Annual Report 2018

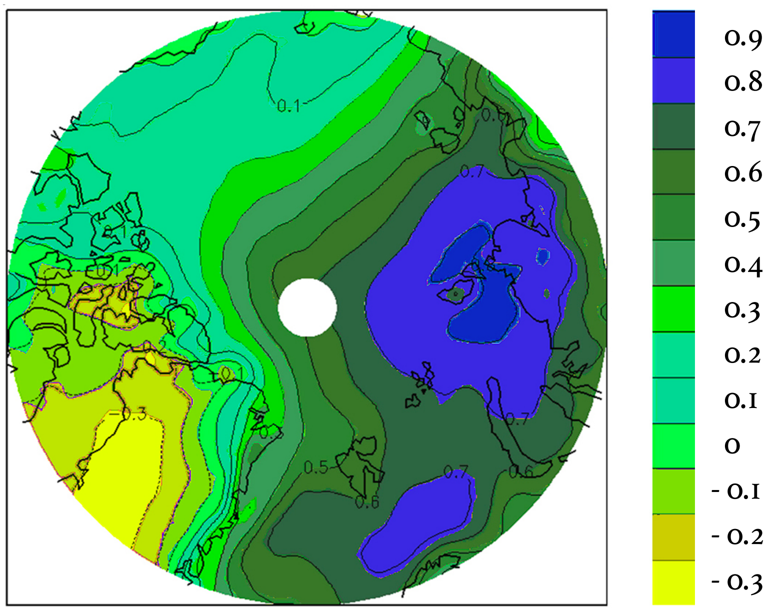
Nansen International Environmental and Remote Sensing Centre

St. Petersburg, Russia

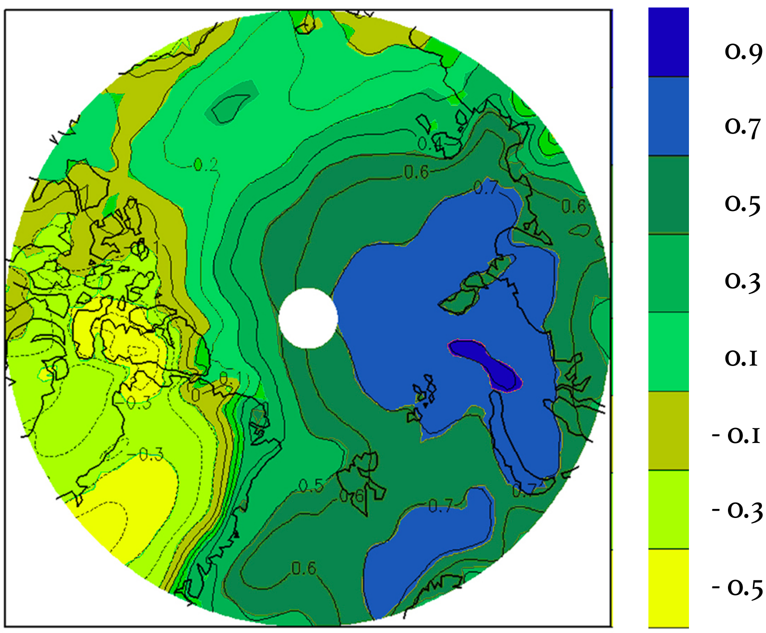
Non-profit international centre for environmental and climate research

Founded in 1992

Sensitive heat flux - temperature correlation



Latent heat flux – temperature correlation



Atmospheric heat transport through Atlantic Gate amplifies winter Arctic warming

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Cover page: *Correlation between winter meridional atmospheric transport of sensible and latent heat through the Atlantic "gate" (70°N, 0-80°E) and surface air temperature in the Arctic over the period 1980–2015 (Alekseev G, Kuzmina S, Bobylev L, Urazgildeeva A, Gnatiuk N. Impact of atmospheric heat and moisture transport on the Arctic warming. Int J Climatol., 2019, 1-11, https://doi.org/10.1002/joc.6040)*

Report from the General Meeting of Founders

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.

Major Research Areas

- Climate Variability and Change in High Northern Latitudes
- Aquatic Ecosystems in Response to Global Change
- Applied Meteorological and Oceanographic Research for Industrial Activities

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 a license from Roscosmos for conducting space-related research activities.

Staff

At the end of 2018 NIERSC staff incorporated 32 employees comprising core scientists, including one full Doctor of Science and 8 PhDs, part-time researchers, and administrative personnel. Three PhD-students and two Master students were supervised and supported financially by the Nansen Fellowship Programme, all holding also part-time positions of Junior Researchers at NIERSC.

Production

In 2018, totally 40 publications were published, including 16 papers in peer reviewed journals, 6 papers in other journals and 18 conference proceedings (see reference list at the end of the report).

National and International Activities

NIERSC has a long-lasting cooperation with Russian organisations such as St. Petersburg State University, institutions of the Russian Academy of Sciences, Federal Space Agency, Federal Service for Hydrometeorology and Environmental Monitoring including the Northern Water Problems Institute, Scientific Research Centre for Ecological Safety, Arctic and Antarctic Research Institute, Russian State Hydrometeorological University, Voeikov Main Geophysical Observatory, Murmansk Marine Biological Institute, and other, totally about 40 institutions.

Fruitful relations are established also with 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, and especially with the NIERSC founders. Close cooperation is established with the Nansen Centre in Bergen. Most of scientific results described below are achieved within the joint research activities of both Nansen Centres, in St. Petersburg and Bergen, and cooperating partners.

Nansen Fellowship Programme

The main goal of the Nansen Fellowship Program (NFP) at NIERSC is to support PhD-students at Russian educational and research institutions, including Russian State Hydrometeorological University, St. Petersburg State University, Arctic and Antarctic Research Institute, and others. The research areas include climate and environmental change and methods and techniques of satellite remote sensing with focus on the Arctic and Sub-Arctic, based on integrated use of *in situ* and satellite observation data and numerical modelling. NFP provides PhD-students with Russian and international scientific supervision, financial fellowship, efficient working conditions at NIERSC, training and research visits to international research centres within the Nansen institutions network and beyond, involvement into international research projects. NFP is sponsored by the 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.

Lyudmila Lebedeva, the participant of the Nansen Fellowship Programme, has successfully defended her Thesis "Formation of river flow in the permafrost zone of Eastern Siberia" on 30 November 2018 at the Institute of Geography of RAS in Moscow.

Thus, 29 young Russian PhD-students have got their doctoral degrees under the NFP since 1994.

Main Research Projects

[Integrated Arctic observation system (INTAROS)] is the EU H2020 project carried out by a consortium comprising 47 partners (https://intaros.nersc.no). NIERSC participates in this project under the INTAROS-Russia sub-project funded by the Russian Ministry of Science and Higher Education. The other partners of the INTAROS-Russia sub-project are: Russian Research Institute for Hydro-Meteorological Information, Obninsk, and Arctic and Antarctic Research Institute, St. Petersburg.

The overall objective of INTAROS is to develop an integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems in the different regions of the Arctic. INTAROS has a strong multidisciplinary focus, with tools for integration of data from atmosphere, ocean, cryosphere and terrestrial sciences, provided by institutions in Europe, North America and Asia.

[Impacts of climate change and climate extremes on the agriculture and forestry in the Europe-Russia-Turkey Region (AFTER)] is the interdisciplinary project under the ERA.Net RUS Plus programme and involves research groups from Russia, Germany, Belgium, Latvia and Turkey (https://www.projectafter.net/).

AFTER aims at bridging the usability gap between state-of-the-art regional climate information and the demand for information at regional scale for climate change impact assessment and adaptation. The main objective of AFTER is to provide state-of-the-art climate information to assess: (i) impact of ongoing and projected global climate change and subsequent changes in climate extremes on the agriculture and forestry in selected regions of Europe, Russia and Turkey; and (ii) the level of contribution, which these changes in agriculture and forestry can provide to climate change mitigation and adaptation due to existing feedbacks.

Project partners: Nansen International Environmental and Remote Sensing Centre (St. Petersburg, Russia, coordinator); Ghent University (Gent, Belgium); Climate Service Centre Germany (Hamburg, Germany); Latvian Environment, Geology and Meteorology Centre (Riga, Latvia); Vlaamse Instelling voor Technologisch Onderzoek (Brussels, Belgium); Iskenderun Technical University (Iskenderun, Turkey).

AFTER project started with the kick-off meeting in Ghent in June 2018 (Photo 1) and will last until 2021.

