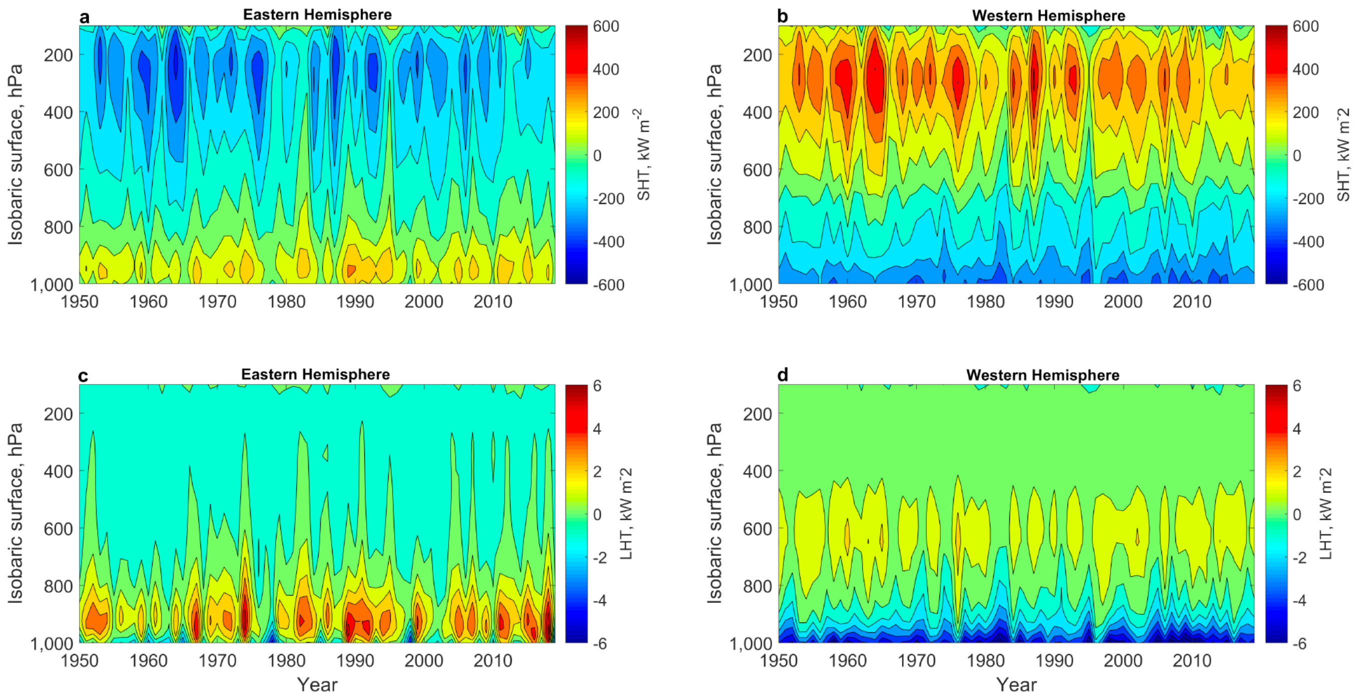
Annual Report 2021

Nansen International Environmental and Remote Sensing Centre

St. Petersburg, Russia

Non-profit international centre for environmental and climate research
Founded in 1992

Dipole pattern of meridional atmospheric heat transport to the Arctic



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Cover page: *Heat transport components, their interannual variability and anti-phase pattern between the hemispheres: annual average (a,b) sensible heat transport (SHT) and (c,d) latent heat transport (LHT). Positive values indicate northward heat transport (Latonin et al., 2022. Dipole pattern of meridional atmospheric internal energy transport across the Arctic gate. Scientific Reports, 12, 2363).*

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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. Leonid Bobylev)*
- 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 national and international governmental agencies, research councils, space 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 2021 NIERSC staff incorporated 26 employees, 14 full-time and 12 part-time, comprising research and administrative personnel. Research personnel included one full Doctor of Science and 11 PhDs. Four PhD-students were supervised and supported financially through the Nansen Fellowship Programme, all holding also full- or part-time positions of Junior Scientists at NIERSC.

Scientific Production

In 2021, totally 30 publications were published including one book chapter, 16 papers in peer reviewed journals, 1 paper in other journals and 12 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) 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, Institute of Earth Sciences of the St. Petersburg State University, Arctic and Antarctic Research Institute, Institute of Atmospheric Physics of the Russian Academy of Sciences and others. The preferred research areas include current and future climate and environmental changes in the Arctic, North Atlantic and Northern Eurasia, Polar lows in the Arctic, as well as methods and techniques of satellite remote sensing with the focus on the Arctic and Sub-Arctic. NFP provides PhD-students with the Russian and international scientific supervision, financial fellowship, efficient working conditions at NIERSC, training and research visits to the international research institutions within the Nansen Group and beyond, involvement into international and national research projects. Nansen Fellowship Programme is sponsored by the NIERSC, Nansen Scientific Society and Nansen Centre in Bergen, Norway. Postgraduate student activity is supervised by at least one Russian and one international senior scientist. All NFP PhD-students obliged to publish their scientific results in the international refereed journals and make presentations at the international scientific symposia and conferences.

Totally 31 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 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, Helsinki, Finland.

Arctic cooperation between Norway, Russia, India, China and US in satellite Earth observation and education (ARCONOR) is the international project aimed at the sustaining long-term international partnership and cooperation between Norway, Russia, India, China and US in the area of satellite Earth observations for monitoring and forecasting the Arctic and support to Arctic shipping through advancing research, higher education and recruitment. ARCONOR is coordinated by the Nansen Environmental and Remote Sensing Centre (NERSC), Bergen, Norway, with the following partners: Nansen Scientific Society (NSS), Bergen, Norway; NIERSC, St. Petersburg, Russia; Nansen Environmental Research Centre – India (NERCI), Kochin, India; Nansen-Zhu International Research Centre (NZC), Beijing, China; and the University of Connecticut, Storrs, USA. ARCONOR is funded by the Research Council of Norway; NIERSC participation is funded partly by grants from NERSC and NSS, 2017-2021.

Wind speed and wave field dynamics in polar lows and their impact on sea ice is the project devoted to studying distribution of surface wind speed within polar lows in the Arctic, its influence on wind waves and swell generated by polar lows, and their combined impact on sea ice and marginal ice zone. This project is funded by the Russian Science Foundation (RSF), Grant No. 19-77-00092, 2019-2021.

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.

Arctic amplification and its impact on the polar environment is the project with the overall objective to quantify Arctic amplification, estimate contribution of atmospheric and oceanic heat fluxes to its magnitude, and assess its impact on the sea ice in the Arctic seas as well as primary production in the Arctic waters. It is funded by the Nansen Environmental and Remote Sensing Centre (NERSC), Bergen, Norway, 2021.

