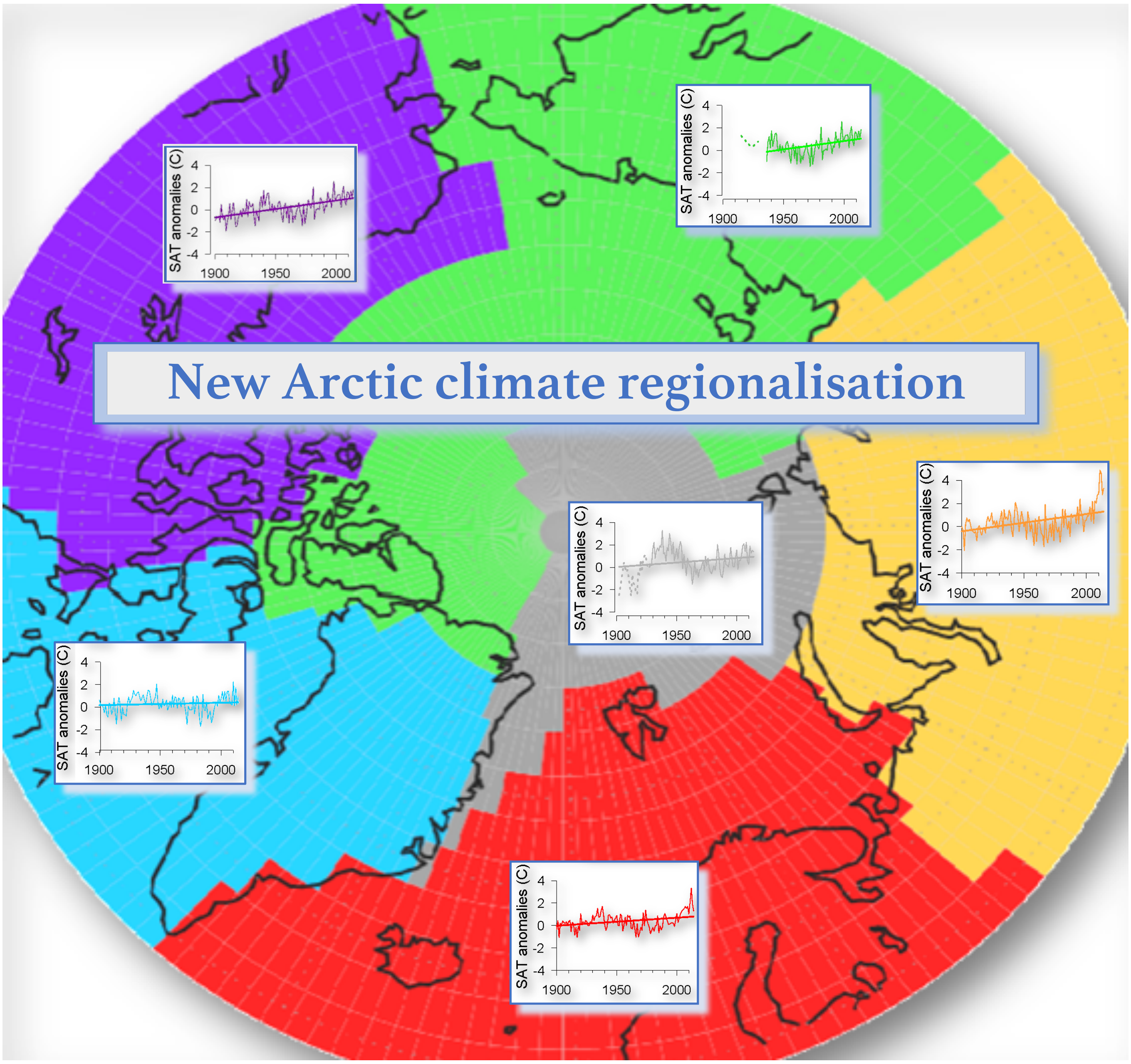
Annual Report 2016

Nansen International Environmental and Remote Sensing Centre

St. Petersburg, Russia

Non-profit international centre for environmental and climate research

Founded in 1992



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Max Planck Society (MPS)
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Nansen Environmental and Remote Sensing Centre (NERSC)
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Saint-Petersburg State University (SPbSU)
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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
- Socioeconomic Impact of Climate Change

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. Additionally, NIERSC receives basic funding from its Founder – Nansen Environmental and Remote Sensing Centre.

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 the space-related research activities.

Staff

At the end of 2016 NIERSC staff incorporated 29 employees comprising core scientists, including one full Doctor of Science and six PhDs, part-time researchers, and administrative personnel. Six Nansen Fellowship PhD-students were supervised and supported financially, all holding also part-time positions of Junior Researchers at NIERSC.

Production

In 2016, totally 54 publications were published, two book chapter, 9 papers in peer reviewed journals,7 papers in other

Cover page: *Arctic climate regionalisation created from hierarchical cluster analysis, which identifies six major natural regions in the Arctic that reflect surface air temperature (SAT) variability features. Plots in the clusters show SAT anomalies and trends over 1900-2014 (Johannessen et al., Tellus, 2016).*

journals and 36 conference proceedings (see the reference list at the end of 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 Science, 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, Research Centre of Operational Earth Monitoring and other, totally about 40 institutions.

Fruitful relations are established also with number of foreign and international organizations, universities and institutions including European Space Agency, Global Climate Forum, Max-Planck Institute for Meteorology (Germany), Friedrich-Schiller-University (Germany), Finnish Meteorological Institute (Finland), University of Helsinki (Finland), University of Sheffield (UK), Stockholm University (Sweden), Johanneum Research (Austria), 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 objective 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 are climate and environmental change and satellite remote sensing, including integrated use of satellite Earth observation techniques in combination with supporting *in situ* observations and numerical modelling for studies of the Earth System. NFP provides PhD-students with Russian and international scientific supervision, financial fellowship, efficient working conditions at NIERSC, training and research visits to international research institutions within the Nansen Group 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.

Julia Smirnova, the participant of the Nansen Fellowship Programme, has successfully defended her Thesis “Study of polar lows in the Nordic and Barents seas using satellite passive microwave data” on 17 February 2016 at the Russian Hydrometeorological University.

Thus, 26 young Russian PhD-students have got their doctoral degrees under the NFP since 1994.

Research Projects

Below is the list of the research projects implemented at NIERSC in 2016 in close cooperation with other national and international scientific institutions:

- Knowledge Based Climate Mitigation Systems for a Low Carbon Economy (COMPLEX, EU-FP7, 2012-2016)
- Ships and Waves Reaching Polar Regions (SWARP, EU-FP7, 2014-2017)
- Great Lakes (Michigan Technical University, US, 2015-2016)
- Arctic sea ice book (NERSC s/c (ESA), 2014-2016)
- Meridional heat and moisture transport into Arctic and its role in the Arctic amplification (Russian Fund for Basic Research (RFBR), 2015-2017)
- Development of sea ice monitoring and forecasting system to support safe operations and navigation in Arctic seas (SONARC, Russian-Norwegian Project: RFBR-NORRUS, 2015-2017)
- Terrestrial ecosystems and soil carbon accumulation (RFBR, 2015-2017)
- Consumer choice and herding behaviour in microeconomics (RFBR, 2015-2017)
- Sea Ice CCI (ESA Climate Change Initiative), Phase 2 (ESA/subcontract to NERSC, 2015-2017)
- MON-SWARP (Subsidy from Ministry of Education and Science of RF No.14.618.21.0005 for the project “Ships and Waves Reaching Polar Regions”, 2015-2017)
- Role of soil temperature and moisture in linking the autumn Arctic sea ice and the summer climate over Eurasia (Russian-Chinese Project, RFBR, 2016-2017)
- Ladoga-Onega Lakes (s/c to Northern Water Problems Institute, Petrozavodsk, Russia, 2016)