Photo 1. *Members of the AFTER Project. Kick-off Meeting at Ghent University, Belgium, 28 June 2018.*

[Assessment of calcifying phytoplankton role in CO_2 dynamics in the atmosphere-ocean system at subpolar and polar latitudes] is project financed by the Russian Science Foundation (RSF). The objectives of the project are the following: (i) assess the dynamics of spatial extent and duration of blooms of *Emiliania huxleyi* (Fig. 1) as the major calcifying microalga in pelagic waters of the North, Norwegian, Labrador, Greenland, Barents and Bering seas; (ii) estimate intensity of inorganic carbon production; (iii) assess CO_2 partial pressure within blooms and in the atmospheric layer above them; and (iv) perform projections of this phenomenon till the mid of the present century.

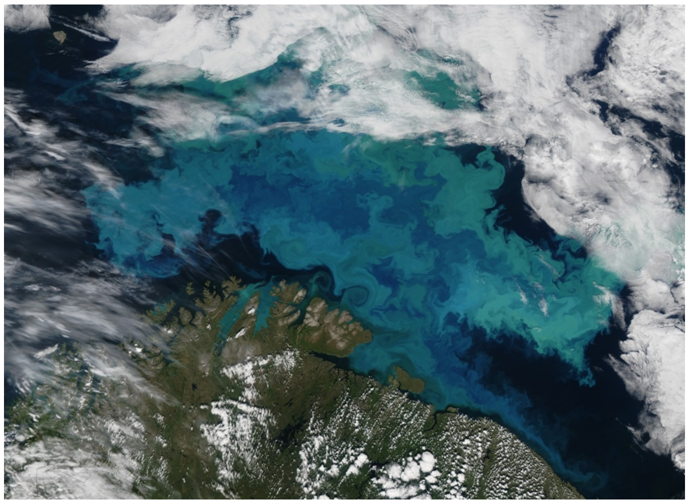

Figure 1. *MODIS Aqua image of E. huxleyi bloom, 14 August 2011 (from NASA website).*

[Dynamics of deep oceanic convection in subpolar and polar oceanic regions under the climate change, its relation to freshwater and heat fluxes and its effect on the Atlantic Meridional Overturning Circulation (AMOC)] is a joint project of NIERSC and St. Petersburg State University funded by RSF. The goal of the project is to assess interannual variability of intensity of deep convection in the Nordic and Labrador-Irminger seas as an element of the global climate system.

The first stage of the project implementation is devoted to deriving interannual variations of convection intensity in the Greenland, Labrador and Irminger seas. The second stage aims at revealing interannual variations of the freshwater and heat fluxes to the regions of deep convection. A link between the interannual variations of convection intensity and AMOC are investigated during the third stage of the project.

[Complex assessment of polar low impact on maritime activities in the Arctic Ocean under the ongoing climate changes] is the project also funded by RSF. Project goal is to estimate polar low (Fig. 2) frequency over the whole Arctic Ocean, construct their trajectories, obtain characteristics of polar lows, such as their size and life time, maximum wind speed and significant wave height, estimate spatial distribution of these characteristics and assess polar low related danger in specific regions of the Arctic Ocean, including identification of the most and the least vulnerable regions, and, finally, estimate the impact of polar lows on the decreasing Arctic sea ice extent.

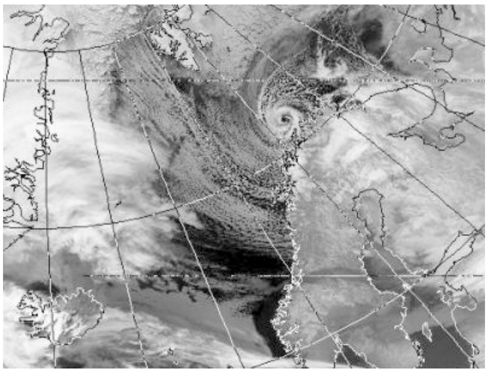

Figure 2. *Polar low forms off the coast of northern Norway, 14 December 2010.*

[Transferable Knowledge and Technologies for High-Resolution Environmental Impact Assessment and Management (TRAKT).] The main objective of the project is to implement a novel advanced technology for the high-resolution environmental impact assessment. This technology consists of three integrated modules: (i) citizen observations and data fusion; (ii) satellite remote sensing; (iii) high-resolution urban modelling. The technology has been successfully demonstrated in Bergen (Norway) and Helsinki (Finland) with different technical realizations of all three components and data sources. It assures flexibility and transferability of the approach.

Project partners are: Nansen Environmental and Remote Sensing Centre (NERSC), Bergen, Norway; University of Helsinki, Helsinki, Finland; Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia; Kola Science Centre of Russian Academy of Science (Apatity, Russia) and Scientific Research Centre for Ecological Safety, Russian Academy of Science, St. Petersburg, Russia.

[Sea Ice in the Arctic: Past, Present and Future (book)] is the project with financial support from the European Space Agency and the Nansen Scientific Society aimed at the writing in-depth book on the Arctic sea ice. This book provides information about sea ice in the Arctic from paleoenvironment variability to recent and present changes in past and current centuries and then to future projections of its transformation in the 21st century. The book is written by the group of authors affiliated mostly with the Nansen Centres in St. Petersburg and Bergen, as well as with some other universities and institutes. The editors are Prof. Ola M. Johannessen, Dr. Leonid P. Bobylev, Dr. Elena V. Shalina and Prof. Stein Sandven. The book will be printed by Springer in 2019.

[Arctic cooperation between Norway, Russia, India, China and US in satellite Earth observation and Education (ARCONOR)] is the project funded by the Research Council of Norway. Its overall objective is to sustain long-term international partnership and cooperation between Norway, Russia, India, China and US through advancing research, higher education and recruitment within satellite Earth observations for monitoring and forecasting the Arctic and support to Arctic shipping.

Specific objectives are: (i) to organize exchange visits, including guest lectures, for scientists, students and institution leadership among the partners; (ii) to develop, implement and host summer schools and scientific workshops including the project partners and external participation; (iii) develop and validate an interdisciplinary curriculum related to shipping in the Arctic, with focus on the Northern Sea Route; (iv) coordinate, plan and submit future research project proposals within and beyond ARCONOR participation.

ARCONOR partners are: NERSC, Norway; Nansen Scientific Society, Norway; Nansen International Environmental and Remote Sensing Centre, Russia; Nansen Environmental Research Centre, India; Nansen-Zhu International Research Centre, China; University of Connecticut, USA. Uliana Prokhorova, a PhD student at the Arctic and Antarctic Research Institute and NIERSC, gets fellowship from the ARCONOR project.

Five NIERSC staff members participated in the International Arctic Winter School "The Arctic Ocean: atmosphere, ice and ocean interactions – implications for future climate and human activities" held in the framework of ARCONOR project at the ESSO-National Centre for Polar and Ocean Research, Vasco da Gama, India, at the end of October-beginning of November 2018 (Photo 2).

Photo 2. *Participants of the International Arctic Winter School, Vasco da Gama, India, 29 October 2018.*

St. Petersburg, 26 March 2019

Nikolay N. Filatov, NIERSC President, KarRC RAS

Valentin Meleshko, NIERSC Co-President, VMGO

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Leonid P. Bobylev, Director

Scientific Report

Climate Variability and Change in High Northern Latitudes

Impact of Atmospheric Heat and Moisture Transport on the Arctic Warming

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Dr. Svetlana Kuzmina, Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia
Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia
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The effect of the meridional atmospheric heat and moisture transport on the Arctic warming is estimated using the ERA-Interim reanalysis over 1979-2015. Major influx of sensible and latent heat into the Arctic occurs through the Atlantic sector 0-80°E between the surface and the 750 hPa level. This influx explains more than 50% of the average temperature variability in the area 70-90°N in winter with almost equal contribution of both fluxes. Calculations using MPI-ESM-MR Earth System model from the CMIP5 ensemble showed the similar effect of the meridional atmospheric heat and moisture transport and its increase by the end of the century (Fig. 3). Mean summer transport in the low troposphere is directed from the Arctic and transfers out the moisture produced by summer melting of sea ice. The major drivers of summer warming are the radiation processes especially downward longwave radiation.

Acknowledgment: This study was supported by the Russian Foundation for Basic Research (RFBR) projects #18-05-00334 and #18-05-60107.

