Impact of arctic sea-ice cover reduction on the planktonic ecosystem

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Sea-ice exerts a major control on the Arctic Ocean ecosystem. Significant reduction of the sea-ice cover has recently been observed [*Stroeve et al.*, 2007], and future large-scale reduction in the sea-ice cover is predicted by climate models. This will certainly have cascading consequences on the food web, which need to be quantified. Ice cover impacts ecosystem through light limitation for primary producers, thermal and freshwater stratification, wind-driven vertical mixing and shelf break upwelling, which in turn control the nutrient supply to the surface waters [*Carmack et al.*, 2004]. The resulting changes in timing and magnitude of primary production will affect the entire food web, with different regional impacts.

To address the complex effects of ice-cover reduction, a coupled physical-biological model approach is used. The nitrate-based food web model includes two phytoplankton classes, two zooplankton species and a microbial loop. First, one-dimensional configurations spanning three ice-cover regimes are used to study the actual ecosystem behavior as well as to calibrate the model. Simulations in the ice-free areas of the Greenland Sea, in the seasonally ice-covered shelf of the Chukchi Sea, and in the permanently ice-covered Western Canadian Basin are conducted and compared to available physical and biological data. Second, a three-dimensional pan-Arctic coupled sea-ice-ocean configuration, based on the parallel ocean and sea-ice model (POIM, [*Zhang and Rothrock*, 2003]) with a 22km resolution, is coupled with the food web model. Several scenarios of average and reduced sea-ice cover are simulated and the regional impacts on primary production, nutrient flux and community structure are analyzed.

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The Elastic-Viscous-Plastic Sea Ice Model on Different Grid Types.

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Sea ice is a major component of climate models because it limits interactions between ocean and atmosphere. It is important to correctly represent sea ice dynamics because it controls the deformation and the creation of open water within the ice. Most of dynamics sea ice models are based on the non-linear viscous-plastic model developed by [*Hibler*, 1979]. Due to its nonlinearity, this rheology is difficult to solve efficiently. To improve numerical performance of the Louvain-la-Neuve sea-ice model (LIM), a new method for solving dynamics has been introduced.

The Elastic-Viscous-Plastic method (EVP) has been proposed by [*Hunke and Dukowicz,* 2002] to solve the non-linear viscous-plastic model (VP). The main idea is to add an artificial elastic term and to solve the equations explicitly within sub-time steps until the elastic waves are damped out. These new method is more efficient and gives better solutions.

Simultaneously the ice model has been discretized on a C-grid to make it more consistent with the numerics of the oceanic general circulation model coupled to LIM. We will outline the differences between VP and EVP and between B-grid and C-grid by a comparison of a 1970-2006 hindcast performed with our global coupled ice-ocean model.

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Marine Transport Scenarios in the Arctic Marine Shipping Assessment of the Arctic Council

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The Arctic Council is currently conducting an Arctic Marine Shipping Assessment (AMSA) under the Protection of the Arctic Marine Environment (PAME) Working Group. AMSA's scenario creation effort has identified two, key uncertainties which may determine the future of Arctic marine transport: the demand for natural resource & trade, and governance. During the next three decades regional exploration and development of Arctic oil and gas, hard minerals, and fisheries will be highly influential in the growth of marine operations throughout the Arctic Ocean. However, governance stability ~ the operating legal and regulatory structures ~ will also be a critical uncertainty in shaping the future of Arctic marine navigation. By crossing these two uncertainties, the AMSA Scenarios Team developed a matrix of four plausible scenarios that are relevant to a wide range of stakeholders: Polar Preserve, Polar Lows, Arctic Race, and Arctic Saga. Changing Arctic marine access in response to the continuing retreat of sea ice should provide opportunities for longer seasons of navigation, especially around the coastal seas of the Arctic Ocean. Several selected wildcard factors also loom large as significant and they add considerable uncertainty to the future: the management of multiple ocean uses in regional Arctic seas, including indigenous uses; the future regulation of Arctic ship stack emissions and discharges; the near-term delimitation of the Arctic continental shelves by five Arctic states under the terms of Article 76 of the UN Convention on the Law of the Sea; the impacts of new icebreaking technologies on convoy operations (and the emergence of independently-operated, icebreaking commercial ships; the potential for new commodities to be shipped out of the Arctic such as fresh water; and, the implications of future pipelines in the Russian Arctic (and other Arctic regions) for marine transport systems. Unclear is the future of seasonal or even year-round transit (trans-arctic) voyages in the Central Arctic Ocean or along historic coastal routes. The findings of AMSA scheduled for completion in spring 2009 will provide a framework for the Arctic states to respond to the challenges of increased marine activity in the Arctic Ocean through the development of effective marine safety and environmental protection strategies.