St. Petersburg, 25 April 2017

Nikolay N. Filatov, NWPI RAS, President

Valentin Meleshko, VMGO, Co-President

Hartmut Grassl, Max-Plank Society, Vice President

Stein Sandven, NERSC, Vice President

Sergey V. Aplonov, SPbSU

Vladislav K. Donchenko, SRCES RAS

Leonid P. Bobylev, Director

SCIENTIFIC REPORT

Climate Variability and Change in High Northern Latitudes

Surface air temperature variability and trends in the Arctic: new amplification assessment and regionalisation

Prof. Ola M. Johannessen, Nansen Environmental and Remote Sensing Centre (NERSC)/Nansen Scientific Society (NSS), Bergen, Norway

Dr. Svetlana Kuzmina, Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, Russia

Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia/NERSC, Bergen, Norway

Dr. Martin Miles, Uni Research/Bjerknes Centre for Climate Research, Bergen, Norway/Institute of Arctic and Alpine Research, University of Colorado, Boulder, USA

Arctic amplification of temperature change is theorised to be an important feature of the Earth's climate system. For observational assessment and understanding of mechanisms of this amplification, which remain uncertain, thorough and detailed analyses of surface air temperature (SAT) variability and trends in the Arctic are needed. Here we present an analysis of Arctic SAT variability in comparison with mid-latitudes and the Northern Hemisphere (NH), based on an advanced SAT dataset NansenSAT (Fig. 1). We define an index for the Arctic amplification as the ratio between absolute values of the Arctic (65-90°N) and NH 30-yr running linear SAT trends. It is demonstrated that the temperature amplification in the Arctic is characteristic not only for the recent warming but also for the early 20th century warming (ETCW) and subsequent cooling. The amplification appears to be weaker during the present warming than in the ETCW, simply because the index values reflect the more pervasive nature of the current warming that reflects the higher background of anthropogenic global warming.

We also produced a new Arctic climate regionalisation created from hierarchical cluster analysis, which identifies six major natural regions in the Arctic that reflect SAT variability features (see cover page). Statistical comparison with several climate indices shows that the Atlantic Multidecadal Oscillation is most significantly associated with the amplified warming or cooling in the Arctic, with a stronger correlation during the ETCW and present warming than during the intermediate period. Regionally, differences are identified in terms of annual and seasonal rates of SAT change and in their correlations with modes of variability.

<u>*Relevant publication:*</u>

Johannessen, O.M., Kuzmina, S., Bobylev, L., Miles M. (2016). Surface air temperature variability and trends in the Arctic: new amplification assessment and regionalization. Tellus A, 68, 28234.

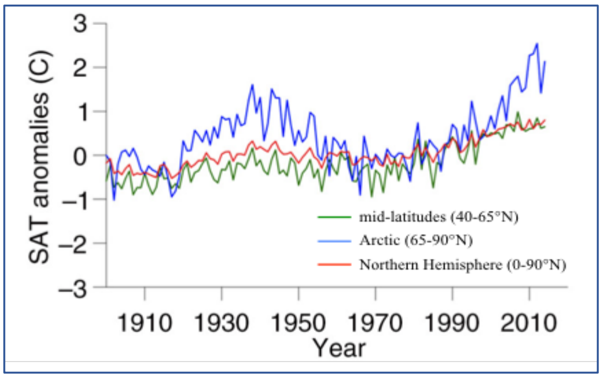

Figure 1. *Annual SAT anomalies relative to the reference period 1961-1990 averaged over three latitudinal zones.*

Seasonal and interannual variations of heat fluxes in the Barents Sea region

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

Dr. Alla Yurova, NIERSC/SPbSU, St. Petersburg, Russia

Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia/NERSC, Bergen, Norway

PhD-student Anna Vesman, Arctic and Antarctic Research Institute (AARI)/NIERSC, St. Petersburg, Russia

Seasonal and interannual variations of advective heat fluxes convergence in the ocean (dQ_{oc}) and atmosphere (dQ_{atm}) in the Barents Sea region were studied for the period 1993-2012 using regional eddy-permitting Massachusetts Institute of Technology primitive equation general circulation model (MIT GCM) and the atmospheric reanalysis ERA-Interim.

MIT GCM run used was nested into MIT-ECCO2 model (http://ecco2.jpl.nasa.gov) optimized for the North Atlantic and Arctic oceans. The nested MIT GCM has the horizontal mesh-size in the Nordic seas of around 4x4 km and 50 vertical levels.

The results show that averaged over 1993-2012 horizontal distributions of temperature and current velocity of the upper ocean in MIT GCM (Fig. 2a) are in good agreement with data of altimetry and World Ocean Atlas 2013. Model reproduces the topographically captured branches of the Norwegian Slope and Coastal Currents, the return flow along the northern slope of the Bear Island Trench, as well as a weak north-eastwards flow along the south-eastern shelf of Spitsbergen. Water volume transport and temperature of inflow across the Barents Sea Opening (BSO) in MIT GCM well correspond to the observed ones (Fig. 2b,c). The oceanic heat flux was computed relative the water freezing temperature of -1.8°C. The volume and heat flux with the North Cape Current and the Norwegian Slope Current across the BSO is around 20% and 80%, respectively (Fig. 2c,d). Consistent with observations, heat inflow to the Barents Sea increases with time (Fig. 3a). The return heat outflow does not show any significant trend since 1995, therefore the integral heat flux into the Barents Sea increased during the 20-year model run (Fig. 3a).

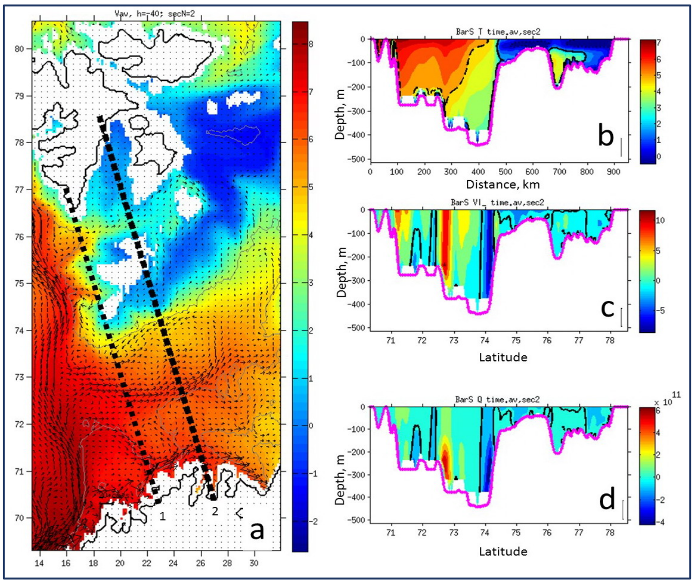

Figure 2. ***(a)*** *Water temperature (°C) and currents (arrows) at 40 m depth. Dashed line marks the sections 1 and 2;* ***(b)*** *water temperature (°C);* ***(c)*** *current velocity (cm s^{-1});* ***(d)*** *heat flux (W) across section 2 (see plate a).*

To investigate the time-varying spectral structure of heat inflow, the wavelet and Singular Spectrum analyses were performed. Here we consider the heat flux across the BSO to be numerically equivalent to the oceanic heat convergence in the Barents Sea. Atmospheric heat convergence over the Barents Sea was computed from REA-Interim data. For both dQ_{oc} and dQ_{atm} we found dominating seasonal, 2-4-year and 5-8 year cycles. In the ocean, seasonal variations of dQ_{oc} were found to be primarily determined by variations of the volume fluxes across the BSO, whereas the observed 20-year trend was mainly determined by variation of the inflow temperature.