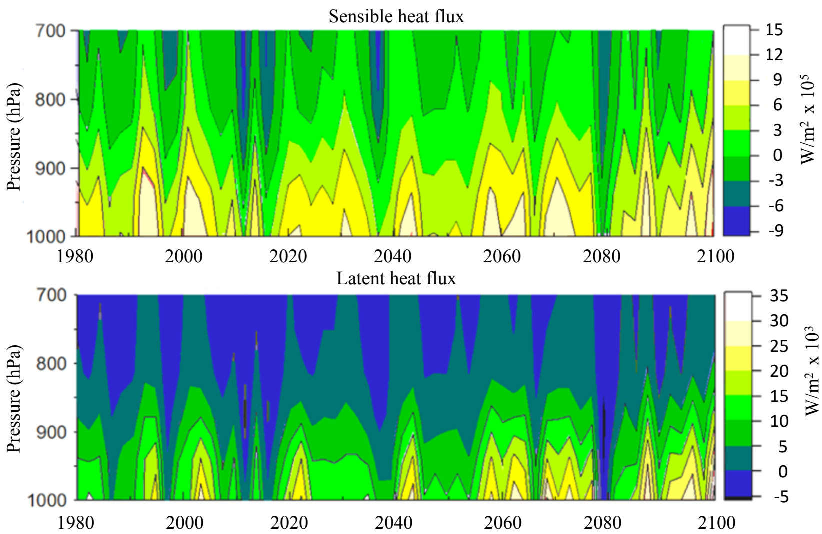

Figure 3. Modelled atmospheric transfer of sensible and latent heat through the "Atlantic Gate" at different isobaric levels under RCP8.5 scenario (MPI-ESM-MR Earth System model).

Relevant publication: Alekseev, G., Kuzmina, S., Bobylev, L., Urazgildeeva A., and Gnatiuk N. (2019). Impact of Atmospheric Heat and Moisture Transport on the Arctic Warming. International Journal of Climatology, https://doi.org/10.1002/joc.6040

Recent, present and future sea ice conditions in the Arctic shelf seas

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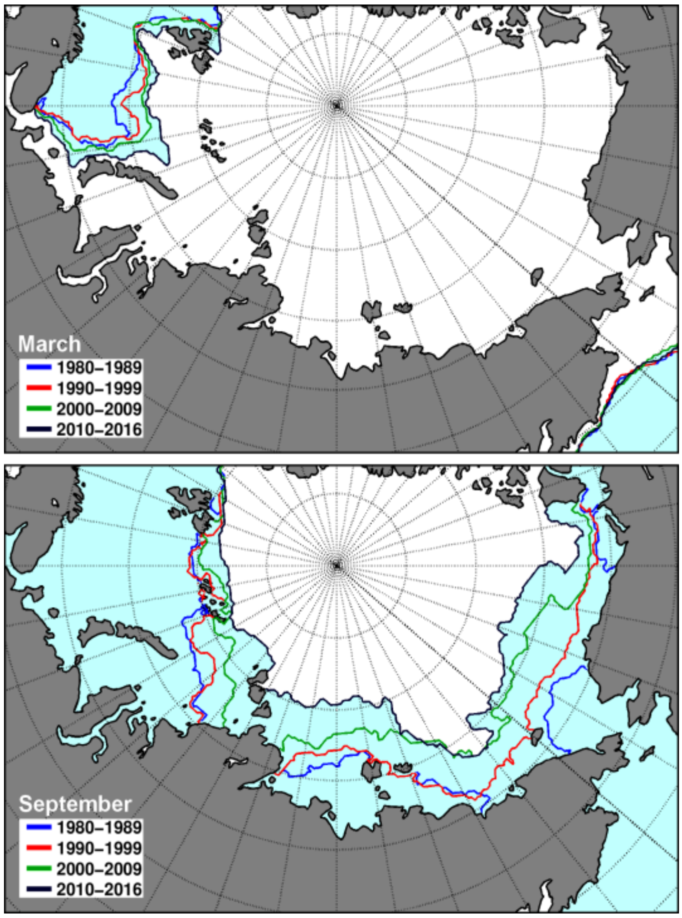

***Figure 4.** Sea ice edge location for winter (March) and summer (September) averaged over different time intervals. White and blue coloured areas indicate correspondingly sea ice cover and open water for the time interval 2010-2016.*

The ongoing sea ice cover transformation in six Arctic shelf seas, namely the Barents, Kara, Laptev, East-Siberian, Chukchi, and Beaufort seas, were analysed using satellite observations. Future sea ice conditions in these seas were assessed using CMIP5 climate model projections.

The retreat of sea ice is illustrated in Fig. 4, where average March and September sea ice edge locations are mapped for 2010-2016 and for the three preceding decades. In March, when sea ice extent is highest, the Arctic shelf seas are completely ice-covered. The sole exception is the Barents Sea, where changes in sea ice edge location in winter can be

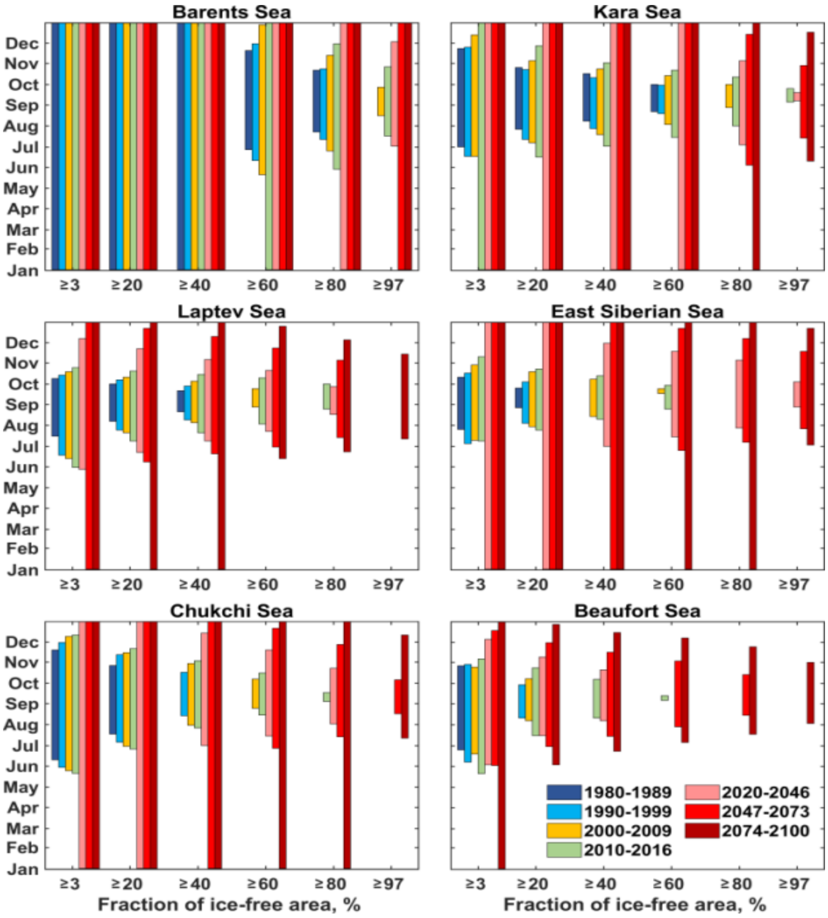

Figure 5. *Duration of periods when ice-free sea area exceeds given fractions of total sea area for different time intervals derived from satellite observations (1979-2016) and selected CMIP5 model sub-ensembles (2020-2100).*

clearly observed. In September, the location of the sea ice edge in all Arctic shelf seas gradually moves towards the pole. Overall, from 1980-1989 to 2010-2016 the sea ice edge shifted approximately 400 km poleward on average. The maximum poleward shift is observed in the Kara, Laptev, and Beaufort seas where it can be as large as 750 km.

Fig. 5 illustrates temporal changes in sea ice cover of the analysed shelf seas derived from satellite passive microwave data for 1980-2016 and from CMIP5 models for three equal periods representing short-term (2020-2046), mid-term (2047-2073), and long-term (2074-2100) perspectives. Since there is a significant difference in the capabilities of different climate models to reproduce observed sea ice extent, and climate model sea ice extent simulations exhibit large spread, out of the initial dataset of 66 model runs from 28 CMIP5 models those runs which best described past sea ice extent in the Arctic shelf seas were selected separately for each sea.

As follows from Fig. 5, the dramatic expansion of open water area is expected in all the Arctic shelf seas. In the Barents Sea at least 80% of the sea area is expected to be permanently ice-free already in the short-term perspective (currently such conditions last only from June to December). Model estimates indicate an even more rapid open water expansion in the Kara Sea with a permanent minimum of at least 60% open water, which was on average observed only from July to mid-October in 2010-2016. In the Laptev Sea models do not indicate such abrupt changes in sea ice coverage in the short-term perspective - for most ice-free fractions there is an increase in duration of about a month. For the East-Siberian and Chukchi seas models indicate that at least 20% of them will be ice-free year-round, while in 2010-2016 such ice-free fractions lasted in these seas from August to mid-October and from July to November, respectively. Periods when the total ice-free area accounts for at least 40% and 60% increase by 2-3 month for both seas. More than 80% of the East Siberian Sea is first expected to become ice-free in the short-term perspective and to last from August to November. Similarly, such conditions are expected to last from August to mid-October in the Chukchi Sea, where they were already very briefly observed in 2010-2016 (about 10 days per year on average). Only slight changes are indicated for the Beaufort Sea in the short-term perspective. In particular, ice-free fractions up to ≥40% increase by about 15-30 days. The very short period of fraction ≥60% observed in 2010-2016 for about 5 days on average does not appear in the short-term perspective, although in the mid-term perspective it becomes considerable and lasts from August to November.