Arctic Sea Ice Changes and Future Access for Marine Operations

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Arctic sea ice is undergoing an historic transformation that has important implications for marine access throughout the Arctic Ocean. The Arctic Climate Impacts Assessment (ACIA) released by the Arctic Council in November 2004 and the 2007 Intergovernmental Panel on Climate Change (IPCC) 4th Assessment document that Arctic sea ice extent and thickness have been declining during the past five decades. Also, of critical importance to marine navigation, the area of multiyear sea ice in the central Arctic Ocean has been decreasing in recent decades. Global Climate Model (GCM) simulations in ACIA and the recent IPCC assessment both indicate a continuous decline in Arctic sea ice coverage through the 21st century; earlier models showed that it would be plausible during mid-century that the entire Arctic Ocean could be ice-free for a short period in summer. Research during 2007 has indicated that the ice-free state of the Arctic Ocean could occur as early as 2040, or even earlier! An Arctic Ocean that is covered only with first-year ice and is devoid of any multiyear ice will be a much more navigable ocean. However, such a 'new state' will require enhanced monitoring and improved regional observations. An Arctic Observing Network (AON) will be an integral element of enhanced marine safety and marine environmental protection systems.

One of the challenges to investigating the future of marine access in regional Arctic seas is that the GCM sea ice simulations are low resolution and too coarse for adequate coverage of such complex geographies as the Canadian Archipelago and Russia's Northern Sea Route. However, the GCM simulations show all coastal Arctic regions to be increasingly ice-free, for longer summer and autumn seasons. It is also plausible that Arctic sea ice will be more mobile in the 'new' Arctic Ocean, especially during spring, summer and autumn; ridged ice in coastal seas may create more difficult conditions for Arctic marine navigation. Despite this potential mobility, the future operating conditions indicate much greater marine access in all Arctic coastal seas and it is highly plausible longer seasons of marine navigation and significantly great access will be the norm throughout the 21st century.

Simulating the climate of the Arctic during the last millennium in a coupled climate model including data assimilation

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A simulation is performed over the past millennium using a three-dimensional climate model of intermediate complexity that is forced to follow temperature histories obtained from a recent compilation of well-calibrated surface temperature proxies. This is achieved using a simple data assimilation technique that could be briefly described as follows. For each year, a large ensemble of simulation is performed (96 here). The member of the ensemble that is the closest to observations is then selected as representative for this particular year and used as the initial condition for the subsequent year. The distance between the model results and the proxy record is measured by a cost function using reconstructed and simulated temperatures at the locations where the proxies are available. The best simulation retained is the one that minimizes this cost function. The simulation obtained by this technique provides a continuous record over the past millennium that is compatible with model physics, with the forcing applied and with the available proxy-records.

The simulated pattern of anomalies are analysed as well as the mechanisms responsible for the climate changes in the Arctic. We will mainly focus our analysis on relatively warm periods covering the 11th and 12th centuries, often called the Medieval Warm Period, as well as the 16th. Those ones will be compared to other periods displaying cold conditions, in particular the early 18th century. We will pay a special attention to modifications in the oceanic circulation, which are able to explain some important changes at those latitudes.

The Arctic Ocean in the Early Holocene – a "greenhouse"-analogue?

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Recent years' alarming messages about the dwindling sea ice in The Arctic Ocean are mostly based on comparison with satellite and submarine observations from the last ca. 40 years, and long-term variations are not well known.