Cross-wavelet analysis of dQ_{oc} and dQ_{atm} showed their nearly in-phase seasonal variations and out-of-phase interannual 2-4-year and 5-8 year variations in the Barents Sea region. The latter was suggested to represent a regional manifestation of the

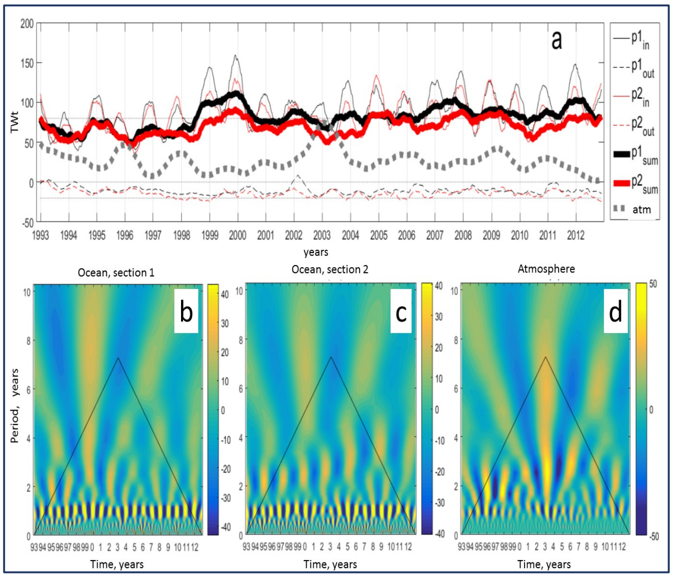

***Figure 3**. (**a**) Time series of oceanic heat fluxes in (thin solid limes) and out (dashed lines) the Barents Sea, oceanic heat convergence (thick solid lines) and atmospheric heat convergence (thick grey dashed line) over the Barents Sea (TW). Fluxes across sections 1 and 2 (Fig. 2a) are marked with red and black colour, respectively; (**b**), (**c**) and (**d**) are Morlet wavelet coefficients of oceanic heat flux across sections 1 and 2 and atmospheric heat flux convergence dQ_{atm}, respectively (TW).*

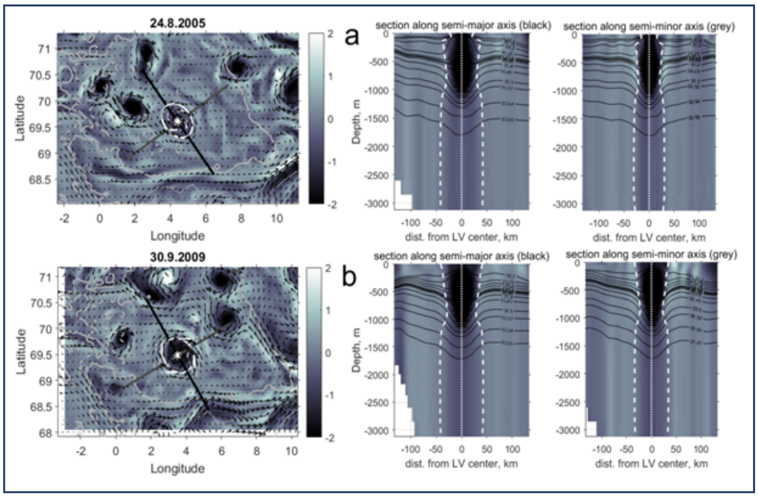

***Figure 4**. Horizontal maps (left-hand panels) and vertical profiles (middle and right-hand panels) of relative vorticity (x10^{-5} s^{-1}) in the Lofoten Basin (LV) at 100 m depth: **(a)** 24.08.2005; **(b)** 13.09.2009. In the maps, horizontal velocity vectors are overlaid; black and grey lines mark the position of vertical section along LV semi-major and semi-minor axes of the approximating ellipse, respectively. The vertical sections show cuts along the semi-major axis (middle panels) and semi-minor axis (right-hand panels) of the vortex. In vertical sections, solid black isolines are $\sigma_{0.5}$ and vertical white dotted and dashed lines mark LV axis and boundaries (dynamic radii), respectively.*

Bjerknes compensation mechanism for the time scales over 2-4 years.

Relevant publication: *Bashmachnikov, I.L., A.Yu. Yurova, L.P. Bobylev, A.V. Vesman. Seasonal and interannual variations of the heat fluxes in the Barents Sea region. Izvestiya, Atmospheric and Oceanic Physics (submitted).*

Vertical structure and stability of Lofoten vortex in the Norwegian Sea

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

Dr. Michail Sokolovskiy, Water Problems Institute (WPI), Moscow, Russia

Dr. Tatiana Belonenko, SPbSU, Saint Petersburg, Russia

Dr. D. Volkov, Cooperative Institute for Marine and Atmospheric Studies (CIMAS), FL, US

Dr. P. Isachsen, Department of Geosciences, Oslo, Norway

Dr. X. Carton, Laboratoire de Physique des Océans (LPO), Brest, France

The Lofoten Vortex (LV), a quasi-permanent anticyclonic eddy in the Lofoten Basin of the Norwegian Sea, is studied with an eddy-permitting primitive equation model MIT GCM nested into the ECCO2 ocean state estimate. MIT GCM has the horizontal mesh-size in the Lofoten Basin of around 4x4 km and uses 50 vertical levels with the mean thickness ranging from 10 m in the upper ocean to 456 m below 2000 m. LV, as simulated by model (Fig. 4), extends from the sea surface to the ocean bottom at about 3000 m and has the subsurface core between 50 m and 1100 m depths. Using the model, we showed that the vertical structure of LV can be casted into four standard configurations, each of which forms a distinct cluster in the parameter space of potential vorticity (PV) anomalies in and above LV core. Stability of LV for each configuration is then studied with a three-layer and a two-layer (winter) quasi-geostrophic (QG) models over a flat bottom and over a bowl-shaped topography. QG model results showed number of common features with those of the primitive equation model. However, in the QG model, simulation of LV is the subject of a rather strong dynamic instability, penetrating deep into the core with 50-95% core volume loss within 4-5 months. The primitive equation model dynamic instability of LV mostly stays at its periphery (Fig. 5), and the decay rate is significantly smaller: for the same intensity of perturbations only 10-30% of volume loss during the same period is detected.

There may be a few explanations for the differences in the performance of two models. The most plausible one is the effect of external strain. Being much stronger at LV boundary in MIT-GCM, it negatively correlates with the intensity of the perturbations at LV boundary. It is suggested, that the resulting localized shear removes growing perturbations before they penetrate deep into LV core by tearing filaments from the vortex. Further wrapping of these filaments around the vortex may prevent the core from breaking into fragments. It was also found that LV decay rates, obtained in both models, are slow enough for eddy mergers and convection being able to restore thermodynamic properties of LV against the decay processes. This justifies the quasi-permanent presence of LV in the Lofoten Basin.