Thermohaline convection in the subpolar seas of the North Atlantic

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Deep convection in the Greenland, Labrador and Irminger seas, being a part of the global ocean conveyor belt, is an important component of the Earth climate system. *In situ* investigations of its interannual variability are challenging due to a small size of the convective cells and variations of their locations within the basins from year to year.

For this study, we used ARMOR data set (1993-2016), which reproduces vertical profiles of density in a more robust way, combining *in situ* and satellite observations.

For refining the areas of possible development of deep convection, we computed frequency of the mixed layer depth (MLD) exceeding 1000 m (the upper limit of the Greenland deep water) during the 24 years of available

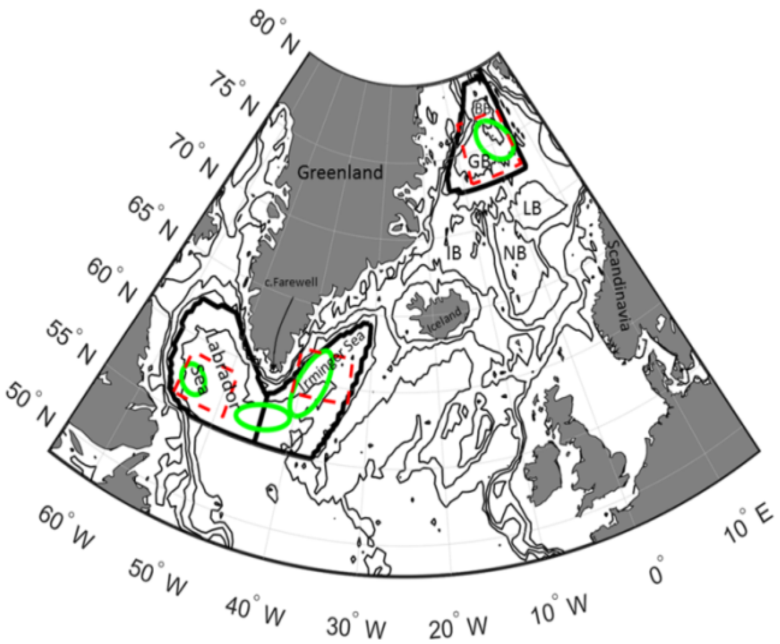

Figure 6. *Areas of a possible detection of convection over 1000 m (black borders), the most frequent detection of convection (green borders), and used for computation of convection indices (red borders).*

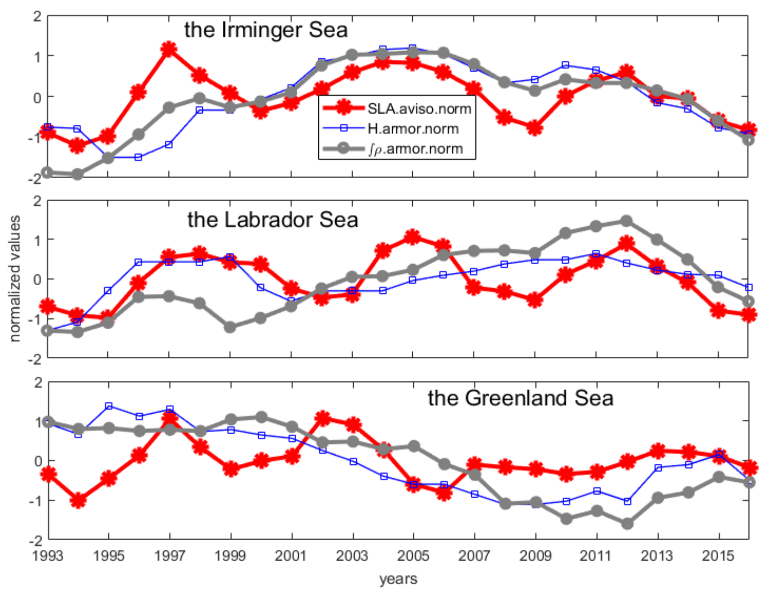

Figure 7. *Three-year sliding means of the normalized maximum mixed layer depth from ARMOR data-set (blue), iSLA convection index (red) and iRho convection index (grey, computed using ARMOR data-set).*

data. In the Labrador and the Irminger seas (Fig. 6), convection over 1000 m can develop in any point of a region, covering almost the entire water area of both seas. Within this region, three sub-regions of the most frequent development of the deep convection were detected. In addition to two traditionally allocated areas in each of the seas, the deep convection also often occurs at the junction of the two seas, south of Cape Farwell. In the region, convection typically reaches its maximum depth in March. In the Greenland Sea, deep convection occurs most often in the central and the south-eastern parts of the sea, as well as in the Boreas basin. Convection typically reaches its maximum depth in April.

Convection depths, derived from ARMOR, were used for testing the efficiency of two indices of the convection intensity: (1) sea-level anomalies from satellite altimetry (iSLA), and (2) the integral water density (iRho), estimated in the areas of the most frequent development of deep convection (Fig. 7). The first index captured some details of the interannual variability in deep convection intensity, however it showed low correlations with the maximum winter MLD (less than 0.5 for the 3-year sliding means). The second index showed high correlation (0.7-0.8) with the maximum winter MLD at all three seas.

Asynchronous variations in the deep convection intensity in the Labrador-Irminger seas and in the Greenland Sea were detected. In the Labrador and Irminger seas, the quasi-seven-year variations in the convection intensity were identified.

<u>Relevant publications:</u> (i) Bashmachnikov, I., Fedorov, A., Vesman, A., Belonenko, T., Koldunov, A., Dukhovskoy, D. (2018). The thermohaline convection in the subpolar seas of the North Atlantic from satellite and in situ observations. Part 1: localization of the deep convection sites. Current problems in remote sensing of the Earth from space (in Russian);

(ii) Bashmachnikov, I., Fedorov, A., Vesman, A., Belonenko, T., Dukhovskoy D. (2019). The thermohaline convection in the subpolar seas of the North Atlantic from satellite and in situ observations. Part 2: indices of intensity of deep convection. Current problems in remote sensing of the Earth from space (accepted, in Russian).

AQUATIC ECOSYSTEMS IN RESPONSE TO GLOBAL CHANGE

Major forsings determining *E. huxleyi* blooms. I. Vector factors

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Svetlana Chepikova, Master student, SPbSU/NIERSC, St. Petersburg, Russia

This study is a follow up of a largely spaceborne comprehensive multi-year (nearly two decadal) research conducted at NIERSC under the three-year project supported by the Russian Science Foundation. At the first stages of the project implementation we investigated the intra- and interannual (1998-2018) spatio-temporal variations in intensity and areal extent/localization of *E. huxleyi* blooms in Sub-Arctic and Arctic seas (viz. North, Norwegian, Greenland, Labrador, Barents, and Bering seas) and total inorganic carbon content within the bloom area, as well as the impact of this alga blooms on both CO_2 partial pressure in the target marine surface waters and CO_2 atmospheric columnar content within the bloom area.

Importantly, the aforementioned spatio-temporal variations inherent in *E. huxleyi* blooms proved to be specific to concrete marine environments. This implies that *E. huxleyi* growth is generally conditioned by multiple factors acting through forward and feedback mechanisms. In order to interpret/comprehend the established variations, further on we passed to revealing and prioritization of the specific factors that condition/control the development of *E. huxleyi* blooms in the target seas.

In 2018, this work was confined to exclusively remotely retrievable vector factors, such as sea surface temperature and salinity (SST & SSS), current speed (CS), Ekman layer depth (ELD), derivable from above water surface wind speed (WS), photosynthetic available radiation (PAR), and phytoplankton chlorophyll (CHL). The analyses were conducted with the application of the multi-dimensional statistical approach, namely Random Forest Classifier, whose realization is available in the scikit-learn library for Python.

