reanalysis ERA5. The study focuses on the surface inundation of warm Atlantic waters and cold East Greenland Current waters, and the role of ocean-atmosphere heat flux and sea surface freshwater balance for two periods: the 1990s (1993, 1994, 1998) and the 2010s (2008, 2011, 2013).

The main mechanisms for the formation of density inversions include ocean-atmosphere heat flux, surface jet intrusions, and positive evaporation-precipitation differences (Fig. 4). These mechanisms can also act in combination to form density inversions. Heat flux from the ocean to the atmosphere is the primary source of inversions and is observed in 93% of all profiles with inversions (per-

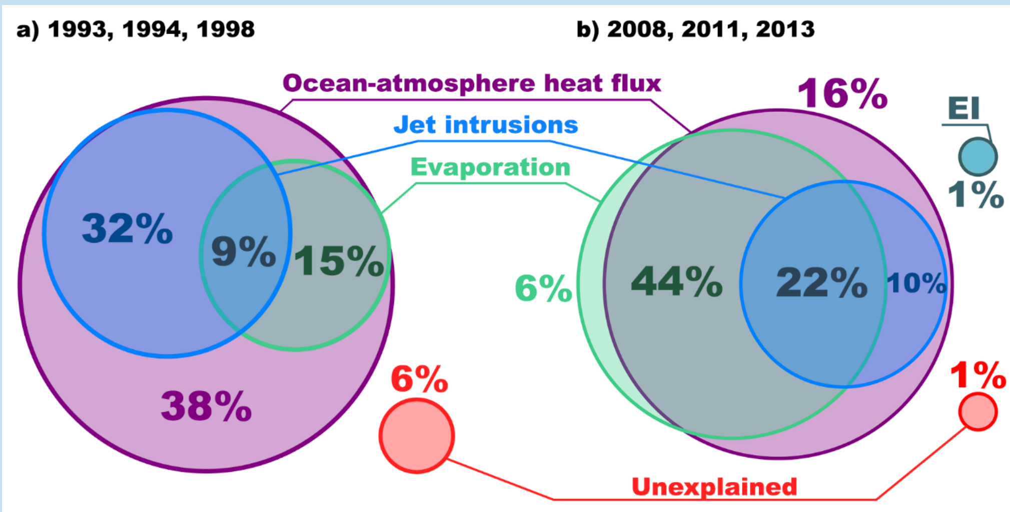

Figure 4. *Euler diagram of the percentage contribution of different mechanisms to the formation of density inversions in the upper Greenland Sea in the 1990s (a) and 2010s (b). EI – evaporation and jet intrusions.*

centage of the number for both periods of analysis). During the 1990s, the second most significant factor was surface jet intrusions and the third was the difference between evaporation and precipitation. In the 2010s, the last two factors were reversed, and the dominance of evaporation over precipitation played a more significant role. The increase in the contribution of this factor occurred simultaneously with the increase in the number of salinity inversions in the 2010s compared to the 1990s and is related to the variability of the dominant winds in this region.

The findings of this work allow us to propose the new hypotheses about the likely important role of the above-mentioned mechanisms of sea surface salinisation in the development of convection in the Greenland Sea and to explain the causes of its interannual variability.

Acknowledgment: This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).

Relevant publication: Kaledina, A.S., Bashmachnikov, I.L. (2023). Mechanisms for the formation of density inversions in areas of regular deep convection in the Greenland Sea. Herald of Saint Petersburg University. Earth Sciences, 68(4).

Dynamics of heat waves in the Arctic: present changes

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Dr. Iuliia Radchenko, NIERSC, St. Petersburg, Russia

Present climate change is manifested by an increase in the number and intensity of extreme events. One of the dangerous extreme events is heat waves. In this work, we studied the spatiotemporal dynamics of changes in the number of heat waves in the Arctic for the period 1950–2020.