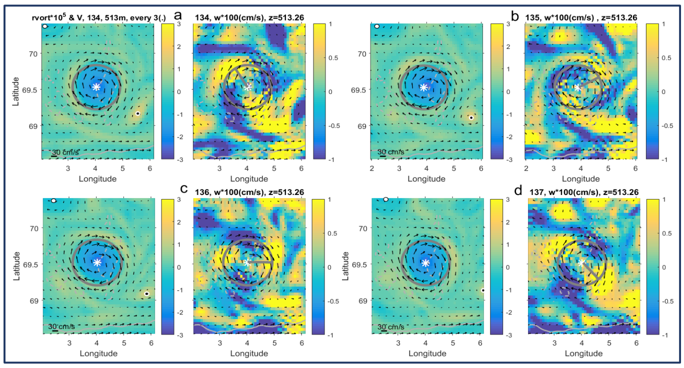

***Figure 5.** Relative vorticity (x10^{-5} s^{-1}, left panels) and vertical velocity (x10^{-2} cm s^{-1}, right panels) at 513 m depth for four consecutive moments of time (a, b, c, d) with the time interval between panel sets of 3 days. White star marks Lofoten Vortex (LV) center, grey circle marks LV dynamic radius, and grey segment starting at LV center – the position of maximum of vertical velocity of perturbations of the second azimuthal mode. Black point with white circle and white point with black circle mark a cyclone and an anticyclone in the vicinity of LV*

Relevant publication: *Bashmachnikov, I.L., Sokolovskiy, M.A., Belonenko, T.V., Volkov, D.L., Isachsen, P.E. and Carton, X. On vertical structure and stability of the Lofoten vortex in the Norwegian Sea. Deep-Sea Research I (submitted).*

Mechanisms of fast ice formation in the South-Eastern Laptev Sea

PhD-student Valeria Selyuzhenok, NIERSC, St Petersburg, Russia/Jacobs University Bremen, Bremen, Germany

Dr. Andrew R. Mahoney, University of Anchorage Fairbanks (UAF), Fairbanks, USA

Dr. Thomas Krumpen, Alfred Wegener Institute (AWI), Bremerhaven, Germany

Dr. Giulia Castellani, AWI, Bremerhaven, Germany

Prof. Dr. Ruediger Gerdes, AWI, Bremerhaven, Germany

Accurate representation of fast ice in numerical models is important for realistic simulation of numerous sea ice and ocean variables. In order to simulate seasonal and interannual variability of fast ice extent, the mechanisms controlling fast ice development need to be thoroughly understood. The objective of this study is to investigate mechanisms contributing to advance of fast ice edge to its winter location in the South-Eastern Laptev Sea. The study was based on time series of SAR imagery for winters 2007/08 and 2009/10. Overall, we obtained 21 SAR scenes between 03 December 2007 and 23 January 2008 and 10 scenes between 1 December 2009 and 15 February 2010. Using the Environment for Visualizing Images tool (ENVI) we derived Lagrangian drift of sea ice features in the area by manual tracking the features on consecutive images. Next, each feature was attributed to a date when it was incorporated into fast ice.

We split all features in four fast ice groups (Groups I-IV) according to the date when a feature was classified as fast ice. Group I features became immobile first and Group IV features were incorporated into fast ice last. Fig. 6 shows the final location of sea ice features. In both seasons, Group I features are located not only in the vicinity (< 50 km) of the shore, where fast ice is typically expected to start forming, but also further offshore surrounded by still mobile pack ice. The location of these offshore features corresponds to the shallow banks indicating that the ice is grounded there. The mean water depth at the location of Group I features is 10 m. Notably, the Group I features reoccur at the same location in both seasons. The location of Groups II and III features does not show any spatial pattern. Features that remained mobile until the latter third of each investigation period (Group IV) occupied the deepest waters and were found in two different regions. Most Group IV features were observed in the seaward most portion of fast ice, which is typically last to stabilize.

A detailed examination of SAR-based ice drift in winters 2007/08 and 2009/10 showed that grounding is a key mechanism of fast ice formation in the South-Eastern Laptev Sea. The grounded ice features (stamukhi) are formed offshore prior to fast ice expansion. These features become an obstacle restricting the motion of the surrounding ice before it becomes stationary and serve as stabilizing points during fast ice formation. Reoccurrence of grounded features reduces interannual variability in fast ice extent in the region. Small interannual variations in fast ice edge position can be explained by formation of deep ridges further offshore. Contrary to previous studies, we conclude that grounding is a key mechanism of fast ice

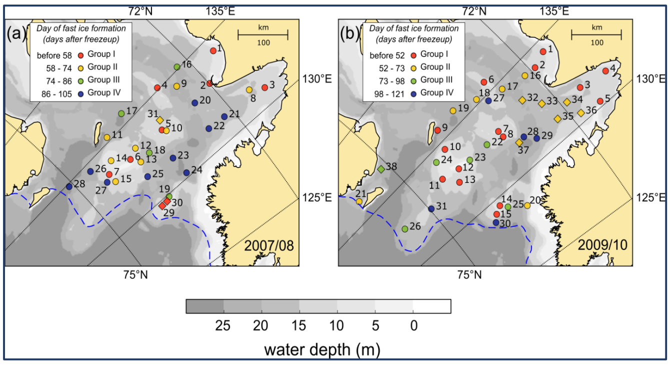

Figure 6. *Final location of the tracked features:* ***(a)*** *2007/08;* ***(b)*** *2009/10. The point colour shows time intervals of fast ice formation. The days have been counted after freeze-up. The dash blue line shows the position of fast ice edge on 23.01.2008* ***(a)*** *and 16.02.2010* ***(b)*** *taken from the operational AARI sea ice charts.*

development in the South-Eastern Laptev Sea.

<u>*Relevant publication:*</u> *Selyuzhenok V., Mahoney A.R., Krumpen T., Castellani G., Gerdes R. Mechanisms of fast ice development in the southeastern Laptev Sea: A Case study for winter of 2007/08 and 2009/10. Polar Research (submitted).*

Estimation of current snow depth distribution on the Arctic sea ice using historical data

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

Prof. Stein Sandven, NERSC, Bergen, Norway

Within the framework of ESA Sea Ice CCI Phase 2 Project (see p. 3 of the Report), analysis of data from the high-latitude airborne expeditions Sever has been performed. The expeditions carried out observations of snow depth and other parameters of snow cover on the sea ice in the central Arctic and in the Kara, Laptev, East-Siberian and Chukchi seas in 1959-1989 mainly in March-May (MAM) months. One of the main results of our study is a new snow depth climatology for the end of Arctic winter. We also provided statistics describing different snow parameters and relations between snow depth and ice thickness as well as between sastrugi height and the depth of surrounding snow cover. The widely used and discussed Warren climatology does not give any description of snow on the seasonal ice since all data used in building that climatology was collected on the multi-year (MY) ice. The new snow depth distribution obtained in our study refines the description of snow depth in the central Arctic and provides detailed information on snow depth in the marginal seas in 1960s-1980s that corresponds to typical ice distribution in that time.

However, currently we observe quite different ice conditions in the Arctic. Sea ice extent has decreased from the end of 1970s. The highest ice loss has been observed in September, causing reduction of MY ice fraction and substitution of the oldest ice by the seasonal ice that changes conditions for snow cover formation. Later onset of freeze and correspondingly later start of snow accumulation is another important factor that determines snow depth distribution in present time.

Thus, the described above new climatology cannot be used directly in present Arctic conditions. However, it is possible to do an assessment of present distribution of snow depth on the sea ice using statistics obtained in our study. The dependence of snow depth on the ice thickness and the relation between snow depth and the height of sastrugi that may form in response to blowing wind can be employed to describe snow depth on the first-year (FY) ice exposed to wind impact. Required ice thickness can be derived from satellite data using algorithms that do not involve estimated snow depth in calculations. PIOMAS sea ice thickness also

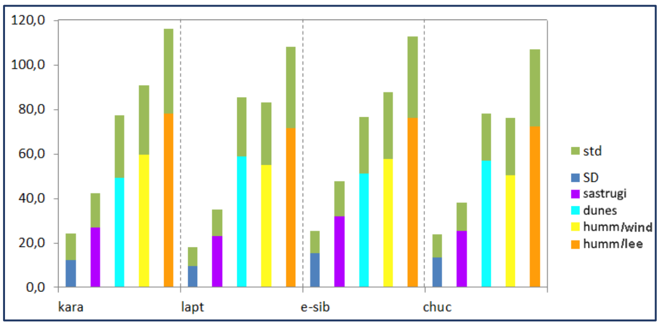

Figure 7. *Sever snow depth (cm) observation statistics in the MAM months: snow depth on the level ice (SD), snow depth of sastrugi, depth of snow dunes extending out from ice ridges, depth of snow on windward and leeward sides of the hummock and corresponding standard deviations. Data shown are averages for the four seas: Kara, Laptev, East-Siberian and Chukchi.*

can be used. As to MY ice, though its age and thickness has substantially decreased, it is difficult to judge how that affected snow depth distribution. The most important aspects in gaining snow depth on the MY ice are meteorological conditions and ice roughness. Recent observations from AWI snow buoys are few, but give an idea how different may be snow depth on the MY ice in the MAM months due to different meteorological conditions: the range of snow depth measured by different buoys is from 10.5 to 36.2 cm. Average snow depth