Arctic Research project includes study of generation of oceanic internal waves by eddies, Arctic sea ice and air temperature relationship with the concentration of greenhouse gases in the atmosphere, impact from population on climate, with the Arctic as an example, as well as CIMIP6 modelling of sea ice and air temperature in the Barents, Kara and Laptev seas. It is funded by grant from the Nansen Scientific Society (NSS), Bergen, Norway, 2021.

Large-scale regionalization of meridional atmospheric sensible and latent heat fluxes into the Arctic

Dr. Mikhail Latonin, Nansen Centre (NIERSC), St. Petersburg, Russia

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

Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia

Atmospheric meridional energy transport (AMET) strongly shapes the polar climate. The AMET is interrelated to many environmental parameters, such as air temperature, humidity, sea ice, etc. At the same time, it is important for the heat exchange and redistribution between the polar and middle latitudes. Based on the climate reanalysis ERA5, we have investigated the instantaneous sensible and latent heat fluxes in the troposphere across the Arctic gate at 70°N. To study large-scale features of heat fluxes, we decomposed the sensible and latent heat transports across 70°N, calculated at every grid point (functions of longitude, isobaric surface, and time), into the empirical orthogonal functions (EOFs). The results of this EOF decomposition are presented in Fig. 1.

As seen, the leading modes of variability are almost exactly divided into the Eastern and Western Hemispheres: variability of the sensible heat transport dominates in the Western Hemisphere, whereas that of the latent heat transport dominates in the Eastern Hemisphere. This division is more pronounced for the latent heat transport. The three EOFs in the figure explain about 50% of the variability for each heat transport component. The hemispheric pattern in the modes of variability with a similar nature of the time-altitude variability of the heat transport components is preserved if additional EOFs are added. For the sensible heat transport, the first eight EOFs explain 81% of the variance, and the first eight EOFs for the latent heat transport explain 79% of the variance. These results confirm the robustness of the identified hemispheric division for the sensible and latent heat fluxes.

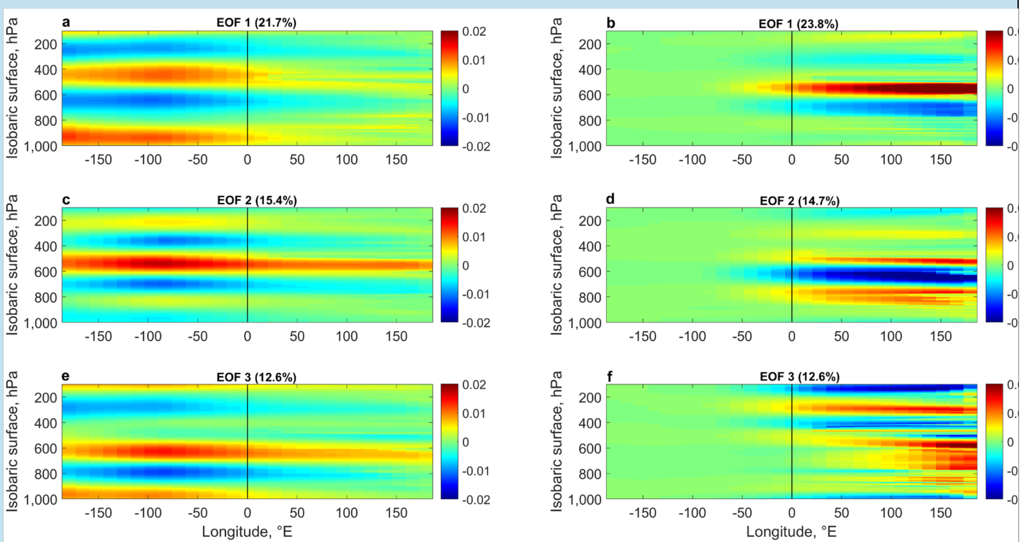

Figure 1. *Empirical orthogonal functions (EOFs) of the sensible (left) and latent (right) heat transport components (SHT and LHT). (a) First EOF for the SHT (21.7%). (b) First EOF for the LHT (23.8%). (c) Second EOF for the SHT (15.4%). (d) Second EOF for the LHT (14.7%). (e) Third EOF for the SHT (12.6%). (f) Third EOF for the LHT (12.6%). The reference lines are drawn at the prime meridian 0°. The values in the parentheses are the fractions of variance explained by each mode.*

Acknowledgment: *This study was funded by the Saint Petersburg State University, project number 75295423. The authors also acknowledge the financial support of the Nansen Environmental and Remote Sensing Center (NERSC) and the Nansen Scientific Society (NSS), Bergen, Norway. In addition, R.D. acknowledges the project KeyCLIM funded by the Norwegian Research Council, project number 295046.*

Relevant publication: *Latonin, M.M., Bobylev, L.P., Bashmachnikov, I.L., Davy, R. (2022). Dipole pattern of meridional atmospheric internal energy transport across the Arctic gate. Scientific Reports, 12, 2363.*

Subsequent analysis showed that there is also an anti-phase pattern between the hemispheres. However, sensitivity experiments with respect to the dividing meridian indicated that this is not a unique feature for the geographical definitions of the Eastern and Western Hemispheres (i.e., separated by the prime meridian 0° and by the date line 180°). In contrast, the significant differences in the variability between the hemispheres, revealed from the EOF analysis, were confirmed in the sensitivity experiments.

What might explain the dominance of latent heat transport in the Eastern Hemisphere and sensible heat transport in the Western Hemisphere? This requires further in-depth studies. We suggest the following conceptual explanation. Regarding the dominance of latent heat transport in the Eastern Hemisphere, first, the extratropical cyclones, originating in the North Atlantic, carry moisture to the northeast, thus affecting the Arctic in the western and central parts of the Eastern Hemisphere. Second, the cyclone tracks from the North Pacific are predominantly directed northwest, thus affecting the Arctic in the far eastern area of the Eastern Hemisphere. Third, the Siberian atmospheric rivers are responsible for the dominance of latent heat transport in the central and eastern parts of the Eastern Hemisphere. The three different processes work simultaneously and give rise to the large-scale convergence of moisture transport into the Arctic in the Eastern Hemisphere. According to the results of our study, the dominance in the variability of sensible heat transport in the Western Hemisphere is over the isobaric surfaces 1000–100 hPa. This might be related to the trend in the cold air outbreaks, which has a pronounced negative sign in the Western Hemisphere according to the ERA5 reanalysis; at the same time, the frequency and magnitude of cold air outbreaks in the Eastern Hemisphere have not changed significantly since 1979.

Interannual variability of upper ocean heat advection between the North Atlantic Subpolar Gyre and the Nordic Seas

PhD-student Diana Iakovleva, SPbSU/NIERSC, St. Petersburg, Russia
Dr. Igor Bashmachnikov, SPbSU/NIERSC, St. Petersburg, Russia
Dr. Richard Davy, Nansen Centre (NERSC), Bergen, Norway

In this study we investigate the interannual variability of the heat content of the upper North Atlantic, as well as its possible driving mechanisms: the ocean-atmosphere heat exchange and oceanic heat advection. The data from the combined in situ and satellite-based dataset ARMOR-3D (1993-2018, 0.25°×0.25°), and from the ocean reanalyzes ORAS5 (1958-2018, 1°×1°) and SODA3 (runs with two different atmospheric forcings were used, 1980-2018, 0.5°×0.5°) were used. The different datasets show similar patterns of a decadal interannual variability of the area-mean heat contents and heat fluxes.