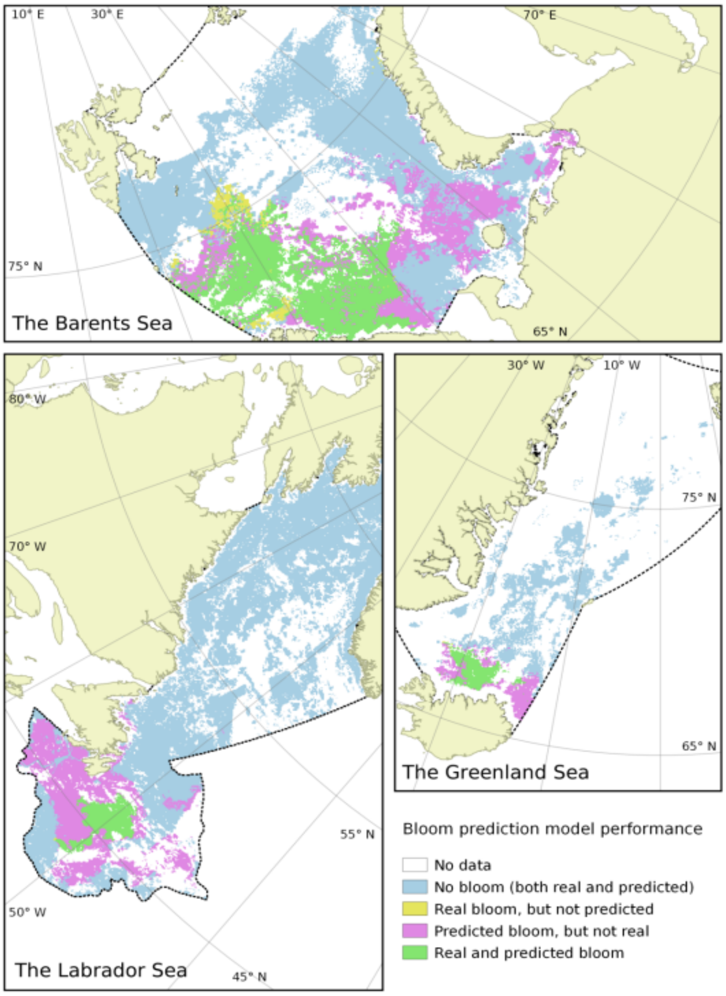

Figure 8. *A cartographic visualization of predictive model quality for the Barents, Greenland and Labrador seas.*

It was shown that the set of vector factors conditioning either the bloom formation or its absence in each of the target seas might be marine environment specific.

Thus, in the case of the Greenland and Labrador seas, it was SST that played the leading role, whereas in the Barents Sea SST was paired with PAR. In the North Sea, in addition to SST, CS proved to be the first runner up. In the North Sea, in addition to SST, some sensible influence is exerted by CS (up to 20%).

However, the preservation of factor prioritization order with the time period extension did not hold on in all target seas. Thus, in the case of the Norwegian Sea ELD was the leading factor during 2010-2016, but with the time period extension, the role of ELD dropped down and SST and PAR became the most important. In the case of the Bering Sea it was CS that prevailed with the time period extension. Possibly, such a rearrangement of forcing factor prioritization order was driven by some specific environmental conditions that occurred during 1998-2001 when there were outbursts of anomalously huge *E. huxleyi* blooms.

The assessment of accuracy of bloom localization predicted by a forecasting model can be performed through cartographic visualizations that illustrate the misfit of modelled and real-life/actually observed blooms. Such cards for some cases in the Barents, Greenland and Labrador seas are shown in Fig. 8. All cards revealed one and the same feature: the percentage of predicted blooms was very high, and there were practically no marine areas within which the actual bloom has not been predicted by the model. This result explicitly testifies to the correctness of the identified bloom driving factors, and the adequacy of the developed models, and their usefulness for prioritization of factors importance can't be questioned.

Acknowledgment: *this study was conducted under the Russian Science Foundation support (project No. 1717-01117).*

Relevant publication: *Kondrik, D., Kazakov, E., Chepikova, S., Pozdnyakov, D. Prioritization of physical factors controlling Emiliania huxleyi blooms in subarctic and arctic seas: A multidimensional statistical approach. Biogeosciences (submitted).*

Atmospheric columnar CO_2 enhancement over *E. huxleyi* blooms: Case studies in the North Atlantic and Arctic waters

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Among marine biosystems, a coccolithophore *E. huxleyi* (class Prymnesiophycea) is the most productive calcite producing organisms in the world's oceans. In addition to the production of particulate calcite, *E. huxleyi* blooms are capable of increasing the dissolved CO_2 partial pressure within their blooming areas. The aforementioned *E. huxleyi* bloom-driven enhancement of dissolved CO_2 partial pressure can reduce, nullify or even reverse the flux of CO_2 at the atmosphere-ocean interface.

We conducted several case studies in the North, Greenland and Barents seas in order quantify the atmospheric columnar XCO_2 over *E. huxleyi* blooms based on remote sensing data from the Orbiting Carbon Observatory OCO-2. The identified situations were further analysed as case studies in order to investigate on a quantitative base if there was any impact of *E. huxleyi* bloom areas on XCO_2 (i.e. ΔXCO_2) registered by OCO-2. Thus, to assess ΔXCO_2, XCO_2 values registered along the OCO-2 footprint both over the bloom area and beyond it (either prior to reaching the bloom area or after leaving it) were compared. The resultant change in XCO_2, i.e. ΔXCO_2, was considered as a measure of the *E. huxleyi* bloom impact on the CO_2 exchange at the atmosphere-sea water interface, and hence, of the change in the CO_2 atmospheric columnar content.

All case studies also included the analysis of above water surface wind force and direction over the bloom area in order to clarify the issue of air mass advection across the satellite footprint trajectory.

The results of eight satellite-based case studies from the Barents, Greenland and North seas are illustrated in Fig. 9. Note that the red lines show the limits of the beyond-bloom areas used in this study for assessing ΔXCO_2; black arrows illustrate the force and direction of wind over the bloom area; black areas are *E. huxleyi* blooms. As seen, in 5 cases out of 8 (Fig. 9a-e) OCO-2 registered an increment of XCO_2 over *E. huxleyi* bloom areas ranging between 0.6 and 3.0 ppm. These numbers are fully consistent with the results obtained by us in our study of *E. huxleyi* -induced XCO_2 in the Black Sea as registered in 2016-2017.

However, in three cases (Fig. 9f-h) relating to the South Greenland and North seas, no XCO_2 enhancement was found. A combined OCO-2 and wind data analysis has