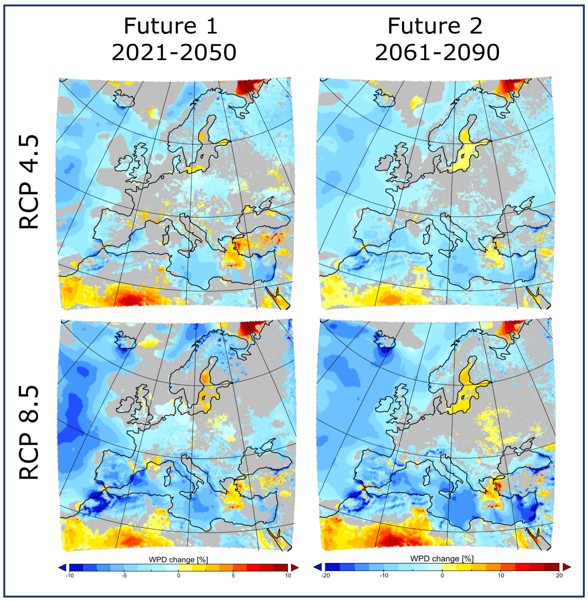

Figure 8. *The percentage change in Wind Power Density from the historical period to the Future1 period (left column) and to the Future2 period (right column), under the RCP 4.5 (upper) and RCP 8.5 (lower) scenarios. This is the ensemble-mean change, shown for all regions where at least four of the five simulations agreed as to the direction of change (other areas are marked in grey).*

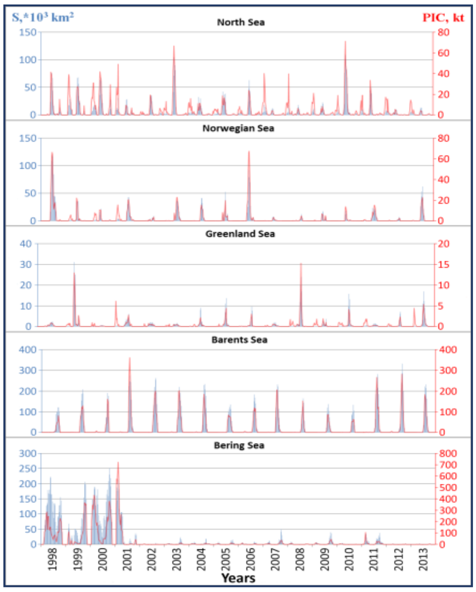

Figure 9*. Interannual dynamics of E. huxleyi outbursts, respective bloom surfaces and within-bloom inorganic carbon contents (designated in blue and red, respectively) as retrieved from space across the target seas over 1998-2013. Note: data on PIC in the Bering Sea during winter-early spring should be considered as conditional.*

on the MY ice in recent years is 24.3±0.7 cm according to IMB buoy measurements and 21.2±9.4 cm according to AWI snow buoy measurements. These values are in the agreement with the statistics obtained for snow on MY ice in our study (21.2±10.9 cm). Therefore, we suggest to use climatological snow depth for the MY ice in the current ice conditions.

Statistics derived from Sever expeditions data (Fig. 7) describes the amount of spatial variation of snow parameters in the MAM months. The average standard deviation (std) of snow depth measured on the level ice was 10.4 cm, average std of sastrugi was 14.0 cm, for snow dunes attached to ice ridges it was 25.2 cm, and for snow on hummocks it was 28.8 cm on the windward side and 36.4 cm on the lee side of the hummock. Sever observation statistics assembled in Fig. 7 facilitate comparison of average snow parameters observed in different seas. Though snow depth on the level ice is naturally the lowest, it has the highest spatial variability revealed by estimated standard deviation that amounts from 66% in the East Siberian Sea up to 100% in the Kara Sea.

Climate change impacts on offshore wind energy potential in the European domain

Dr. Richard Davy, NERSC, Bergen, Norway

Natalia Gnatiuk, NIERSC, St. Petersburg, Russia

Lasse Pettersson, NERSC, Bergen, Norway

Dr. Leonid Bobylev, NIERSC, St. Petersburg, Russia/NERSC, Bergen, Norway

We may anticipate that climate change will bring changes to the intensity and variability of near surface winds, either through local effects or by altering the large-scale flow. The impact of climate change on European wind resources has been assessed using a single-model-ensemble of the latest regional climate model from the Rossby Centre, RCA4, at an approximately 12 km spatial resolution. These simulations used data from five of the global climate CMIP5 models as boundary conditions, and the results are publicly available under the CORDEX project.

Overall, we find a consistent pattern of a decrease in the wind resources over the European domain under both the RCP 4.5 and RCP 8.5 climate scenarios, although there are some regions, principally North Africa and the Barents Sea, with projected increases in wind resources (Fig. 8). The pattern of change is both robust across the choice of scenario, and persistent: there is a very similar pattern of change found in the latter part of the 21st century as in the earlier. A case study was chosen to assess the potential for offshore wind-farms in the Black Sea region.

We developed a realistic methodology for extrapolating near-surface wind speeds up to hub-height using a time-varying roughness length, and determined the extractable wind power at hub-height using a realistic model of contemporary wind-turbine energy production. We demonstrate that, unlike much of the Mediterranean basin, there is no robust pattern of a negative climate change impact on wind resources in the studied regions of the Black Sea. Furthermore, the seasonality of wind resources, with a strong peak in the winter, matches well to the seasonality of energy-demand in the region, making offshore wind-farms in the Black Sea region a viable source of energy for neighbouring countries.

Relevant publication: *Davy R., Gnatiuk N., Pettersson L., Bobylev L. Climate change impacts on offshore wind energy potential in the European domain, focusing on the Black Sea. Renewable & Sustainable Energy Reviews (submitted).*

Aquatic Ecosystems in Response to Global Change

E. huxleyi blooms influence on carbon cycle

PhD-student Dmitry Kondrik, NIERSC/AARI, St. Petersburg, Russia

Prof. Dmitry Pozdnyakov, NIERSC, St. Petersburg, Russia/NERSC, Bergen, Norway

Lasse Pettersson, NERSC, Bergen, Norway

The main aim of this study was to evaluate the influence of vast E. huxleyi blooms on the carbon cycle in the atmosphere-ocean system. On a basis of our previous results from bloom delineation process in North, Norwegian, Greenland, Barents and Bering seas two significant steps were performed. First step was to evaluate the total amount of Particulate Inorganic Carbon (PIC) produced by each bloom during every year, and the second step was to estimate CO_2 partial pressure increase (ΔpCO_2) due to E. huxleyi bloom presence.

After obtaining the bloom areas we could evaluate the total content of PIC, *Mpic*, for each 8-day time-period by multiplying the carbon mass per coccolith *m*, the coccolith concentration C_{cc}, mixed layer depth *MLD* and the bloom area *S*. The value of *m* was equalled to 0.2 pg. The results of above mentioned procedure were then plotted along with the bloom area dynamics for the whole period of study (Fig. 9).

The bloom areas in the North Atlantic-Arctic waters were lowest in the Greenland Sea and by one order of magnitude higher in the Barents Sea (highest values are 250 000-300 000 km^2). The same pattern was observed for the PIC maximum production within E. huxleyi blooms: 0.4 kt-0.14 Mt in the Greenland Sea and ~0.35 Mt in the Barents Sea. As for the E. huxleyi bloom areas in the Bering Sea during 1997-2001, they are rather similar with those of the Barents Sea. However, the PIC production in the Bering Sea appeared to be higher than in the Barents Sea by a factor of two, with maximum values reaching 0.4 Mt and, in one case (in 2001), even ~0.7 Mt.