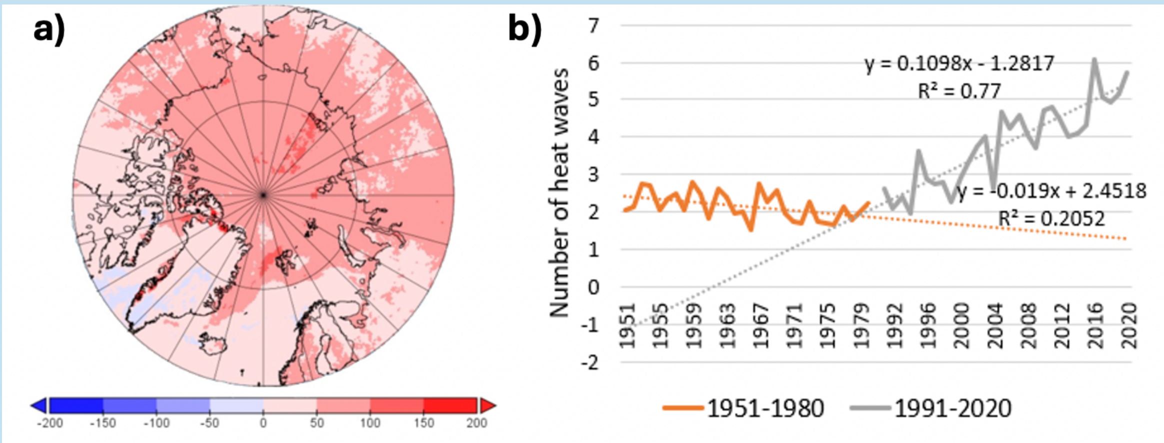

Figure 5. *a) Changes in the number of heat waves between 1991–2020 and 1951–1980. b) Interannual variability of the number of heat waves in the Arctic for the period 1951-2020.*

Heat waves were determined by the criterion when the values of surface air temperature exceed for five days the value of the 90th percentile of air temperature at a given point calculated over the previous 30-year period. The analysis was performed based on data from the ERA5 climate reanalysis.

According to the results obtained (Fig. 5a), most of the Arctic territory is characterized by a significant increase in heat waves over the past 30 years, relative to 1951-1980. A decrease in the number of heat waves was obtained only for Greenland, Labrador and Norwegian seas.

The increase in the frequency of heat waves is also visible from the plot showing their interannual variability averaged for the Arctic territory (Fig. 5b). The plot indicates very different trends at the beginning of the period under the study and over the last 30 years.

Acknowledgment: This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).

21st century Arctic ice rain frequency estimates based on CMIP6 models

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Dr. Natalia Gnatiuk, NIERSC, St. Petersburg, Russia

Changes in Arctic freezing rain in the 21st century relative to the present time were estimated using data from CMIP6 climate models. Freezing rain events were determined using the method of Cantin and Bachand (1993), which based on the analysis of the difference in geopotential layers at 850-700 hPa (≥ 1540 m) and 1000-850 hPa (in the range 1290-1310 m), provided that the surface air temperature ≤ 0°C, and precipitation ≥ 1 mm (McCray et al., 2022). Future projections of freezing rain were calculated using the sub-ensemble of six CMIP6 models that most realistically reproduce precipitation and air temperature in the Arctic for historical period, selected by the method of Gnatiuk et al. (2020) from 25 CMIP6 models. Bias correction of model data was performed using the Delta method.