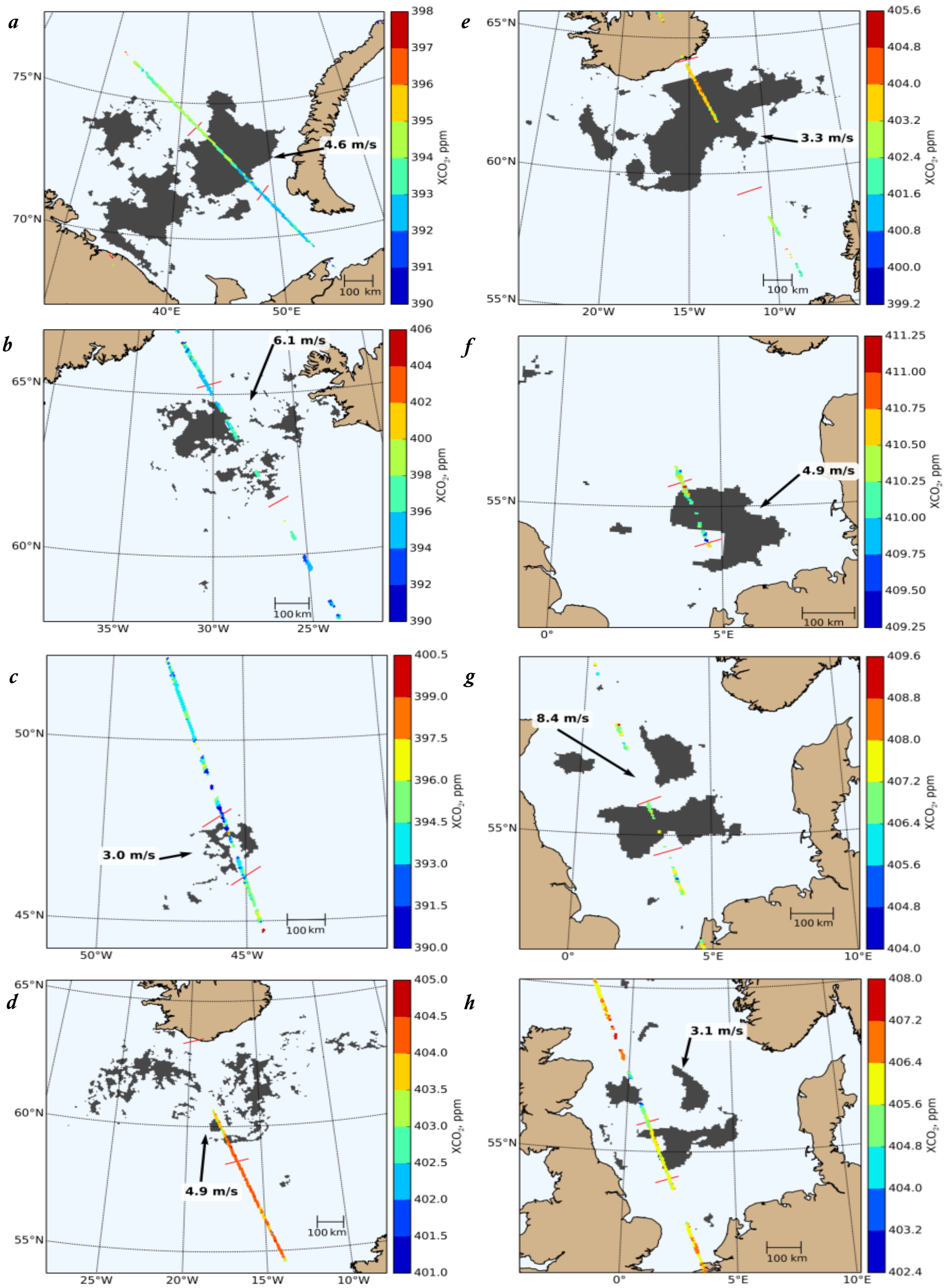

Figure 9. *OCO-2 footprint trajectory and along track XCO_2 (ppm) values in the Barents (a), South Iceland (b, d, e), South Greenland (c), and North (f-h) seas as detected with the OCO-2 instrument in the time period 2015-2018.*

shown that the explication of apparent absence of *E. huxleyi* blooming upon XCO_2 might reside in the effect of above water air mass advection. Indeed, in these cases the meteorological and *E. huxleyi* blooming conditions were specific: the wind blew from the bloom-void area thus advecting the air masses with CO_2 background values.

Besides, in the case shown in Fig. 9f, the blooming area was essentially inhomogenous/fractionized, and the wind direction was southern, i.e. bringing airmasses from the parts of the sea free of any *E. huxleyi* bloom influence.

Thus, the eight case studies conducted with the employment of OCO-2 satellite data have shown that the impact of *E. huxleyi* blooming phenomenon on the atmospheric CO_2 partial pressure over the North, Greenland, and Barents seas proved to be appreciable and of the same order of magnitude as over the Black Sea (0.6-3 ppm). It is also shown that the magnitude of CO_2 enhancement in the atmospheric column is significantly controlled by the air advection in the boundary layer. Arguably, this might be an indication of some inherent property of *E. huxleyi*, and the obtained results on the increment of CO_2 in the atmospheric column over the blooms of this alga can be considered as representative of this phenomenon across the oceanic tracts, at least, in the Northern Hemisphere.

Acknowledgment: this study was conducted under the Russian Science Foundation support (project No. 1717-01117).

Relevant publication: Morozov, E., Kondrik, D., Chepikova, S., Pozdnyakov, D. Atmospheric columnar CO_2 enhancement over E. huxleyi blooms: Case studies in the North Atlantic and Arctic waters. Limnology and Oceanography (submitted).

Bering Sea: A possible explanation to extraordinary bloom outburst of *E. huxleyi* in the late 1990s - early 2000s

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Emiliania huxleyi is a photosynthetic and calcifying primary producer of organic and inorganic carbon in the world oceans, and as such it enriches ambient ocean surface water with both particulate calcite and dissolved carbon dioxide. This property is relevant to marine biogeochemistry and climatology. *E. huxleyi* blooms occur throughout the oceans in both hemispheres, they tend to gradually propagate in the poleward direction, and are generally very extensive. Altogether, these features impart to this phenomenon a pan-planetary significance, and call for special attention in light of the presently accelerating changes in climate and marine ecology.

Obtained throughout two previous decades, the spaceborne data are strongly indicative that the intensity of *E. huxleyi* blooms in the marine tracts at temperate, subpolar and polar latitudes of the northern hemisphere exhibited very substantial interannual variations whose nature is frequently either unknown or conjectural.

The aforementioned interannual variability stems from the susceptibility of *E. huxleyi* blooms to be controlled by a wealth of external and internal factors that may act both directly and through a sophisticated system of feedback mechanisms. This strongly suggests that the patterns of *E. huxleyi* blooms variations in space and time should be marine environment specific. In particular, the blooms of this alga exhibited a very specific pattern in the Bering Sea. In the temporal pattern of blooms there was a period between 1996-1997 and 2001 marked by very intense blooming. However, starting right after 2001, the blooming intensity has undergone a steep drop in both the number of occurrences and spatial extent of this phenomenon.

We developed our tentative explanation of the phenomenon. Our hypothesis relies on both the salient transport anomalies of the Bering Sea Slope Current, the Alaskan Stream, and the Near Strait (Fig. 10) throughflow

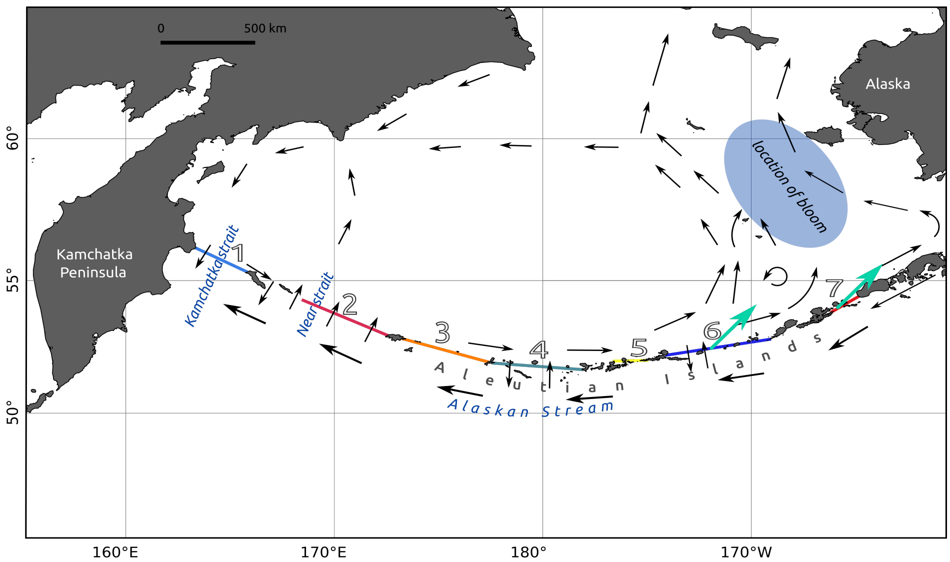

Figure 10. *Locations of selected gates (1-7) to the Bering Sea, and a schematic presentation of the Bering Sea surface circulation (adopted from Panteleev et al., 2012). The blue ellipse indicates the typical location of E. huxleyi blooms. The green arrows are the most frequent current directions at gates 6 and 7 during the period of E. huxleyi outbursts.*

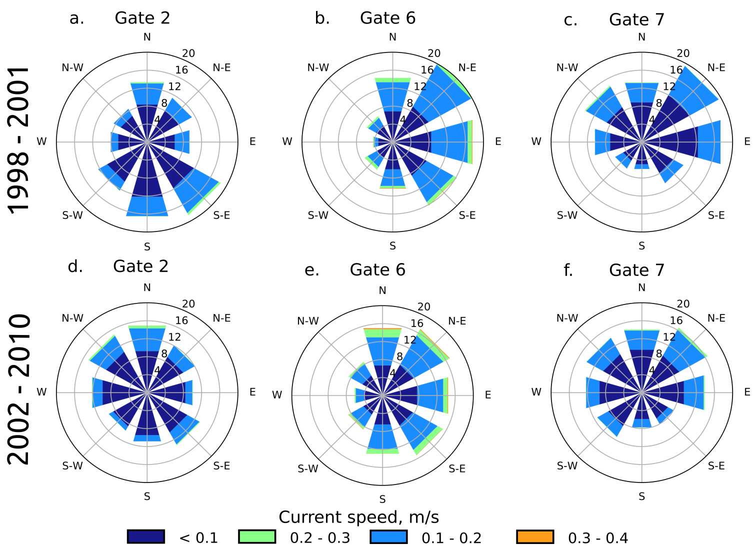

Figure 11. *Water current roses at gates 2, 6 and 7 drawn for the periods of intense (a-c) and low (d-f) intensity/undetectable E. huxleyi blooms.*

documented elsewhere for the above period, and the retrieved space-borne time series of geostrophic current velocities and water particle trajectories in the Bering Sea. This was done through reconstructing the water current roses, and Lagrangian trajectories (Fig. 10) approximating the movement of water particles (WPs) from the North Pacific (Fig. 10) prior to their arrival at the *E. huxleyi* bloom area. WPs were tracked back in time for a period of up to one year.