The second significant step of our study was dedicated to estimation of changes in CO_2 partial pressure related to E. huxleyi blooms. To complete this step, at first, we calculated E. huxleyi-driven changes in

pCO_2, i.e. ΔpCO_2, based on the *in-situ* values of pCO_2 and the pCO_2 "background" values $(pCO2)_b$ which were obtained through empirical dependency of pCO_2 from NO_3 concentrations for non-calcifying regions. Then we established a statistically robust relationship between such increments and the respective values of *Rrs* (λ = 490 nm) for every pixel that had *in-situ* values of *pCO2*. After that, on a basis of this relationship, we could estimate the pCO_2 increase for every bloom pixel for the whole study period.

Further for every pixel we normalized the pCO_2 increments determined in surface waters within *E. huxleyi* blooms in the target seas to respective background pCO_2 values and found that normalization result proved to be sea- and year-variable: the mean maximum and maximum maximorum values of normalization result within the *E.*

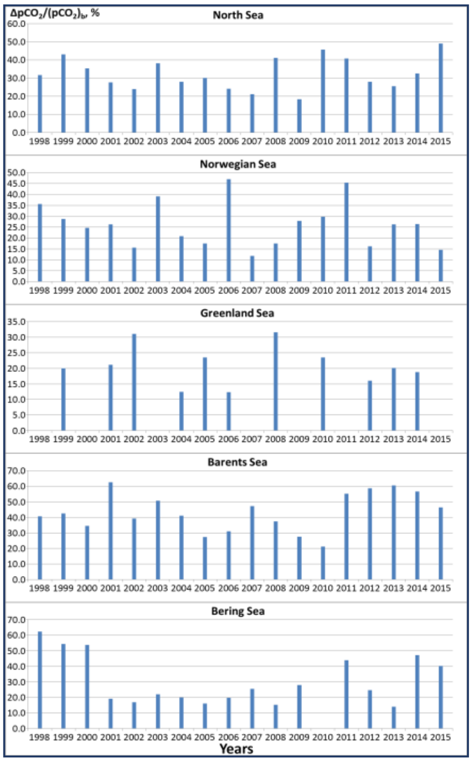

Figure 10*. Spatial and temporal variations in* $[\Delta pCO_2/(pCO_2)_b]\cdot 100\%$ *maximum maximorum values within E. huxleyi bloom areas in the North, Norwegian, Greenland, Barents, and Bering seas during 1998-2015. Note: data are absent for some years and target seas as the respective* ΔpCO_2 *values proved to be lower the assessed retrieval error of 23.4 μatm.*

huxleyi blooming area and over 18 years of observations varied in percent in the target seas between 21.0-43.3, and 31.6-62.5, respectively, with the highest and lowest values belonging to the Greenland and Barents seas. As it is illustrated in Fig. 10, the time series of $\Delta pCO_2/(pCO_2)_b$ maximum maximorum values through 1998-2015 do not exhibit any discernible trends but show a rather irregular pattern with intermittent periods of enhanced and relatively subdued peaks.

Thus, our results showed that vast E. huxleyi bloom areas can indeed play significant role in the carbon balance of the atmosphere-ocean system.

<u>*Relevant publication:*</u> *Kondrik D., Pozdnyakov D., Pettersson L. Particulate inorganic carbon production within E. huxleyi blooms in subpolar and polar seas: A satellite time series study (1998-2013). International Journal of Remote Sensing (submitted).*

Bio-optical retrieval algorithm for the optically shallow waters of Lake Michigan

Dr. Anton Korosov, NERSC, Bergen, Norway
Prof. Dmitry Pozdnyakov, NIERSC, St. Petersburg, Russia/NERSC, Bergen, Norway
Dr. Robert Shuchman, Michigan Technical Research Institute (MTRI), Ann Arbor, USA
Artem Moiseev, NIERSC, St. Petersburg, Russia

Lake Michigan is a second largest lake from North American Great Lakes by catchment area. It is an oligotrophic water body with optically clear waters. Due to high water clarity, the bottom influence exerted on the light coming out from beneath the water surface is strong enough to contaminate the satellite signal so remote sensing of the water quality in this case is a serious methodological problem.

In this work, we developed a multi-band **B**io-**O**ptical **RE**trieval **AL**gor**I**thm for **O**ptically **S**hallow **W**aters coined BOREALI-OSW. The algorithm allows to retrieve colour producing agents (CPA) concentrations from remote sensing reflectance in clear waters for a variety of bottom depths and bottom types. Realization of BOREALI-OSW is based on the Levenberg-Marquardt multi-variate optimization procedure, and recently established hydro-optical model of Lake Michigan. It is an extension of the BOREALI algorithm that has been previously developed for optically deep and turbid waters that went through thorough verification campaigns and proved its efficiency for a wide variety of water bodies including the North European and North American Great Lakes.

One of the most important features of the developed algorithm is its ability to simultaneously retrieve chlorophyll (CHL), suspended minerals and dissolved organic matter concentrations.

In case of remote sensing of optically shallow waters the problem of retrieving CPA concentrations of against the background of the light signal originating from bottom reflections becomes more challenging. We pursued two avenues. Firstly, through the spectral signature variations of subsurface remote sensing reflectance (R_{rsw}) we analysed the modifications of the upwelling signal for cases of different bottom types and depths. Afterwards we passed to inverse problem simulations in order to test the sensitivity of our calculations of CPA concentrations. To do that, we developed a retrieval algorithm (BOREALI-OSW) dedicated specifically to cope with optically shallow waters.

Secondly, we applied the developed algorithm to process both *in-situ* radiometric and satellite data from stations, at which *in-situ* measurements of CHL were run concurrently with, respectively, *in-situ* radiometric measurements and satellite overflights. To achieve the forward problem solution, we employed the hydro-optical model developed for Lake Michigan water. We considered the bottom types encountered in this water body: silicon sand, Cladophora/Chara, limestone rocks,

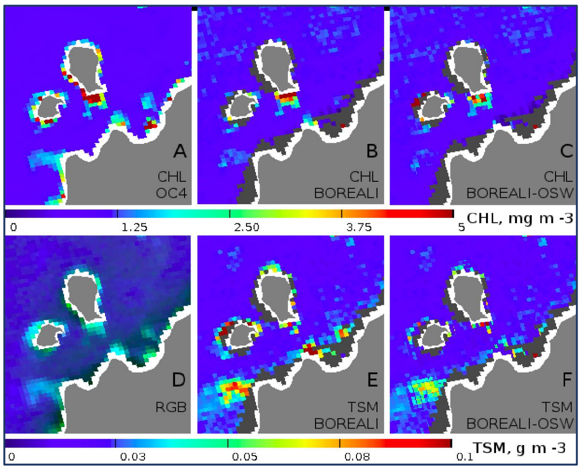

Figure 11*. Comparison of spatial distribution of water quality parameters derived using various methods:* ***A*** *– CHL, standard NASA MODIS OC4 algorithm;* ***B*** *– CHL, BOREALI without bottom correction;* ***C*** *– CHL, BOREALI-OSW with bottom correction;* ***D*** *– RGB composite from 412, 555 and 670 bands;* ***E*** *– TSM, BOREALI without bottom correction;* ***F*** *– TSM, BOREALI-OSW with bottom correction. Land is masked by light grey colour, dark grey areas stand for negative pixels; white areas signify clouds or absence of data.*

and silt. Our simulations have shown that even at very low CPA the optical influence of the bottom becomes indiscernible, if the bottom depth H approaches 20 m. In waters containing the total suspended matter (TSM) in quantities of about 0.5 g/m^3 the bottom optical influence ceases at H slightly above 10 m. An analogous critical value of H was found if the adsorption coefficient of coloured dissolved organic matter a_{CDOM} was 0.5 m^{-3}, while CHL and TSM kept infinitesimal.