Acknowledgment: *This study was funded by the Saint Petersburg State University, project number 75295423.*

Relevant publication: *Iakov-leva, D.A., Bashmach-nikov, I.L. (2021). On the seesaw in interannual variability of upper ocean heat advection between the North Atlantic Subpolar Gyre and the Nordic Seas. Dynamics of Atmospheres and Oceans, 96, 101263.*

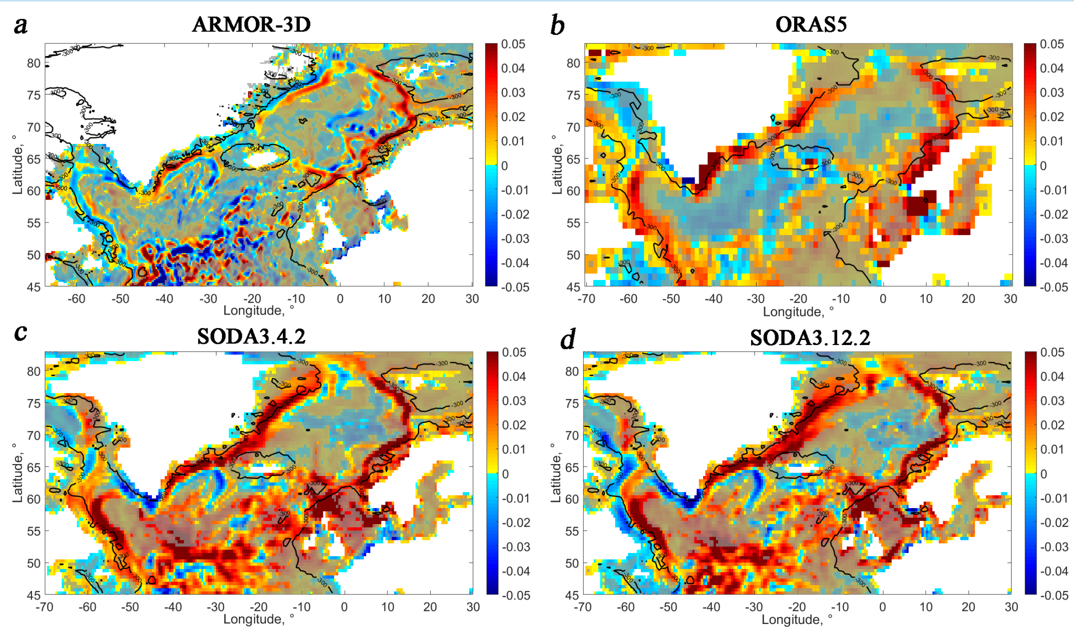

Figure 2. *Spatial distribution of the January-March anomaly the modulus of the sea-surface current velocity (m s^{-1}) for: a – ARMOR-3D (1993-2018), b – ORAS5 (1975-2017), c – SODA3.4.2 (1980-2017), d – SODA3.12.2 (1980-2017). The anomaly represents the difference of the modulus of the current velocity for years with high NAOI (>0.9) menus low NAOI (<-0.1). The gray shading shows regions where the current velocity is less than 0.05 m s^{-1}. The black line marks the 300-m isobath.*

The decadal variation of the upper ocean heat contents in the Subpolar Gyre (the Labrador and Irminger seas) showed strong negative correlations with North Atlantic Oscillation Index (NAOI), while the latter practically did not affect the heat content of the upper Norwegian Sea. The current velocities of the North Atlantic, East Greenland and Labrador currents in all datasets increase with the NAOI, but the velocities of the Irminger and West Greenland currents, on contrary, decrease (Fig. 2). The opposite effect of the NAOI on the Irminger and Norwegian currents forms a seesaw between the upper ocean heat advection in the Subpolar Gyre and in the Nordic Seas, differently redistributing the heat of the North Atlantic Current between the basins for different NAO phases. In the Subpolar Gyre, the periods of high NAOI are associated with negative anomaly in the oceanic heat convergence and an intensified sea-surface heat release to the atmosphere, both making a significant input to the "immediate" response of the heat content of the upper Gyre. 8–10 years later, a second increase in the cross-correlations of the NAOI with the heat content in the eastern Subpolar Gyre is presumably a delayed response to the positive temperature anomalies in the Gulf Stream region, previously formed as an immediate response to high NAOI. The upper ocean heat content of the Norwegian Sea shows practically no link to variability of the NAOI, in spite of a somewhat stronger oceanic heat flux across its southern boundary during high NAOI.

Density inversions in the Greenland Sea during the cold period of 1993-2019

A. Kaledina, SPbSU, St. Petersburg, Russia

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

In this study we discuss spatial and temporal variability of characteristics of density inversions in the Greenland Sea during the cold period (November to April) of 1993–2019, as well as investigate possible mechanisms of formation of these inversions. This will permit better understanding the mechanisms governing winter convection in the sea.

We use in situ vertical profiles of temperature and salinity from the EN.4.2.1 dataset (Met Office Hadley Center database). Over the study period we found over 500 profiles, where inversions of potential density in the upper ocean exceeded 0,001 kg m-3 over a vertical extent not less than 150 m. The biggest vertical extent of about 400 m was recorded during the years with the high convection intensity (2008, 2011, 2013), while the largest density gradients in the inversions was observed in the 1990s, when convection was less intensive. We attribute this to a limited amount of the potential energy available for the convective mixing which could be accumulated in an inversion before the mixing begins.

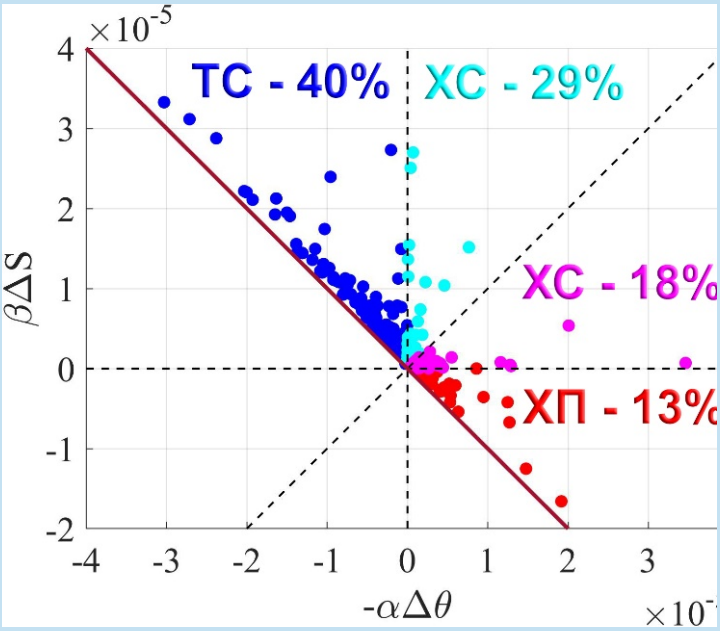

Figure 3. Scatterplot of the haline (βΔS) versus thermal (-αΔθ) terms of the seawater equation of state in the density inversions in the Greenland Sea. Pure haline inversions are marked by blue dots (TC – warm and saline surface water), mixed thermal and haline inversions with the dominating haline destabilization are marked by cyan dots, and with the dominating thermal destabilization – by magenta dots (XC – cold and saline surface water), red are pure thermal inversions (XП – cold and fresh surface water).