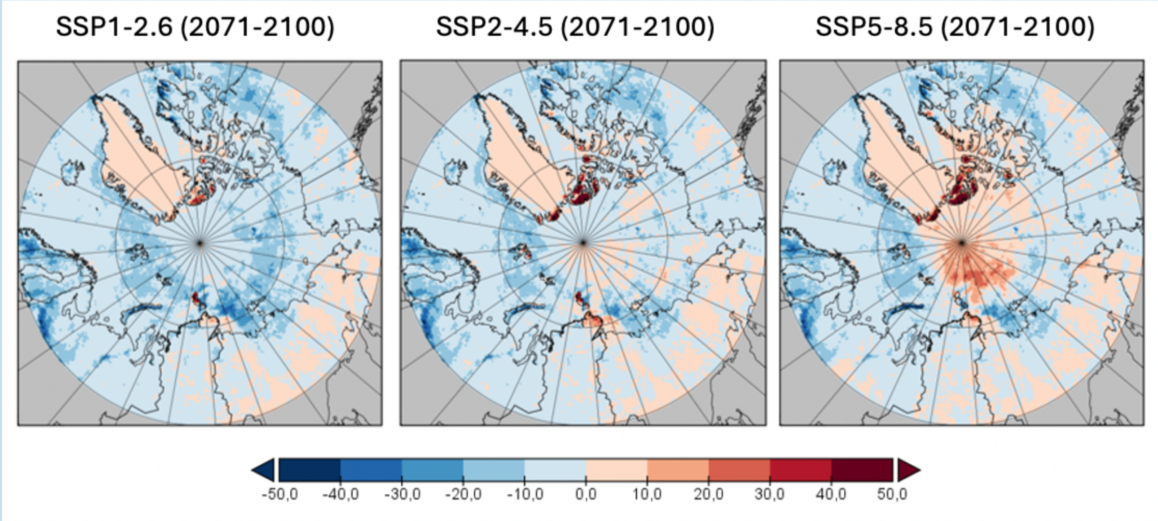

Figure 6. *Difference in the number of days with freezing rain for the Arctic for the period 2071–2100 relative to the period 1991-2020.*

Fig. 6 shows the spatial distribution of changes in the number of days with the freezing rain in the Arctic for the period 2071–2100 relative to the period 1991-2020 (according to climate reanalysis ERA5) for three climate change scenarios of projected socioeconomic global changes and the corresponding concentrations of greenhouse gases and aerosols: SSP1-2.6 (2.0 °C); SSP2-4.5 (3.0°C) and SSP5-8.5 (5.0°C). The expected level of the global air temperature increase at the end of the 21st century relative the pre-industrial one is indicated in parentheses.

According to the results obtained, freezing rain events are expected to decrease in the Arctic seas, and increase, especially for high-emission scenarios, for the central Arctic, Taimyr Peninsula and in the Laptev Sea.

Acknowledgment: *This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).*

New relationship between the thickness of sea ice and its age

Dr. Elena Shalina, NIERSC/ SPbSU, St. Petersburg, Russia

A new relationship between the thickness of sea ice and its age based on the latest satellite data has been obtained. Satellite products used in this work were CS2SMOS (ice thickness) and EASE-Grid Sea Ice Age /NSIDC-0611 (ice age). CS2SMOS contains data on sea ice thickness in the Arctic based on joint processing of measurements from the Cryosat-2 and SMOS satellites, and the NSIDC product is built on data on sea ice concentration and ice movement received from passive microwave satellite observations. Since sea ice thickness data cannot be obtained for the melting season, relationships between ice thickness and ice age are obtained for the period from October to April.

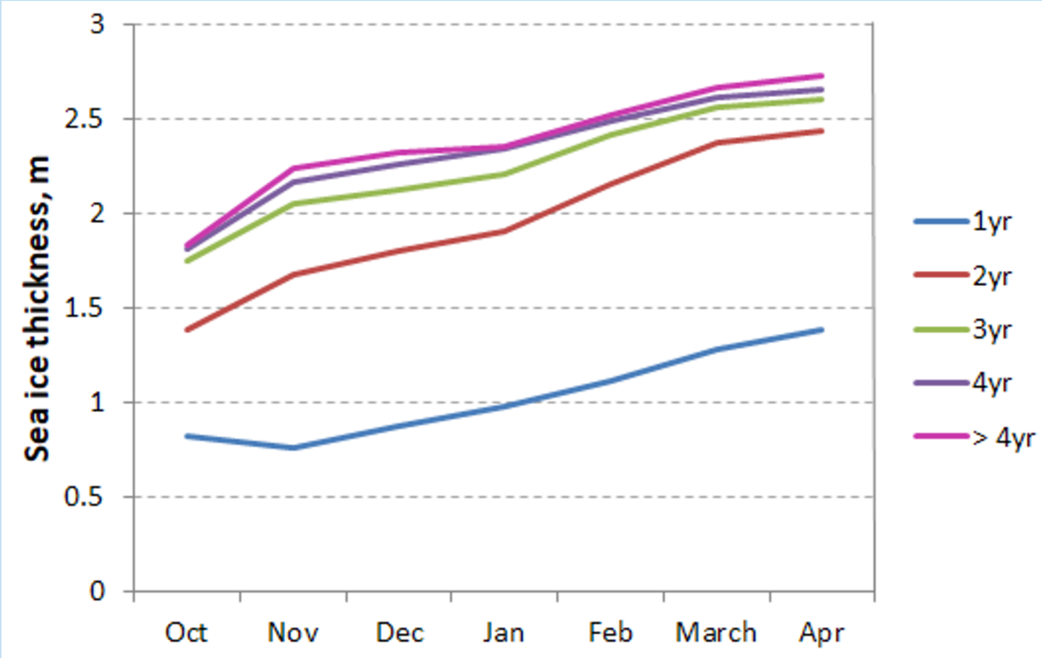

Figure 7. *Monthly average thickness of the sea ice of different age from October to April.*