The noise sensitivity analysis has shown that the shallower the water column and higher bottom albedo the more significant is the ensuing error in CPA retrievals. However, even in the case of a sandy bottom and a water column of 5 m, a 10% error in determining its albedo leads to a 18%, 28% and 10% error in retrieving, respectively, CHL, TSM and CDOM. In the case of deeper waters (H=10 m) the noise in all considered CPA retrievals becomes lower than 4%, 10% and 4% for CHL, TSM and CDOM, respectively.

Our numerical assessment of the BOREALI-OSW algorithm performance in real conditions of Lake Michigan convincingly shows that at least for bottoms depths less than 10 m its application to *in-situ* radiometric data yields CHL values appreciably closer to those determined in the laboratory as compared to CHL retrievals performed with the algorithms neglecting the bottom effect. At sites with the deeper bottom depths, the difference between the retrievals progressively decreases, however, remains appreciable thus giving addition evidence in favour of the application of the developed algorithm.

Application of the developed operational tool to processing MODIS-Aqua data has also convincingly shown its advantage over the OC4 performance in lacustrine optically shallow waters at all sampling stations (Fig. 11). The application of the BOREALI-OSW to MODIS-Aqua data from Lake Michigan yielded less accurate retrievals of CHL as compared to those obtained from *in-situ* radiometric measurements, however, they proved to be appreciably closer compared to the tested procedures that neglect the bottom optical influence.

The reasons of a less accurate performance of the BOREALI-OSW algorithm with space borne data are at least threefold. First and foremost, is the inaccuracy of atmospheric correction. Secondly, the spatial resolution of MODIS-Aqua data is 1x1 km, which lead to reducing the accuracy of accounting for the depth and bottom cover in comparison with *in-situ* data. The last reason resides in diurnal variability of epilimnetic chlorophyll.

It can be foreseen that with the development of more precise bathymetric and bottom type maps within the coastal zone, the application of the BOREALI-OSW algorithm will also yield more accurate CPA retrievals.

<u>*Relevant publications:*</u>

Korosov A., Pozdnyakov D., Shuchman R., Sayers, Sawtell, Moiseev A. Bio-optical retrieval algorithm for the optically shallow waters of Lake Michigan. I. Model description and sensitivity/robustness assessment. Limnology (accepted).

Korosov A., Pozdnyakov D., Shuchman R., Sayers, Sawtell, Moiseev A. Bio-optical retrieval algorithm for the optically shallow waters of Lake Michigan. II. Efficiency assessment. Limnology (submitted).

Satellite monitoring of Arctic ice

Sea ice monitoring and forecasting system for supporting safe operations and navigation in the Arctic seas

Dr. Vladimir Volkov, NIERSC, St. Petersburg, Russia

Eduard Kazakov, SPbSU/NIERSC, St. Petersburg, Russia

Denis Demchev, AARI/ NIERSC, St. Petersburg, Russia

The increased flows of different spatial data, complicated mechanisms of their processing and applying new methods of thematic interpretation have determined the need for creation of single integrated information system at the Nansen Centre. This system addresses the following main objectives: (i) provision of continuous automatic collecting and archiving satellite data; (ii) storage and presentation of these data in standard GIS-formats, provision of access to them by means of different interfaces, also in the Internet network; (iii) thematic data processing; (iv) publication of thematic products in standard GIS-formats, provision of their operational delivery to users; (v) provision of functional and convenient set of tools for data loading and processing to the staff of the Nansen Centre.

The key idea in the architecture of the system, which is being created, is its universal character allowing structuring data flows and using subsets of these data for specialized tasks, e.g. monitoring ice situation in the Arctic for supporting safe navigation. The system consists of two large subsystems – *server* and *client*, the latter includes different applications for interaction of end-users with the system. The main hub of the server subsystem realizes interfaces for manipulation and access to all other blocks of the system – the so-called software interface of the system. Interaction of all other system blocks is performed exclusively via the main hub and the direct links between them are excluded. The blocks of the server subsystem include: (i) Data storage for storage of different data directly in the standard file system; (ii) Metadata storage, which is one of the main parts of the system. Using Database management system (DBMS) PostgreSQL /PostGIS, it provides storage of all meta-information for the data, registered in the data storage; (iii) Data processing modules, which process data from the storage using different software packages (modules of ice drift, ice classification, filtration of thermal noise of radar images, etc.); and (iv) Data acquisition modules which automatically load data from external sources, structure and load them to the data storage with addition of metadata.

The users' applications performing interaction with the main hub of the system can be manifold. As for now, three main users' applications are developed: (i) Internet-portal *NIERSCCentre*, represented by a set of web-interfaces for search and loading of all types of information stored, also with the use of the web-cartographic service; (ii) NIERSC *QGIS Toolbox*, represented by extension for the open geo-information system Quantum GIS, allowing one to search and retrieve data directly in the interface of the fully functional universal GIS; and (iii) NIERSC *Python Interface* – a library for a popular programming language, allowing one to make queries to the system directly from the software code.

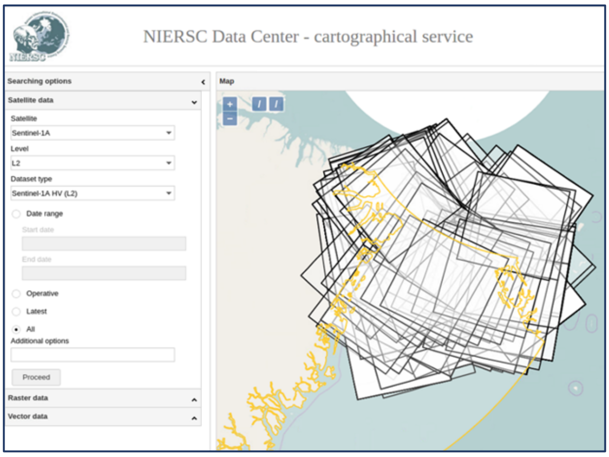

Figure 12. *Web portal for data retrieval: images of the northern part of the Greenland Sea stored in the system.*

At the present, system operates in the testing regime: from June 2016, data of Sentinel-1A/1B satellites for the Greenland Sea and the adjacent areas are loaded daily (Fig. 12). Based on the pairs of images obtained for one and the same territory with a difference up to 2-3 days, calculation of ice drift fields is performed using a highly effective algorithm developed at NIERSC (Fig. 13). It is planned also to launch soon an automatic flow sea ice type classification using authors' techniques, and to link-up it with the algorithm of iceberg detection, which in total will make it possible to perform a full-value operational monitoring of ice regime in the Arctic waters.

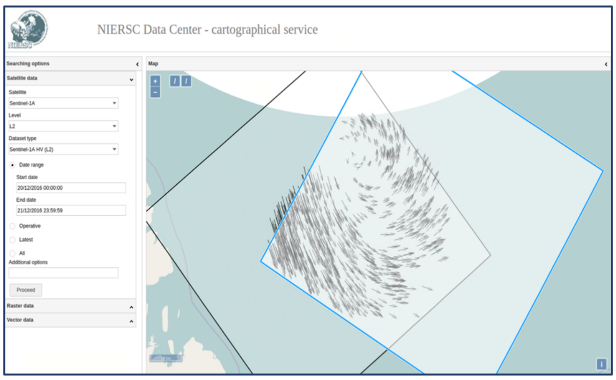

Figure 13. *The spatial coverage of the two images and the field of ice drift calculated from the area of their overlap.*

This work is carried out in the framework of the Project "Ships and waves in polar regions" funded by the RF Ministry of Education and Science, Agreement No. 14.618.21.0005, Unique Project Identifier: RFMEFI61815X0005

Automatic identification of icebergs in the Barents Sea

Dr. Vladimir A. Volkov, NIERSC, St. Petersburg, Russia

Kirill A. Smirnov, NIERSC/SPbSU, St. Petersburg, Russia

The seasonal and interannual variability of iceberg quantity and spatial distribution in the Barents Sea has been poorly investigated. For a long time, observations of icebergs were carried out visually and hence irregularly in time and space. To reveal the true regularities in the seasonal and interannual variability of the number of icebergs in the Arctic it is necessary to use satellite observations and automated approaches to iceberg detection.