Figures 11-12 indicate that there was a linkage between the *E. huxleyi* bloom outbursts observed in 1998-2001 and the increased inflow of subarctic Pacific waters into the Bering Sea though the Aleutian Islands. Later on, i.e. after 2002, this hydrodynamic situation has not reoccurred. This implies that some biogeochemical properties of subarctic Pacific waters are capable of stimulating the outburst of *E. huxleyi* blooms. North Pacific waters are known as Fe-limited. Fe limitation establishes a phytoplankton population dominated by very small algal cells, such as *E. huxleyi* cells. Thus, the invasion of subarctic Pacific waters in the region of south-eastern Bering Sea was bound to be conducive to an unhindered (in terms of nutrients availability) growth of *E. huxleyi* cells as it was documented in satellite observation data. With the termination of the phenomenon related to Near Strait throughflow powered by changes in the circulation properties of the Aleutian Stream and cessation of inflow of subarctic Pacific waters into the south-eastern Bering Sea in 2001-2002, the massive outbursts of *E. huxleyi* came to an end. We admit that the above hypothesis is only tentative, and further on more in-depth studies might be warranted.

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Relevant publication: *Selyuzhenok, V., Kondrik, D., Kazakov, E., Chepikova, S, Pozdnyakov, D. Bering Sea: A possible explanation to the extraordinary bloom outburst of E. huxleyi in the late 1990s - early 2000s. Remote Sensing Letters (submitted).*

Applied Meteorological and Oceanographic Research for Industrial Activities

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The Nansen Centre has developed a logistic model for providing scientific and operational information, products and services to potential users, which is necessary for planning of prospecting and drilling works and management of ice operations on the shelf of the Arctic seas, and ensuring ice and environmental safety.

NIERSC has also developed original innovative methods for processing satellite data for mapping sea ice distribution by age, ice drift and deformation fields, icebergs and other especially dangerous ice

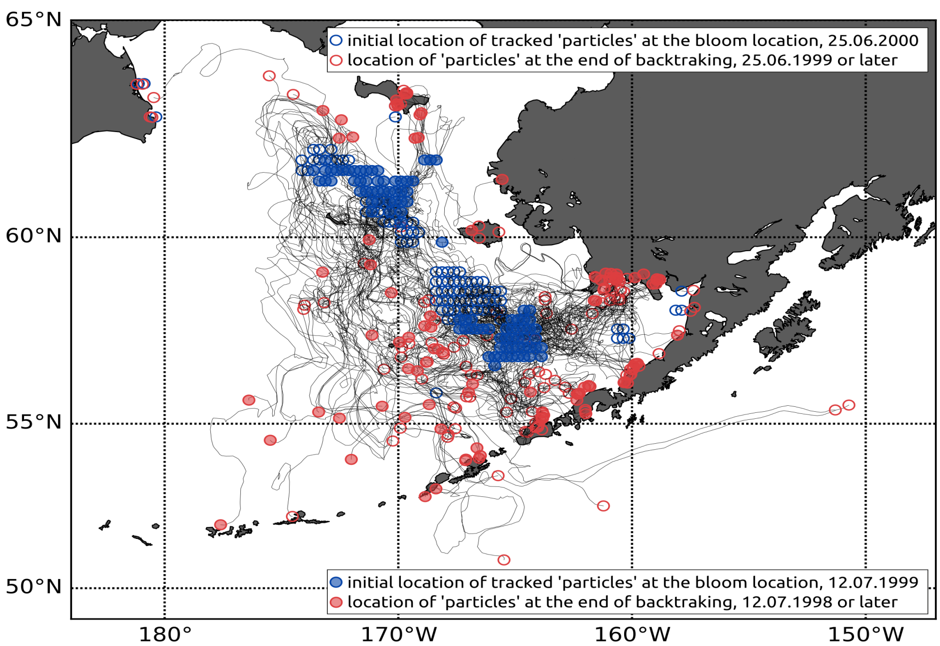

Figure 12. *Lagrangian trajectories of the WPs observed within the E. huxleyi bloom location. Open blue and red circles indicate the location of tracked WPs during and before the bloom, respectively. Filled red and white circles relate to the 1999 and 2000 bloom seasons, respectively. Thin black lines designate WP trajectories.*

formations. These methods are being used in our System for sea ice monitoring (Fig. 13).

An effective way of building such a system should provide: (i) scalability, that means a possibility to extend easily the area of sea ice monitoring and to add new algorithms; (ii) simplicity to deploy the system instances on some other hardware, i. e., on our partners' server; (iii) publication of thematic products in standard GIS-formats, provision of their operational delivery to the users.

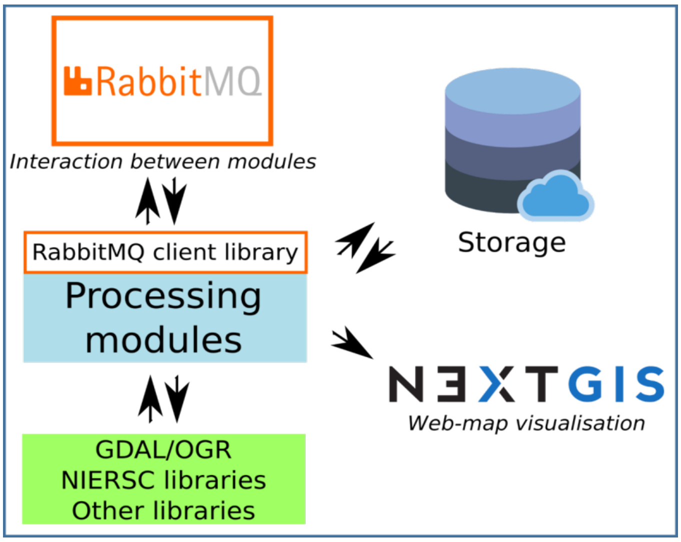

Figure 13. *Scheme of the System of sea ice monitoring.*

All the mentioned requirements are satisfied by microservice architecture we use: small modules doing their own task could be executed on different machines, exchanging data by AMQP protocol. The interaction between modules is provided by RabbitMQ – open-source message-broker software. This approach has two major advantages: first, client libraries to interface with the broker are available for all major programming languages, which means we could easily incorporate in the system not only modules written in Python (like we do now); secondly, additional virtual or physical servers could be always rent to extend the system performance

For publishing our products, we use NextGIS Web – a server-side Web GIS – for storage, visualization for various kinds of geospatial data and services, providing permissions management as well.

Development of robust algorithms for automatic sea ice parameters retrieval is an important challenge since the growing amount of SAR images is available for sea ice observations to support sea ice researches, climate studies, operational ice charting services, ice navigation and other operations in ice-covered seas.

Advanced automated methods for processing satellite radar images made it possible to create maps of ice classification (Fig. 14) that can be used in a quasi-operative mode for navigation and ensuring safe operations on the shelf of the Arctic seas. For the first time, it was possible to perform a new validation and use the method to prepare ice maps for the period of summer thaw. In 2018, daily ice maps were delivered to the customer and were highly appreciated.

NIERSC's feature-tracking algorithm for sea ice drift retrieval from a pair of sequential Sentinel-1 wide-swath images (A-KAZE) is based on the feature tracking comprising feature detection, description, and matching steps. The approach exploits the benefits of nonlinear multiscale image representations and outperforms both ORB and SIFT algorithms up to an order of magnitude in ice drift. The experimental results showed high relevance of the proposed algorithm for retrieval of ice drift at sub-kilometre resolution from a pair of SAR images with 100-m pixel size.