Acknowledgment: *This study is 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; Agreement No 075-10-2021-104 in the RF "Electronic Budget" System).*

Relevant publication: *Kaledina, A., Bashmachnikov ,I. Characteristics of density inversions in the Greenland Sea during the cold period of 1993-2019. Physical Oceanography ("Morskoy Gidrophysicheskiy Journal" (accepted).*

Using the equations of state, we estimated the contribution of temperature and salinity to formation of the density inversions in the Greenland Sea. (Fig. 3). Throughout the region, haline destabilization prevails (about 70% of all profiles with inversions); especially in the northeastern part of the study region. The pure haline destabilization was observed in 40% of all profiles, the pure thermal one – in 13%, while in the remaining 47% of the profiles both haline and thermal destabilizations was detected. After the beginning of the 2000s, the role of salinity in creating density inversions increases. This confirms the conclusions by Bashmachnikov et al. (2021), which was basing on flux balance estimates, it that the development of deep convection in the Greenland Sea during the 2000s-2010s was determined by a stronger inflow of the saline and warm Recirculating Atlantic Waters combined with its subsequent atmospheric cooling. This indicates a significant role of the potential instability in the development of convection in the Greenland Sea.

Arctic sea ice loss projections related to CO_2 emission

Prof. Ola M. Johannessen, Nansen Scientific Society (NSS), Bergen, Norway

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

Climate models are important tools for understanding the key processes governing the observed sea ice loss and estimating the time when a seasonally ice-free Arctic might be witnessed. At the same time, model simulations of the sea ice loss show a large spread of the results. A more direct way to project the sea ice extent is to correlate the sea ice directly with the CO_2 level as well as with other parameters that have or probably have influence on the sea ice loss, like surface temperature and population.

We have studied correlations between CO_2 concentrations, historical data and observations from Mauna Loa, sea ice from the new NSIDC sea ice extent G10010 historical dataset, Berkeley Earth surface air temperature above 70 degree North and population data, using monthly data and addressing all months of the year. Our research has confirmed the results of previous studies that CO_2 is the main driver for the sea ice decline (see Fig. 4) in the Arctic in all months.

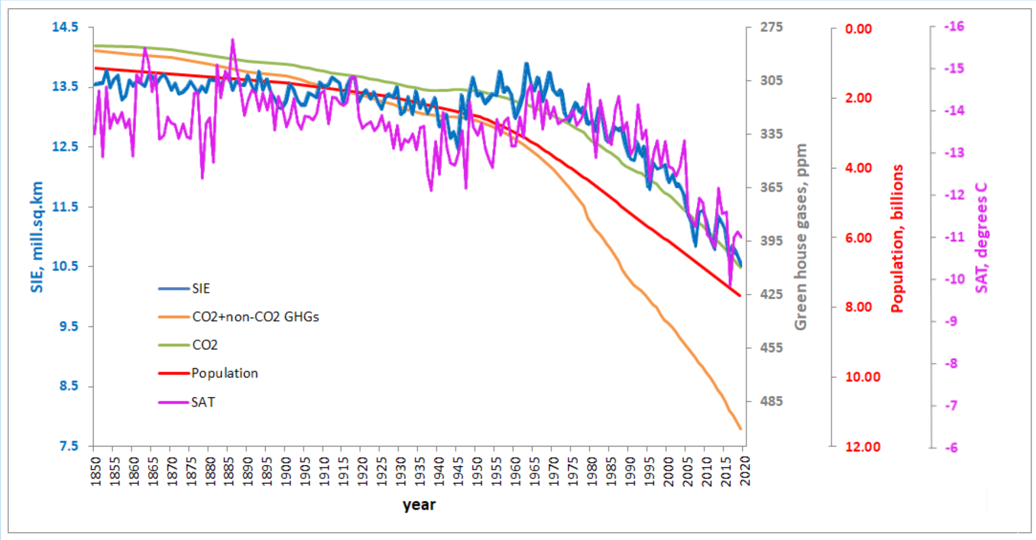

Figure 4. Sea ice extent (SIE), greenhouse gases (CO_2 and non-CO_2) concentrations, population, and sea surface temperature (SAT) from 1850-2020 used for correlation analysis.

Acknowledgment: *This study was supported by the Arctic Research Grant from the Nansen Scientific Society, Bergen, Norway.*

Relevant publication: *Johannessen O.M., Shalina E.V. Population increase impacts the climate, using the sensitive Arctic as an example. Atmospheric and Oceanic Science Letters, 2022, 100192, https://doi.org/10.1016/j.aosl.2022.100192*

The highest correlation between sea ice extent and CO_2 concentration calculated for the robust observational record from 1960-2019 has been received for September (-0.82) and the lowest (-0.70) for March. Relationships established between sea ice coverage and CO_2 concentration suggest that the Arctic will become ice-free in September when CO_2 concentration reaches 580 ppm and the atmosphere need to be ten times more loaded in order to melt the ice in March.

Extratropical cyclones over Arctic in 1979-2020

Dr. Pavel Golubkin, NIERSC, St. Petersburg, Russia
Dr. Julia Smirnova, NIERSC, St. Petersburg, Russia
Vsevolod Kolyada, NIERSC, St. Petersburg, Russia

A list of extratropical cyclone tracks over Arctic for 1979-2020 was derived from ERA5 reanalysis data. Cyclones were identified in 850 hPa relative vorticity fields as this was shown to better capture synoptic scale systems in the early stages of development and to be less influenced by the large-scale circulation than when using mean sea level pressure data. The 3-hourly relative vorticity fields were filtered using spectral coefficients and spherical harmonics retaining only those with a total wavenumber from 5 to 42, which corresponds to the T5-T42 spectral resolution filtering, which excludes mesoscale systems and large-scale circulation, such as, e.g., Rossby waves, while retaining synoptic scale systems. A spectral smoothing coefficient was then used to suppress possible Gibbs oscillations induces by the filtering procedure. Tracking of a cyclone was started upon the T5-T42 850 hPa relative vorticity exceeding 2×10–5 s-1 and was finished as soon as vorticity became lower than this value. The derived cyclone list therefore should not contain any cyclonic disturbances which may be considered too weak. Too short-lived cyclones, i.e., those existing for less than 1 day, were also not included in the list.