It was shown that the quadratic function best approximates the dependence of ice thickness on its age. The reliability of the quadratic approximation lies in the range from 0.99 to 0.93. Of course, the dependency is described only by a part of the quadratic function in the range from 0 to 5. Comparison of the relationship between the sea ice age and its thickness, obtained previously from the ICESat satellite data (2003-2008) and in the present study from CryoSat-2/SMOS data (2011 - 2021) has shown a good consistency of results. Important information that can be extracted from the data obtained is the average thickness of ice of different ages, its current level and changes during the winter season. The change in the Actic average sea ice thickness for different age gradations (first-year, second-year, third-year, fourth-year and older than four-year ice) from October to April for the modern period is shown in Fig. 7.

Acknowledgment: *This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).*

The influence of 4D-Var data assimilation methods on the model reproduction of wind speed fields within polar lows

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The wind speed field is one of the main parameters for the analysis of polar lows as it directly influences the danger they may pose. Wind speed in cyclones is usually estimated based on satellite data from scatterometers or passive microwave radiometers. These data allow obtaining the instantaneous distribution of the wind speed field within a cyclone, however, the data are irregular and cannot capture all of the wind speed dynamics throughout the entire existence of a cyclone. The data from atmospheric reanalyses or operational forecast models are regular but they are not always able to reproduce the complex set of physical mechanisms of cyclone formation. As a result, some polar lows may be missing in these data. In addition, wind speeds in polar lows were shown to often be significantly underestimated in these data.

Thus, in cases when the polar low wind field dynamics throughout its entire lifetime is needed, numerical modelling methods might be more suitable. In this study, we used the Weather Research and Forecast (WRF) numerical atmospheric model and assessed the model accuracy of the wind speed in a polar low. A total of three numerical experiments were carried out. To set the initial and lateral boundary conditions in all experiments, the ERA5 atmospheric reanalysis data were used. The lifetime of the simulated polar low was 24 hours, the simulation began 12 hours before its formation, so the duration of the numerical experiment was 36 hours.

The first experiment was a control one, where the WRF model was initialized without data assimilation. In the second experiment, data from the ERA5 reanalysis were assimilated. In the third experiment, the assimilation of data from the ERA5 and ASCAT satellite scatterometers was carried out. For the purposes of this work, scatterometer data were also taken as "true" wind speed values, with which the simulation results were compared.