Marine cores from the Arctic Ocean now indicate that multiyear pack ice goes back as far as 14 ma. However, the record is too coarse to show variations in extent and over the year; also, the time resolution is too poor to show variations shorter than several millennia.

Recent terrestrial field work along the world's northernmost coasts in North Greenland has shown that over the Holocene sea ice density has varied considerably. Presently these coasts are permanently beleaguered by sea ice, and signs of wave activity are missing. However, raised "staircases" of wave generated beach ridges show that once the coasts were free of ice and washed by waves for at least s short time during the summer. Dating of shells in the beach ridges indicate that this period lasted for c. 1000 years from c. 8500 BP.

This evidence is supported by the occurrence of driftwood on the coast. The driftwood on the Arctic Ocean coast comes from forests in Siberia and Canada, and has been ferried across the ocean on sea ice, a voyage that lasts at least 5-6 years. The changing driftwood frequencies therefore reflect varying amounts of multiyear pack ice on the coast. The age frequency distribution indicates that multiyear pack existed in the Arctic Ocean throughout the Holocene, but rose to a maximum 6000-7000 years ago, after the cessation of beach ridge formation. Finally, marine cores from the Greenland Sea have shown higher production, and less sea ice in these areas saw less than present sea-ice in the Early Holocene.

Modelled predictions of future sea-ice cover, generally show the coasts of northern Greenland and Canada as the last strongholds for late summer sea-ice, indicating that the long-term record from this area is representative for the whole of The Arctic Ocean. Is it possible that the ocean was nearly ice free in late summer, and multiyear pack reduced to scattered floes?

Information on the early Holocene climate constrains the summer sea ice projections for the 21st century.

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The summer sea ice extent strongly decreased in the Arctic over the last decades. This decline is very likely to continue in the future but uncertainty on projections is very large. An ensemble of experiments with the climate model LOVECLIM using 5 different parameter sets has been performed to show that summer sea ice changes for the early Holocene and for the 21st century are strongly linked, allowing to reduce this uncertainty. Using the limited information presently available for the early Holocene, simulations presenting very large changes for the 21st century could reasonably be rejected. On the other hand, simulations displaying low to moderate changes during the second half of the 20th century are not consistent with recent observations. Using this evidence based on observations during both the early Holocene and the last decades, the most realistic projection indicates a nearly disappearance of the sea ice at the end of the 21st century for a moderate increase in atmospheric greenhouse gas concentrations. For a faster increase in those concentrations, the Arctic Ocean would become almost ice-free in summer as early as 2060 AD.

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River flux of total organic carbon to the Arctic Ocean: what are the consequences of the global changes?

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Predicted warming in the Arctic is expected to affect the extent of the permafrost and ice-covered regions, the amount of precipitation and the productivity of terrestrial and aquatic ecosystems which in turn will affect river water and suspended discharges to the Arctic Ocean.

Peterson et al. [2002] have identified long-term trends in discharge from major Eurasian rivers. Over the period of observation from 1936 to 1999, aggregate annual discharge from six largest Eurasian rivers (Yenisey, Ob, Lena, Severnaya Dvina, Pechora and Kolyma) has increased at a mean annual rate of 2.0 ± 0.7 km/year (in total 128 km^3/year greater than in 1930s, or 7%).

Over the period of the discharge records, pan-arctic surface air temperature (SAT) increased by 0.6ºC and Eurasian arctic SAT by 0.7ºC.

The IPCC projects a global rise in SAT of from 1.4 to 5.8ºC by 2100. On this basis the discharge of the six rivers would increase by 315–1260 km^3 by 2100, or from 18 to 70% over present conditions.

We have used a stochastic model by Morehead et al. [2003] for simulation of sediment flux in these six arctic rivers. The model predicts an increase of in a range from 30% to 122%, or from 17.8 x 10^6 t/year to 72.6 x 10^6 t/year, a very significant increase [Gordeev, 2006]. The excess of river water and sediment discharges will increase an input of dissolved and particulate organic carbon into the Arctic Ocean with significant consequences for the coastal ecosystems.