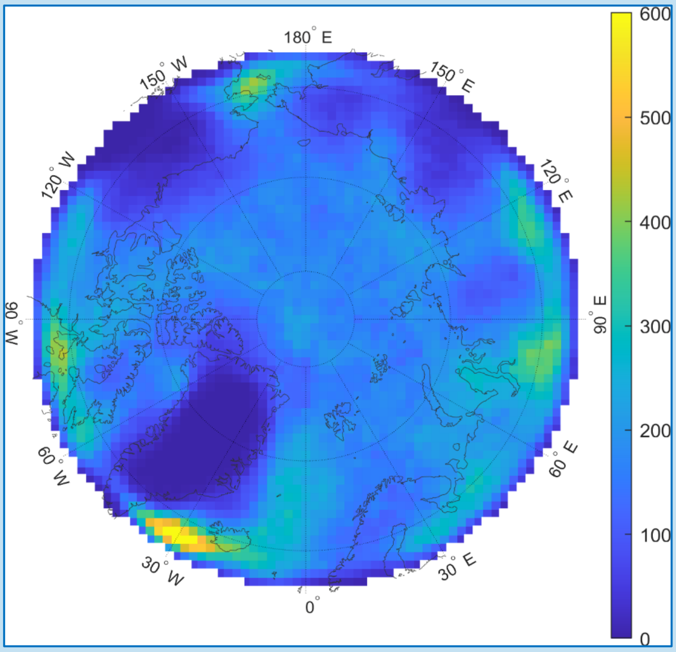

Figure 5. Track density of extratropical cyclones included in the derived list in 100×100 km cells.

Acknowledgment: *This study is 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; Agreement No 075-10-2021-104 in the RF "Electronic Budget" System).*

Overall, 28620 extratropical cyclones were identified for 1979-2020 and included in the list. Fig. 5 shows the cyclone track density, which is the number of times a cyclone centre passed through a 100×100 km cell. The largest cyclone density is observed over the Irminger Sea, which is in good agreement with other studies utilizing automated tracking procedures to detect extratropical cyclones in reanalysis data. Higher than average number of cyclones is also observed over the Greenland and Norwegian Seas, the northern areas of the Hudson Bay and Bering Sea, and over the Yamalo-Nenets Autonomous Okrug and Yakutia. The annual mean number of cyclones was estimated as 680. Interannual and inter-monthly variabilities are rather low, amounting for about 5% and 10% of the mean values, respectively. The highest numbers of cyclones are observed during the colder months, i.e., from October to January, while the lowest numbers are observed in June and July. Several cyclone parameters, such as lifetime, distance traveled, and translation speed were also assessed. The lifetimes of the analysed cyclones may reach up to 10 days, but most of them existed for 1-2 days. The largest observed distance traveled by a cyclone during its lifetime is about 5000 km and the mean value is 1500 km. The mean translation speed is 7 m/s and values from 4 to 9 m/s are observed most often.

Aquatic Ecosystems under Global Warming

Biogeochemical reaction of Lake Ladoga to climate change

Prof. Dmitry Pozdnyakov, NIERSC, St. Petersburg, Russia
Dr. Evgeny Morozov, Marine Hydrophysical Institute (MHI), Sevastopol/NIERSC, St. Petersburg, Russia
Prof. Nikolay Filatov, Karelian Research Centre, Russian Academy of Sciences, Petrozavodsk, Russia
Elizaveta Ignateva, NIERSC, St. Petersburg, Russia
Dr. Richard Davy, Nansen Centre (NERSC), Bergen, Norway

Lake Ladoga is the largest natural fresh waterbody in Europe. Since the 1960s, this waterbody has been in a state of continuous change in terms of its biochemical parameters and trophic state, which were mostly associated with heavy anthropogenic impacts on Lake Ladoga. Previously overlooked/underestimated, ongoing climate warming climate change at the North of the European Territory of Russia (ETR), including Lakes Ladoga and Onego, proved causing seizable alterations to the hydrobiochemical (HBC) regime of the lake, importantly regardless of the anthropogenic load drastic reduction that started some decades ago. In addition to the persisting (also reduced) anthropogenic influence, the HBC changes proceeded under conditions of the annual-average air temperature and the temperature of the surface layer of the lake's water increase, especially in the winter, associated with a significant reduction of ice coverage, delayed freezing, earlier ice-break up, increased incidence of winters without solid ice cover, shifts in the timing of setup and speed of the thermobar movement across the lake.

Relevant publication: *Morozov, E, Pozdnyakov, D., Filatov, N., Ignatyev, E., Davi, R. (2022). Biogeohemical changes in Lake Ladoga: Insights from satellite data. Atmospheric and Oceanic Physics, 12, issue 58.*

Filatov, N., Pozdnyakov, D. (2021). Spring water quality variations in the Lake Ladoga in 2016-2017. Fundamental and Applied Geophysics, 14, 1 (in Russian).

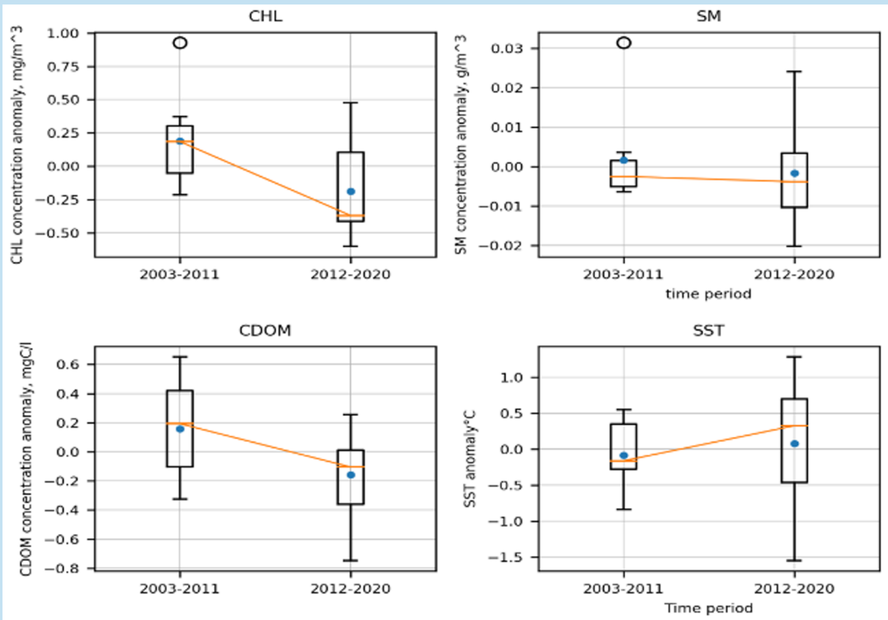

Figure 6. *Box-and-whiskers plots reflecting the difference between the mean vegetation season anomalies of phytoplankton chlorophyll (CHL), suspended minerals (SM), coloured dissolved organic matter (CDOM), and water surface temperature (SST) interannual variations in 2003-2011 and 2012-2020. Red line and blue point within the box stand for the vegetation season median and mean values, respectively. Red line between boxes relates median values. Open circles are outliers.*