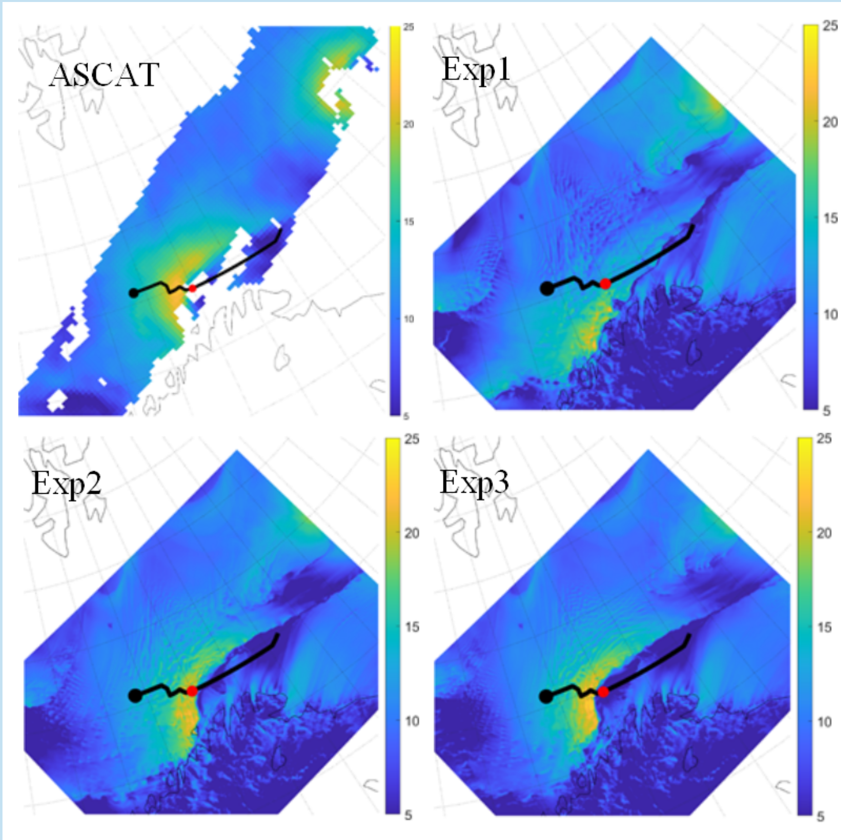

Figure 8. *Polar low wind speed for the same time step according to the ASCAT scatterometer data and the results of WRF simulations (Exp1 is first experiment, Exp2 is second experiment, and Exp3 is third experiment). The black line indicates the cyclone track, the black circle denotes its beginning. The red circle indicates the current position of the cyclone center.*

A comparison of the results for one point in time is shown in Fig. 8. The wind speeds in the cyclone, obtained as a result of calculations without data assimilation (the first experiment), turned out to be significantly lower than those obtained from the ASCAT scatterometer data; the structure of the wind field in the cyclone was not reconstructed accurately enough. When assimilating ERA5 data (second experiment) and ERA5 data together with ASCAT data (third experiment), the wind field in the cyclone was reconstructed more accurately, the maximum wind speeds are in good agreement with satellite data. The smallest wind speed root mean square error was obtained for the third experiment, the largest – for the first.

Thus, it is shown that numerical modeling with 4D-Var assimilation methods makes it possible to obtain correct wind fields in polar low, which enables detailed studies of wind speed dynamics during the entire cyclone lifetime.

Aquatic Ecosystems under Global Warming

Response of the Arctic Ocean primary production to climate warming: Insights from 2003-2022 satellite data

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Arctic Ocean (AO) warming leads to alterations in primary production (PP) and therefore in the marine ecosystem. As the Arctic Ocean warming is expected to continue in the future, it is important to keep trace of PP changes to assess their tendency.

To achieve this goal, satellite data were used covering the period through 2003-2022, namely the latest version of the OC-CCI dataset (v6.0). Tendencies in PP and chlorophyll (Chl) variations were considered separately for the entire AO, its pelagic (off-coastal) and coastal zones as well as for each of the AO marginal seas. The conditional outer boundary of the coastal zone corresponded to a 200 m isobath. The Ocean Colour component of the European Space Agency Climate Change Initiative (OC-CCI) mean monthly data on Chl at a spatial resolution of 4 km were used. For the pelagic AO waters data on Chl were performed through a judicious direct use of the OC CCI.

For the AO coastal waters, the BOREALI Chl-retrieval algorithm was employed. Average retrieval error for Chl retrieval is about 25%.

The PP assessments were performed making use of the algorithm by Behrenfeld and Falkowski (1997). For running this algorithm, exclusively spaceborne input variables required, namely Chl at the depth nearest to the surface, incident Photosynthetic Active Radiation (PAR) irradiance, downwelling irradiance at the sea surface, $E_o(\lambda)$, and sea-surface temperature, SST. The assessed error in PP determinations within the coastal, off-coastal zones, and the entire Arctic Basin proved to be 24%, 26%, and 25%, respectively. As illustrated in Fig. 9a, PP interannual variations in the entire AO exhibit an expressly irregular pattern with a strong tendency of growth with time, as high as 18.5% over the last 20 years. It is noteworthy that there were sharp increases in PP in 2012, 2016 and 2020 and also a splash in 2007. At the same time, PP in 2003 was markedly low. These changes occurred against the background of a significant decline in Chl. In the AO marginal seas, the PP temporal tendency across 2003-2022 revealed prevailingly growing patterns excluding the East Siberian and Chukchi seas where there was no distinct and negative trend.