We used SAR images of ESA satellite Sentinel-1 with a spatial resolution of 40 m and the swath of 400 km. Based on developed automated method of iceberg detection, a test analysis of the seasonal and interannual variability of the number of icebergs in the Barents Sea was performed. The method is based on the algorithm of identification of icebergs using their decoding indications on SAR images. When icebergs are detected on SAR-images, three situations are distinguished: icebergs in open water, icebergs in land fast ice and icebergs among drifting ice. The first situation is the simplest, and the latter does not always allow one to detect an iceberg. In any case, the main decoding indication of iceberg on the SAR-image is a high intensity of the signal. The algorithm allows one to change the sensitivity, which makes it possible to detect icebergs in different conditions.

For the method testing and analysis of regularities in iceberg distribution, the site in the Barents Sea was chosen to the west of the Novaya Zemlya Archipelago (Fig.14), where gas-condensate Shtokman field is located. It was divided into 16 cells equivalent by area. Then an archive of Sentinel-1A/B satellite imagery was generated, which includes 51 images for the period from October 2014 to September 2016. Thus, four successive seasons (winter and summer) were covered, giving a possibility to consider both the seasonal and interannual variability of icebergs. During the considered period, the study region was ice-free much of the time. A total of 765 dots were detected on 51 images for a period of 24 months, which could very likely correspond to icebergs.

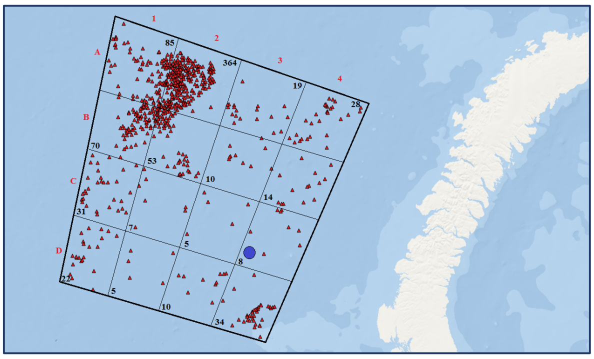

***Figure 14**. Spatial distribution of icebergs in the central region of the Barents Sea. Blue circle denotes location of the Shtokman field. At the corner of each cell, the number of icebergs detected within it is given. Figures and numbers denote columns and lines of equivalent by area cells.*

An obvious non-homogeneity in the spatial distribution of icebergs is noted for the region: their maximum number (about half) is observed in cell A2 and in adjacent cells A1, B1, B2 where their number is also high – 85, 70 and 53, respectively. Thus, 75% of all detected iceberg-like dots is concentrated here. In the eastern part of the region the number of detected icebergs is small and their spatial distribution is sufficiently uniform. In the cell C4, where the Shtokman field is located, only 8 icebergs were sighted during the entire study period.

An analysis of the spatial distribution of icebergs demonstrates consistency with the structure of cold and warm currents in the region. Large number of icebergs in the north-western part of the region is probably determined by currents of south and southwest directions carrying cold waters from the north. The icebergs of the given region according to the chart of currents of the Barents Sea originate most likely from glaciers of the Franz-Josef Land and are exported there by cold currents of south directions. At the same time, the southwestern part of the region is probably influenced by a branch of the warm West Novozemelsky Current, which prevents the drift of icebergs to the south and contributes to their rapid decay. A small number of icebergs in the Shtokman field area can be attributed to the influence of the warm West Novozemelsky Current, which carries waters from the south where icebergs do not form. Probably, icebergs detected in this part of the sea were brought there either from the Kara Sea with the cold Litke current or from the north of the Barents Sea, being entrained into the gyre in the central part of the sea One can also note some features of the influence of the region bathymetry on the distribution of icebergs. According to the bathymetry chart of the Barents Sea, icebergs in the part of the sea corresponding to cell D4 are situated in a compact group and depths here comprise not more than 100 m, which creates conditions for touching seabed by especially large icebergs. In the north-western part of the region, this factor can also produce some influence.

The uniform spatial and temporal intervals in initial data allowed to make for the first time conclusions on the interannual and seasonal variability of the number of observed icebergs.

Economics of Climate Change and Economic Modelling

Fusing Contextual Interaction Theory, systems dynamics and land use modelling

Dr. Dmitry V. Kovalevsky, NIERSC, St. Petersburg, Russia

In 2016, Integrated Assessment modelling (IAM) and economic modelling was performed in the framework of EU FP7 COMPLEX project and RFBR project No. 15-06-05625 (see p. 3 in this Report). As one of the outcomes of COMPLEX project resulting from joint efforts of several participating institutions (including NIERSC), two existing theoretical approaches to environmental policy implementation description, Contextual Interaction Theory (CIT), and Participatory Action Research (PAR), were translated into a quantitative system dynamic (SD) framework, and the resultant SD module of actor dynamics was further incorporated into the APoLUS (Actor, Policy and Land Use Simulator) cellular automata land use model developed in OCT (Spain). In earlier versions of APoLUS, the actor state variables partially adopted from CIT, such as motivation, cognition, resources, power, and affinity were time-independent (static parameters). An approach to model the dynamics of these variables in the SD language was elaborated, and several alternative specifications of SD models of actor dynamics (from quasi-linear to strongly nonlinear) were developed. These SD models now allow simulating the dynamics of the above listed actor state variables, presenting the simulation results as time series.

A new version of APoLUS model incorporates the SD description of evolution of actor behaviour over time, affecting land use claims. Modified model was applied to the case of the Navarre region, Spain, for the example of land use dedicated to solar energy as the renewable energy form vitally important for climate mitigation policies. Simulation results demonstrate the much faster development of solar energy in the region under study with the improved description of model actor dynamics.

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Address/Links

Scientific Foundation "Nansen International Environmental and Remote Sensing Centre"

14th Line 7, Vasilievsky Island
199034 St. Petersburg, RUSSIA

Phone: +7 (812) 324 51 01
Fax: +7 (812) 324 51 02

E-mail: adm@niersc.spb.ru
http://www.niersc.spb.ru

The Nansen Centre in St. Petersburg is the member of the international network of research centres named the Nansen Group, which is lead by Prof. Ola M. Johannessen. The Nansen Group includes:

NANSEN ENVIRONMENTAL AND REMOTE SENSING CENTER

Thormøhlens gate 47
N-5006 Bergen
NORWAY
Phone: +47 55205800
Fax: +47 55205801
e-mail: admin@nersc.no

Svalbard research park
N-9171 Longyearbyen,
Svalbard
Phone: +47 79026447
http://www.nersc.no

Mohn-Sverdrup Center
Global Ocean Studies - Operational Oceanography

GC RIEBER
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 Studies
(BCAS)
House 10, Road 16A
Gulshan-1, Dhaka- 1212, BANGLADESH
Phone: +8801730019213
E-mail: atiq.rahman@bcas.net

TERRA ORBIT AS
Thormøhlensgate 47
N-5006 Bergen, NORWAY
Phone: +47 55205800
Fax: +47 55205801
e-mail: terraorbit@terraorbit.com
http://www.terraorbit.com

Nansen Scientific Society

NANSEN SCIENTIFIC SOCIETY
c/o NERSC,
Thormøhlensgate 47
N-5006 Bergen, NORWAY
Phone: +47 55205800
Fax: +47 55205801
e-mail: ola.johannessen@nersc.no