Remotely, we examined the transformation of the state of Lake Ladoga over an almost twenty-year period (2003-2020). Our analysis of the nearly two-decadal period of observations (2003-2020) was partitioned into two subperiods, vis 2003-2011 and 2012-2020 in order to achieve a clearer understanding of the driving cause and effect interactions/mechanisms leading to the transformation of the Lake Ladoga ecosystem. Because in each time period (i. e. 2003-2011, 2012-2020) we have only 9 annual data/numbers on the desired parameters averaged over the vegetation period, utilization of an approach of histograms of statistical distribution would be inappropriate. Instead, we used the method of box-and-whiskers diagrams or plots which is widely used in the descriptive statistics.

We found that the median values of CHL anomalies over the vegetation periods in 2003-2011 and 2012-2010 with respect to the respective mean values over the 2003-2020 period indicate (Fig. 6) that the median values of phytoplankton CHL have dropped down. It could be only if intra-lake biological mechanisms activated some endogenous replenishment of the reservoir with phosphorus-containing biogenic as a result of lysis of the chromophoric fraction of CDOM of allochthonous origin and rearrangement of the phytoplankton community structure. As a result, the lake continued to maintain its mesotrophic status for some years. Although some indications of self-healing of the lake appeared over time, this process, as it turned out, had the character of "limnological hysteresis": the lake was retracing through other stages of the ecosystem transformation. Indeed, both in situ observations of limnologists together the results of satellite observations obtained by us indicate that the lake ecosystem is still under the influence of internal mechanisms of nutrients replenishment. With a gradually decreasing of Lake Ladoga primary productivity, a gradual decrease in CDOM is observed with numerically similar annual-average tendency. The latter arguably indicates that the CDOM lysis process has not yet stopped. It can be assumed that in its absence, the rate of return of the lake to a truly oligotrophic status could be higher. Our data indicate that the climatic impact on the functioning of the interrelated biotic processes in Lake Ladoga is particularly manifested in the expansion of the time frame of biological activity at the level of primary productivity. Together with the reduction in the ice cover of Ladoga and warmer thermal conditions in the period of early spring, the onset of phytoplankton growth starts earlier in March. Climate warming also affects the timing of the vegetation season termination: at the monthly average water temperature of ~7.5 C, the monthly average CHL in October in recent years often turned out to be about 3 μg/L, and in 2020 it reached a record value of ~4.8 μg/L. Given the decreased anthropogenic influence on Lake Ladoga and a steady pace of climate warming, the environmental processes in Ladoga will eventually be determining factors in the formation and functioning of the lacustrine biocenoses. It might imply a fundamental impossibility of the lacustrine ecosystem to return to its initial "pristine"/prior-to-eutrophication state.

Arctic ocean hydrobiochemistry: calcification-related issues

Anastasia Frolova, NIERSC, St. Petersburg, Russia
Prof. Dmitry Pozdnyakov, NIERSC, St. Petersburg, Russia
Prof. Ola M. Johannessen, NERSC, Bergen, Norway
Dr. Evgeny Morozov, MHI, Sevastopol/NIERSC, St. Petersburg, Russia

The anthropogenically caused increase in the content of carbon dioxide, CO_2, in the atmosphere predominantly determines the observed global warming, and also causes an increase in the process of acidification of the surface waters of the ocean, which in turn triggers the process of transformation of the biotic system in the ocean along the chain of biogeochemical reactions. Calcifying microalgae participate in such reactions. The most widespread and effective algal calcifier is Emiliania huxleyi. This calls for a surveillance of E. huxleyi spatial and temporal dynamics. Our previous studies have shown that E. huxleyi blooms are most extensive and intense in Barents, Norwegian, and Greenland seas the as compared to other areas in the North Atlantic and Arctic. This intensified our examination of the contemporary features in the dynamics of the E. huxleyi blooming phenomenon. Based on satellite data, E. huxleyi

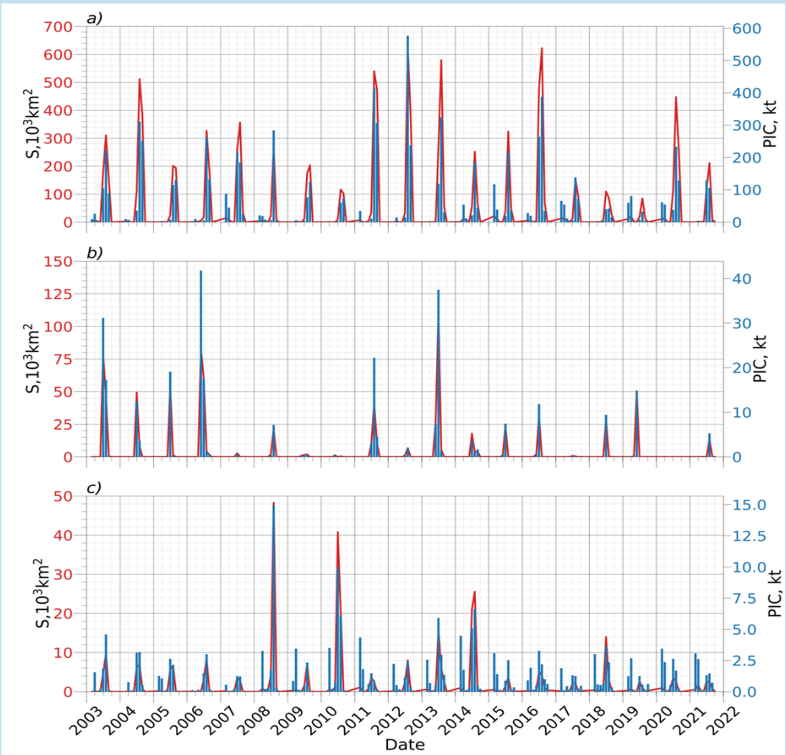

Figure 7. Interannual dynamics of E. huxleyi outbursts, respective bloom surfaces (defined with our spectral algorithm) and within-bloom inorganic carbon contents (designated in blue and red, respectively) as retrieved from space across the target seas over 2003–2021: (a) Barents Sea, (b) Norwegian Sea, and (c) Greenland Sea.