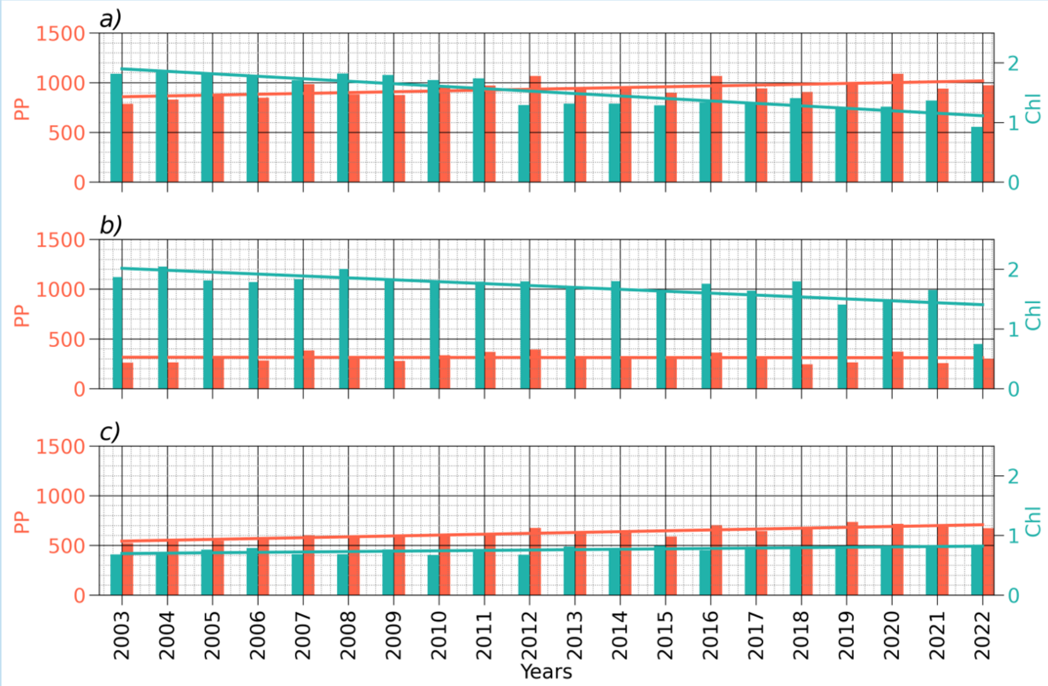

Figure 9. *20-year time-series of PP (TgC·yr^{-1}) (left axis) and phytoplankton Chl (mg·m^{-3}) (right axis) variations across the entire AO (a), its coastal (b) and pelagic (c) zones. Green columns = Chl; red columns = PP; green and red straight lines are tendencies of Chl and PP, respectively.*

Acknowledgment: *This study was funded by the Ministry of Science and Higher Education of the Russian Federation under the project No. 13.2251.21.0006 (Unique Identifier RF-225121X0006) and supported by the European Union's Horizon 2020 Research and Innovation Framework Programme under Grant Agreement No. 101003590 (PolarRES).*

Relevant publication: *Frolova, A.V., E.A. Morozov, D.V. Pozdnyakov (2023). The Arctic Ocean primary production in response to amplification of climate change: Insights from 2003-2022 satellite data. Izvestiya, Atmospheric and Oceanic Physics. 12.*

The results obtained are explicitly indicative that during 2003-2020 the overall PP growth in the AO is predominantly due to its growth in the pelagic zone. (Fig. 9b,c). The observed increasing tendency in PP within the pelagic zone is thought to be a result of increasing ice-free area during the time-period considered herein. Altogether, our study provides solid evidence that, at least over the last several decades, the Arctic amplification stimulated the AO primary productivity.

Ongoing dynamics of the Arctic Ocean acidification, and its projections for the current century

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The world's oceans are largest carbon reservoirs and a major sink for anthropogenic CO_2 emissions. An increase in atmospheric CO_2 leads to larger flux of CO_2 into the ocean.

Dissolved CO_2 interacts with water molecules to form carbonic acid, which dissociates into bicarbonates and free hydrogen ions. As the number of these ions increases, acidification of the environment occurs, i.e., a decrease in pH over decades or longer periods of time. Significant ocean acidification (OA) can cause changes in metabolism in marine organisms and affect biogeochemical cycles, altering ecosystems and their interactions.