The developed NIERSC's ice tracking system performance is demonstrated by an operational ice drift and

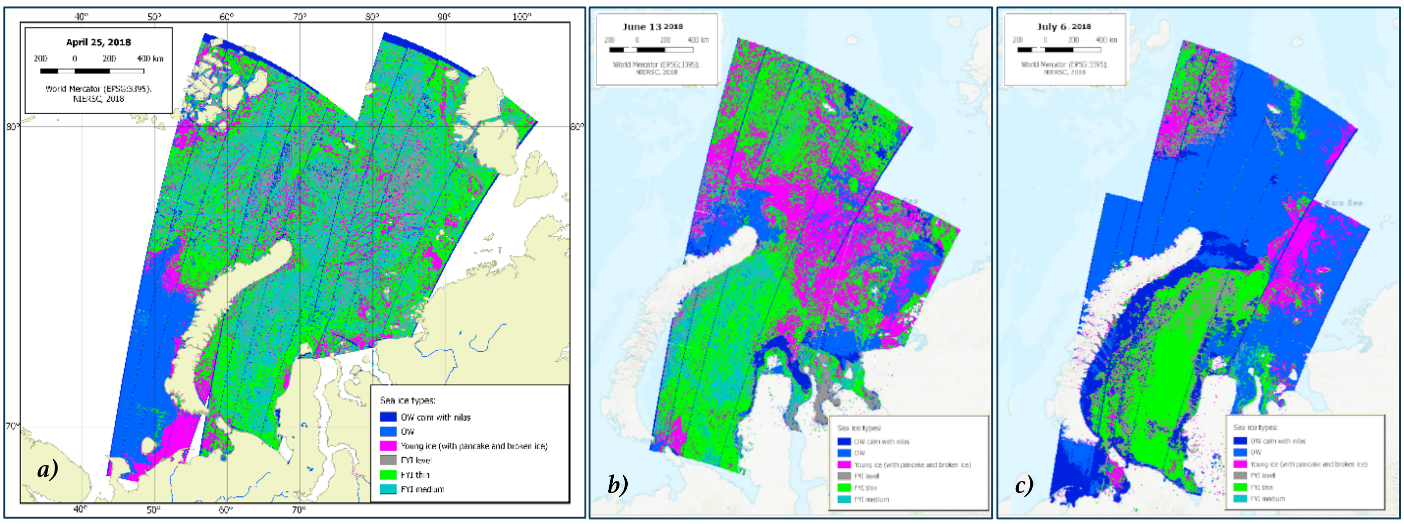

Figure 14. *Result of sea ice types classification of Sentinel-1 EW images, taken over the Kara Sea and eastern part of the Barents Sea on: a) April 25, 2018; b) June 16, 2018, and c) July 06, 2018.*

deformation analysis over the Kara Sea for a winter season of 2017-2018 using Sentinel-1A/B data. This application is of high relevance to navigation purposes as well as climate study and numerical model tuning. Ice deformation characteristics such as divergence/convergence could reveal location of the zones with compacting/ ridging or lead/crack opening within sea ice cover. In the frame of this important topic, the focus will be on regime analysis of ice kinematics in the Russian Arctic seas. An example of the product of ice drift and divergence is shown in Fig. 15.

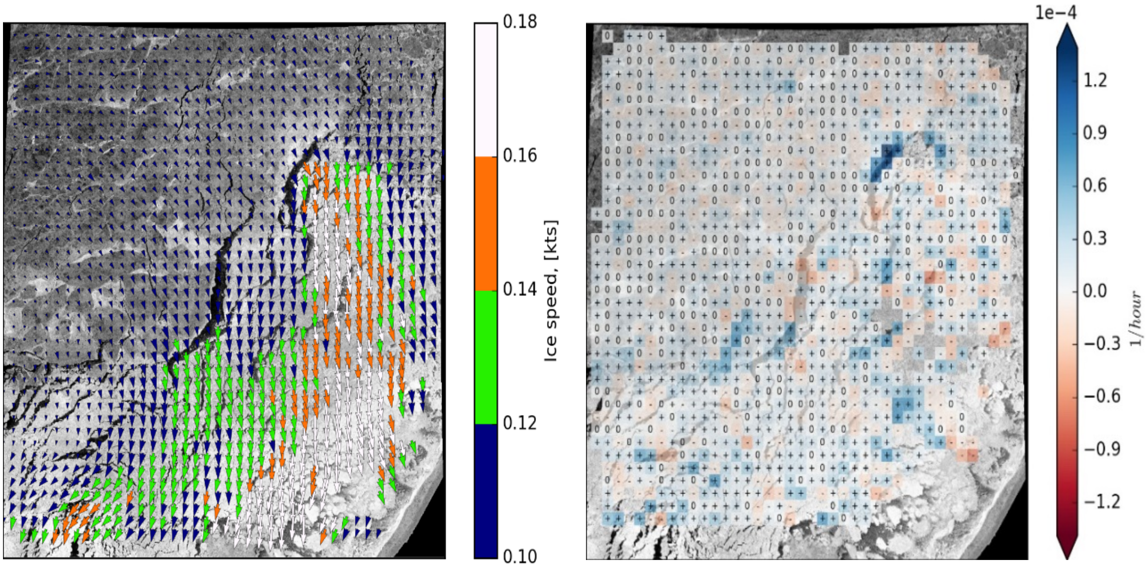

*Figure 15. (**left**) mean ice drift speed between 24 and 25 April, 2018; (**right**) ice divergence between 24 and 25 April, 2018: "–" means ice ridging/compacting; "+" means lead/crack opening; "0" means no divergence.*

The developed automated method allows detecting icebergs and dangerous ice formations with high accuracy in open water.

Test calculations by the method for the Barents Sea area showed its effectiveness and allowed to put forward a hypothesis about the seasonal variability of the number of icebergs (Fig. 16).

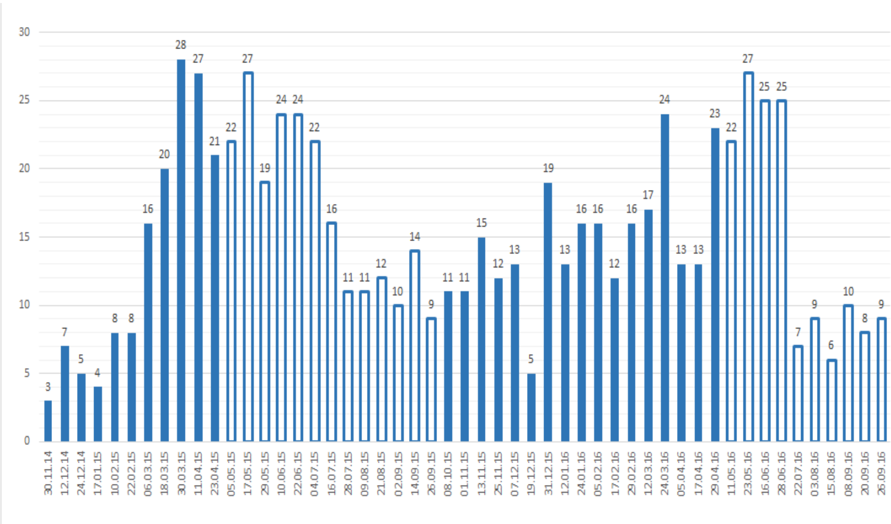

Figure 16. Seasonal variability of number of icebergs in the Barents Sea area.

Based on the analysis of satellite data for 1978-2018 (NOAA/NASA Polar Pathfinder), the patterns of changes in the large-scale structure of sea ice drift fields in the Arctic Ocean have been established and a new classification of main drift field types has been developed. Three main types of large-scale sea ice drift fields, characteristic for the winter season, have been identified (Fig. 17). It has been shown that the (a) and (c) types of ice circulation formed conditions favourable for the growth of ice, whereas type (b) contributed to the intensity of the ice removal from the Arctic Basin. This study revealed a close relationship between the types of ice movement and the certain types of atmospheric circulation.

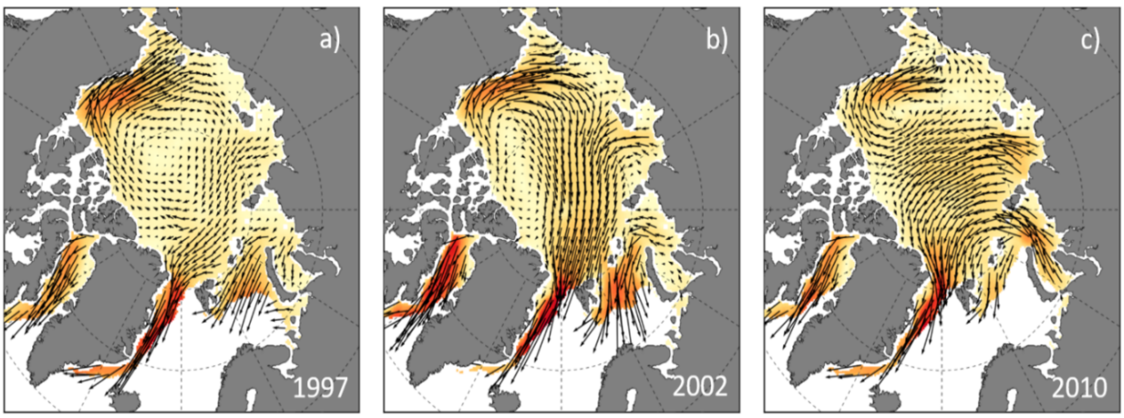

Figure 17. The main structures of ice drift in the winter of 1979-2018: a) intense Beaufort Gyre; b) intense Transarctic current; c) "dividing" drift.

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