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***Relevant publication:** Frolova, A., Pozdnyakov, D., Johannessen, O., Morozov, E. A satellite study of the E. huxleyi phenomenon in the Barents, Norwegian, and Greenland seas in 2003-2021: Temporal dynamics of the bloom areal extent, inorganic carbon production and CO_2 partial pressure in surface water. Theoretical and Applied Hydrophysics (under review).*

bloom contouring, quantification of particulate inorganic carbon (PIC) production and increment of CO_2 partial pressure, (pCO_2) in surface water were performed. 18-year (2003-20210) time series of these variables are obtained for the above seas (Fig. 7). The bloom areas in the North Atlantic–Arctic water are the lowest in the Greenland Sea varying from 10·103 km^2 to (20–40)·103 km^2. In the Norwegian and Barents seas they reach in some years (60-80)·103 km^2 and (500-600)·103 km^2, respectively. The total PIC content within E. huxleyi blooms rarely exceeds in the Greenland and Norwegian seas 12-14 kilotons and 40 kilotons, respectively. In the Barents Sea, in some years, it can be up to 550 kilotons. The highest increase of pCO_2 within E. huxleyi blooms in surface waters in the Barents Sea was ~350 μatm. In the Norwegian Sea, pCO_2 in surface waters within the E. huxleyi bloom was also close to 350 μatm, but most often it remained about 250 μatm. In the Greenland Sea, there were only four years of relatively enhanced pCO_2 (up to 250 μatm), otherwise remaining below the level of confident determination by our method. As E. huxleyi blooms are generally very extensive, occur throughout the entire World Oceans (and hence in sum occur all year around), this phenomenon has a potential to both decrease to some degree the role of the World Oceans as sinkers of atmospheric CO_2, and affect the carbonate counter pump.

Summing up, although varying between the target seas, the influence of E. huxleyi blooms on the hydrochemistry was nevertheless obviously significant in terms of enriching the marine surface water with both suspended carbon and dissolved carbon dioxide. Given that E. huxleyi blooms are generally very extensive, occur throughout the World Oceans in both Hemispheres (and hence all year around), this phenomenon has a potential to both decrease the role of the World Oceans as sinkers of atmospheric CO_2, and affect the carbonate counter pump.

Primary production dynamics in the Arctic over the last nearly two decades

Dr. Evgeny Morozov, MHI, Sevastopol/NIERSC, St. Petersburg, Russia
Anastasia Frolova, NIERSC, St. Petersburg, Russia
Prof. Dmitry Pozdnyakov, NIERSC, St. Petersburg, Russia
Lasse Pettersson, NERSC, Bergen, Norway
Prof. Ola M. Johannessen, NERSC, Bergen, Norway

The ongoing climate warming in the Arctic is accompanied by a host of consequences of both physical and biological nature. Owing to alterations in air–sea CO_2 exchanges and the ensuing ocean acidification, and in combination with warming-driven physical forcings, the biological implications encompass inter alia changes in nutrient availability and algal cell metabolism rates, and enhancement of primary productivity in the water column. Monthly spaceborne data were used to investigate changes in primary production (PP) by phytoplankton in the Arctic Ocean (AO) from 2003 to 2021. In conformity with our previous assessments of PP dynamics in this part of the World Ocean (Petrenko et al., 2013), PP shows a steady growth in both pelagic and coastal waters (Fig. 8). Over the above 18-year period, PP (TgCyr-1) in the entire AO grew from ~1310 to ~1600, in its pelagic/deep and coastal/marginal zones, respectively, ~800 to ~1000, and ~480 to ~600. Considered individually, the Baffin, Barents, Greenland, Kara and Laptev seas also exhibited appreciable increase in PP, although in three other seas, the level of annual PP either remained more or less invariable (the Beaufort and East Siberian seas), or even had a tendency to decline (the Chukchi Sea). It is noteworthy that since 2010 the PP tendencies have proved a rather different pattern: both in the Beaufort and East Siberian seas, PP trend has rather flattened, whereas in the Chukchi Sea it switched to an appreciable decline.

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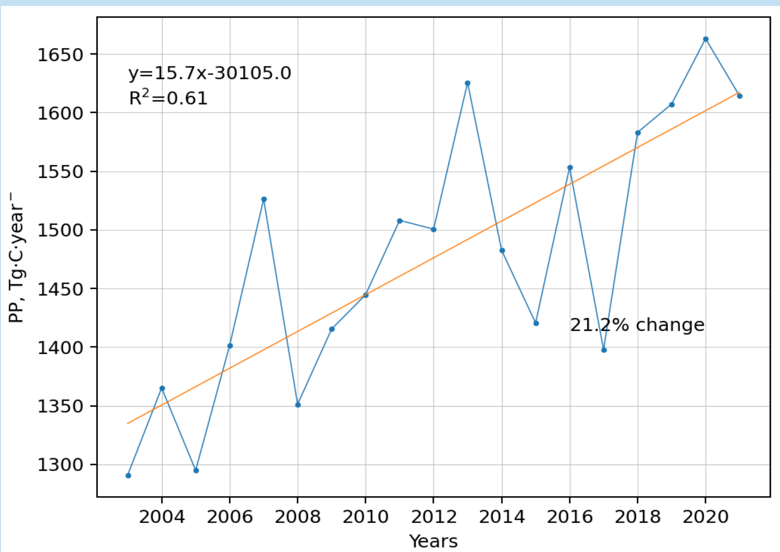

Figure 8. *Dynamics of PP in the entire (pelagic+ coastal) waters of the Arctic Ocean through 2003-2020 as retrieved from space.*

Our spaceborne estimations are expressly indicative of a steady decrease in ice cover in the AO since 2003 onward. Our quantitative spaceborne assessments show that the summer minimum ice cover changed through the 1980-2021 decreased from ca. 4.5·1016 km2 to ca 2.9·1016 km^2. This is in all evidence is the principal driver of intensification (by over 21%) of the Arctic Ocean primary production (Fig. 8), although some other factors are of consequence, such as decrease of the ice-free period, enhancement of wind-driven vertical mixing in upper ocean layers that drives rising the provision of nutrients from below, strengthening of vertical stratification, etc. This investigation will be further employed to project the PP dynamics in the AO making use of the CMIP6 climatic models: most successful models will be chosen through their closest conformity with the PP dynamics within 1980-2014, and based on this result, predictions of PP levels at the end of the current century will be performed.

Applied Meteorological and Oceanographic Research

Optimized Neural Network based method of automated iceberg and ship identification on radar images

Dr. Vladimir Volkov, NIERSC, St. Petersburg, Russia
Anton Volkov, NIERSC, St. Petersburg, Russia
Dr. Denis Demchev, Arctic and Antarctic Research Institute (AARI)/NIERSC, St. Petersburg, Russia

Arctic icebergs pose a threat to ships, offshore oil/gas platforms and other industrial facilities. To identify icebergs in polar night conditions and the presence of clouds, it is advisable to use satellite radar images as initial data, on which icebergs are displayed as bright points or areas. However, ships and other man-made objects are displayed in a similar way on the same type images. An automated combined algorithm for the identification and monitoring of icebergs in the open water based on Synthetic Aperture Radar (SAR) images using a Convolutional Neural Network (CNN) was proposed in 2021 by the Group of Applied Meteorological and Oceanographic Research (Fig. 9), including the function of dividing the "bright" objects highlighted in radar images into "iceberg" and "ship" classes.