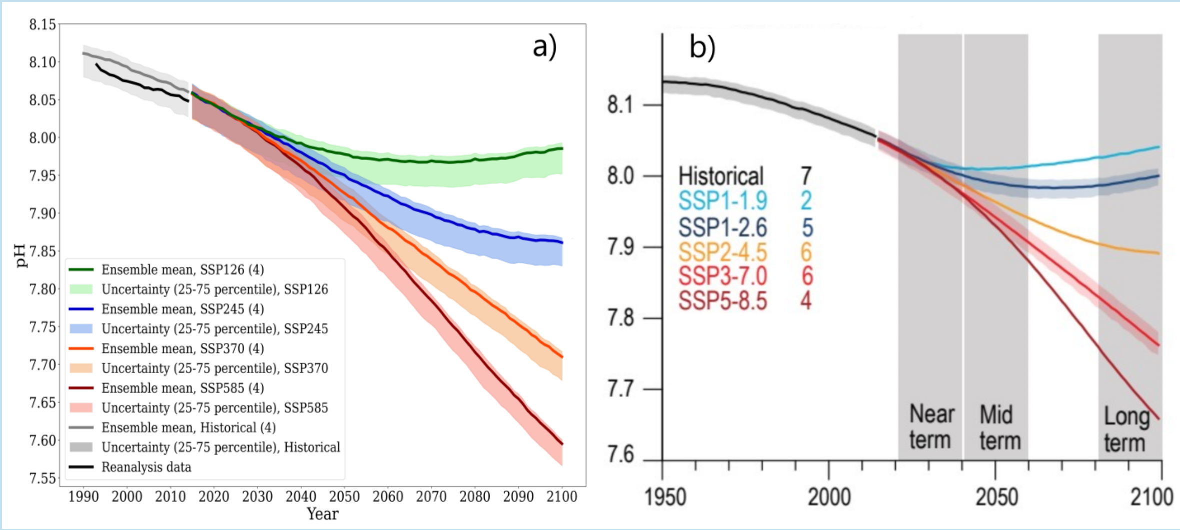

Figure 10. *Projection of water acidification in the Arctic Ocean (a) and the World's Ocean (b).*

Under the conditions of ongoing climate change, in high latitudes OA occurs twice as fast as in the tropics and subtropics. In the Arctic, OA is increasing due to low water temperatures, increased freshwater availability (river runoff and ice melt), and the influx of low pH Pacific waters. In light of the above, it was of interest to (i) numerically assess the present-day (1993-2021) dynamics of Arctic Ocean acidification, and (ii) analyse future OA trends. These tasks were accomplished using GLODAPv.2021 and Global Ocean Biogeochemistry Hindcast reanalysis data for the pH parameter in the waters of the Arctic region (60-90°N) for the period 1993-2021. It is shown that for this period the range of pH values from GLODAP data was 6.97–9.35, with a mean value of 8.14±0.13. The distribution of values appeared to be close to normal and the rate of decrease of pH value in the Arctic Ocean was -0.03% (Fig. 10a). The spatial distribution of pH in the Arctic Ocean seas is characterized by considerable heterogeneity.

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Relevant publication: *Malysheva A., Radchenko Yu., Pozdnyakov D. (2023). Arctic Ocean Acidification Dynamics during 1993-2021 and its Projections for the Rest of this Century. Fundamental and Applied Hydrophysics.16 (24).*

The prediction of the Artic Ocean acidification trend up to the end of the 21st century was carried out using four best models selected from CMIP6 ensemble: MPI-ESM1-2-LR, NorESM2-MM, NorESM2-LM and CMCC-ESM2. The prediction results indicate that acidification of Arctic waters will continue through the end of this century (Fig. 10a). The highest rates of pH decrease (-4.9% and -6.2%) correspond to the SSP3-7.0 and SSP5-8.5 scenarios, assuming a 3.6°C and 4.4°C increase in global mean temperature, respectively, at the end of the 21st century relative pre-industrial level. If such extremely high rates of atmospheric warming are taken as unlikely, then more realistic rates of Arctic Ocean acidification would be in the range -1.4% – -2.9%.

Our results and results obtained by other authors indicate that by the end of this century, the rate of acidification in the Arctic should be expected to be higher than the global ocean average (Fig.10b).

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