At present, an average dissolved and particulate organic carbon (DOC and POC) concentrations in these six arctic rivers are 8.3 mg/L and 1.4 mg/L accordingly [Gordeev and Rachold, 2003]. If to assume the same concentrations in river water and suspended sediments of the rivers in XXI century than the flux of total organic carbon (TOC) will increase from 3.3 to 13.3 x 10^6 t/year, or from 20 to 80%. This TOC amount will be compared to input of TOC from another sources of material to the ocean such as coastal erosion, aeolian deposition and underground discharge.

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Contribution of the Pacific-to-Atlantic pathway to the sea ice cover and water characteristics in the Arctic Ocean

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As reported in recent articles, the sea ice cover in the Arctic Ocean has declined in the last 40 years, while its decadal variability has increased (Ikeda et al., 2005; Wang et al., 2005). The Polar Vortex has more significant decadal oscillations than the trend. Then, in the summer of 2007, the sea ice cover showed a record low. It is crucial for a future prediction which portion is attributable to the trend mainly caused by anthropogenic global warming, or the decadal variability due to a natural cause. If this year event represents the trend, the Arctic sea ice cover would change into a seasonal one in 20 years or so.

Although we have to wait for evidence next 10 years, the Arctic scientists should objectively make efforts to figure out the portions related to the trend and the variability. The recently archived data extending from clouds, the atmospheric boundary layer to biogeochemical components in the Arctic Ocean have been analyzed for providing a close insight into Arctic environmental change (Ikeda et al., 2005; Shoutilin et al., 2005). A new focus is given to the Arctic pathway from the Pacific Ocean to the Atlantic Ocean. An analysis has been extended to the sea level height in the Bering Sea vs. the Greenland Sea, and shows variability mostly caused by atmospheric circulation and its contribution to inflow of the Pacific Water into the Arctic Basin. The timing of the Pacific Water inflow matched with the sea ice reduction in the Pacific sector and suggests a significant increase in heat flux.

This component should be included in the model prediction for answering the question when the Arctic sea ice becomes a seasonal ice cover. The sea level height is divided into a barotropic component (by water mass) and a steric height component (by water density). The steric height can be examined using regional hydrographic data, whereas the barotropic component is associated with all structures between two end regions such as the Equatorial Currents and the Antarctic Circumpolar Current. Therefore, a global ocean model is required for simulating the pathway transport and consequent change in the sea ice cover.

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Physical Oceanography of Frontal Zones in the Subarctic Seas

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The Arctic Ocean and Subarctic Seas are important components of the global climate system and are the most sensitive regions to climate change. Physical processes occurring in these regions influence regional and global circulation, heat and mass transfer through water exchange with the Atlantic and Pacific Oceans. One of the overall objectives of Arctic and Subarctic oceanographic research is to gain a better understanding of the mesoscale physical and biological processes in the seas. A presentation is based on the book "Physical Oceanography of Frontal Zones in the Subarctic Seas" by A.G. Kostianoy, J.C.J. Nihoul and V.B. Rodionov published in Elsevier in October 2004. This book presents the systematization and description of accumulated knowledge on oceanic fronts of the Norwegian, Greenland, Barents, and Bering seas. The work was based on numerous observational data, collected by the authors during special sea experiments directed to the investigation of physical processes and phenomena in areas of the North Polar Frontal Zone (NPFZ) and in the northern part of the Bering Sea, on archive data of the USSR Hydrometeocenter and other research institutions, as well as on Russian and Western literature. The book contains general information on the oceanic fronts of the Subarctic seas, brief history of their investigation, state of the current knowledge, as well as detailed description of the thermohaline structure of all frontal zones in the Norwegian, Greenland, Barents, and Bering seas and of neighboring fronts of Arctic and coastal origins.