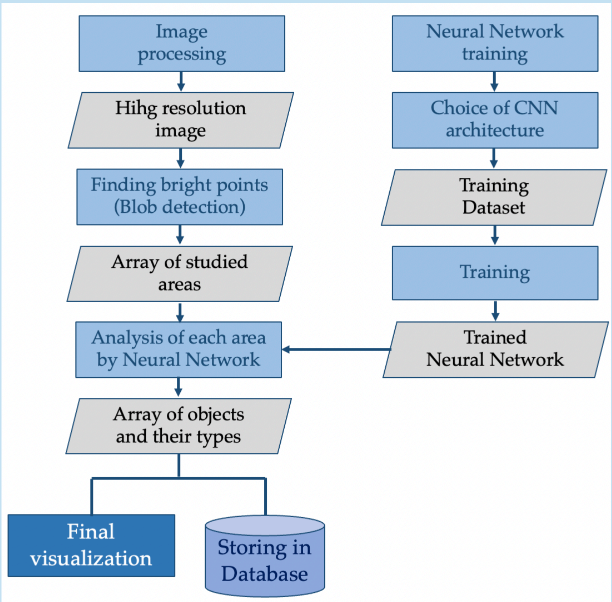

Figure 9. General scheme of iceberg detection algorithm.

The processing algorithm includes three main steps: (1) training CNN based on ground data; (2) preliminary image segmentation to detect areas containing potential signs of icebergs and ships; and (3) CNN prediction for iceberg / ship classification. The high efficiency of the proposed algorithm is shown in terms of object detection accuracy (~ 0.89%) and computational costs (time~ 8 seconds on NVIDIA GTX 1060 GPU for 7 Megapixel image).

For algorithm tuning and testing the Baffin Bay has been chosen characterized by the permanent presence of quite a lot of icebergs as well as fishing and merchant ships. This choice was also determined by the availability of SAR image from the Sentinel-1A satellite for this region (https://www.polarview.aq/arctic) with the high spatial resolution of 15 m and the Neural Network training and validation data on the actual distribution of ships and icebergs. Example of detection of iceberg and ship by means of proposed algorithm is shown in Fig. 10.

Relevant publication:
Volkov, V.A., Volkov, A.S., Demchev, D.M. (2021). Program for identification of icebergs and ships on the radar images using Neural Network. Certificate of the State Registration of the computer program No 2021662722.

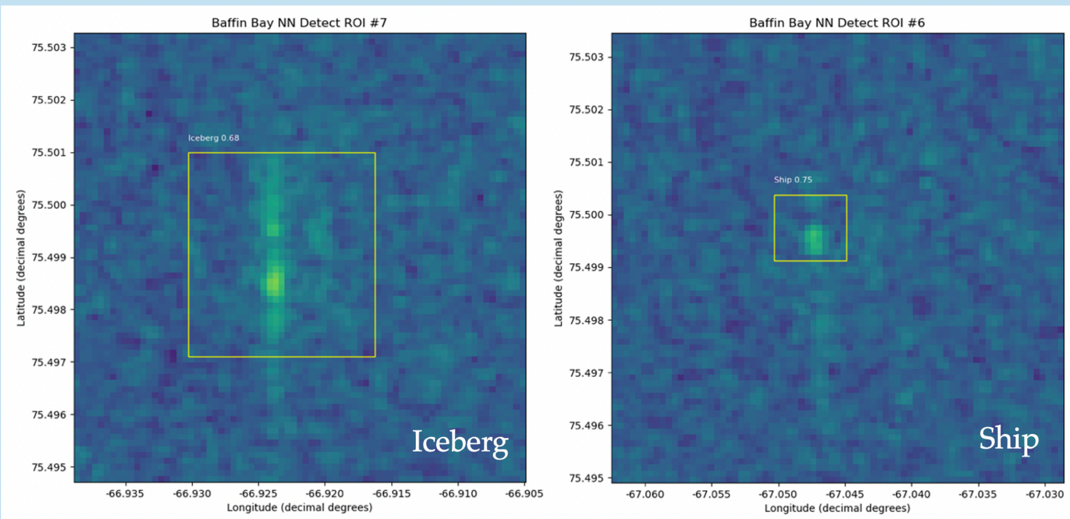

Figure 10. Example of detection of icebergs and ships on the radar image.

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International family of the Nansen institutions

Nansen Environmental and Remote Sensing Center

Thormøhlens gate 47
N-5006 Bergen
NORWAY
Phone: +47 55205800
Fax: +47 55205801

Svalbard research park
N-9171 Longyearbyen,
Svalbard
Phone: +47 79026447

e-mail: post@nersc.no http://www.nersc.no

GCRIEBER Climate Research Institute

Nansen International Environmental and Remote Sensing Centre
14th. Line V.O. 7A, office 34-35
199034 Saint Petersburg, RUSSIA
Phone: +7 812 324 5103/01
Fax: +7 812 324 5102
E-mail: adm@niersc.spb.ru
http://www.niersc.spb.ru

Nansen Environmental Research Centre - India
6A, Oxford Business Centre, Sreekandath Road
Kochi 682016 Kerala - INDIA
Phone: +91 484 2383351
Fax: +91 484 2353124
E-mail: nerci@ipath.net.in
http://www.nerci.in

Nansen-Zhu International Research Centre
c/o Institute of Atmospheric Physics,
Chinese Academy of Sciences,
PO Box 9804, Beijing 100029, CHINA
Phone: +86-10-62063256
E-mail: nzc@mail.iap.ac.cn
http://nzc.iap.ac.cn

Nansen-Tutu Centre for Marine Environmental Research
c/o Marine Research Institute
University of Cape Town
Rodebosh 7701 - SOUTH AFRICA
Phone: + 27 21 650 3281
E-mail: bjorn.backeberg@uct.ac.za
http://ma-re.uct.ac.za/nansen-tutu-centre/

Nansen International Centre for Coastal, Ocean and Climate Studies
c/o Bangladesh Centre for Advanced Studie (BCAS)
House 10, Road 16A
Gulshan-1, Dhaka- 1212, BANGLADESH
Phone: +8801730019213
E-mail: atiq.rahman@bcas.net

Nansen Scientific Society
c/o NERSC
Kong Christian Fredriks Plass 6
5006 Bergen, NORWAY
Phone: +47 901 35 336
E-mail:
ola.johannessen@nansenscientificsociety.no
http://www.nansenscientificsociety.no

Address/Links:

Scientific Foundation "Nansen International Environmental and Remote Sensing Centre"

14th Line 7, Vasilievsky Island	Phone: +7 (812) 324 51 01	E-mail: adm@niersc.spb.ru
199034 St. Petersburg, RUSSIA	Fax: +7 (812) 324 51 02	http://www.niersc.spb.ru