In the presentation we will show vertical and horizontal thermohaline structure of every front in the Norwegian, Greenland, and Barents seas, as well as a simultaneous view of all these fronts all together. Besides, examples and statistics on mesoscale eddies will be given. Special attention will be given to the multifrontal character of the NPFZ and to the peculiarities of its internal structure. Observations are completed by the results of numerical modeling of the northern Bering Sea where an extensive five-year survey was carried out in the scope of the NSF ISHTAR Program. The obtained frontal positions and characteristics may be regarded as a reference points to the ongoing change in the oceanography of these Subarctic seas.

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Coastal zone meteorology in the Barents and White seas as derived from in-situ and satellite altimetry data in 1992-2007

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Significant changes in the regional climate have happened in different parts of the Arctic Ocean and the Subarctic seas. In order to investigate interannual variability of key meteorological parameters in the Barents and White seas and their trends during last 16 years we used the global surface summary of day data produced by the National Climatic Data Center (NCDC) in Asheville, NC (http://www.ncdc.noaa.gov/cgi-bin/res40.pl). The data used in building these daily summaries are obtained from the USAF Climatology Center, located in the Federal Climate Complex with NCDC. Over 9000 stations' data are included currently in the database. Global summary of day data for 18 surface meteorological elements are derived from the synoptic/hourly observations contained in USAF DATSAV3 Surface data and Federal Climate Complex Integrated Surface Data (ISD). From this database we selected 41 meteo stations located at the coasts of the Barents Sea and 29 meteo stations located at the coasts of the White Sea. This set also includes meteo stations located at Bear Island, Svalbard, Franz Josef Land, and Novaya Zemlya. We restircted our analysis by the following five meteo elements: mean air temperature, mean sea level pressure, mean wind speed, precipitation amount, and snow depth, derived in the period between 1992 and 2007. Seasonal and interannual variability of these parameters, general statistics, and geographical distinctions will be shown in the presentation.

The analysis of in-situ meteo data was coupled with the analysis of satellite observations, which are a unique source of information about the coastal ocean. Radar altimetry is an important remote technique for directly sensing sea state from space, providing along-track measurements of sea surface height, wave height and wind speed. While it provides favourable results in the open ocean conditions, in coastal zones it lacks accuracy due to a number of problems that need to be assessed and solved. A 15-yr long data record from a variety of radar altimeters over costal regions is currently available globally. Under the umbrella of European Union within the INTAS cooperation program, the ALTICORE project (www.alticore.eu) has been running since December 2006 aiming at determining the extent to which this unprecedented data set can be improved and usefully exploited along the European coasts, specifically over selected validation sites in the Mediterranean, Black, Caspian, White and Barents seas. A comparison of satellite and in-situ wind speed data was made for the Barents and White seas, in particular, which showed distinctions between different parts of the coastal zone, derived from the correlation analysis.

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A finite element sea-ice model to resolve the Canadian Arctic Archipelago

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A finite element, unstructured grid sea-ice model is used to investigate the benefits from resolving small-scale processes in sea-ice modeling. Our model has representations of both dynamic and thermodynamic sea-ice processes and includes viscous-plastic rheology along with a complete parametrization of the atmospheric fluxes. Unstructured meshes, with their natural ability to fit boundaries and increase locally the mesh resolution, propose an alternative framework to capture the complex oceanic areas formed by coasts and islands. In particular, higher mesh resolution in the vicinity of the coastlines and the islands allows for representing the formation of shelf-water polynyas. We show such an example in the Svalbard Archipelago where an offshore-oriented wind along with fine mesh resolution yields a rapid decrease in the mean ice thickness and the ice concentration on a 10-days period.

Furthermore, a numerical experiment has been performed to investigate the influence of resolving the narrow straits of the Canadian Arctic Archipelago on the sea-ice features in the Arctic. Our study shows that no significant change is found on the large-scale sea-ice features in our model, the impact on the thickness pattern being merely local. However, we emphasize that the local and short-term influences of the ice exchanges are non negligible. In particular, depending whether the straits are open or closed in the numerical experiment, the domain boundary and the associated boundary condition influence directly the numerical solution in the proximity of those straits. Moreover, the ice fluxes through the Archipelago represent a non-negligible freshwater flux towards Baffin Bay and the Labrador Sea, whose impact on the convective overturning is still unclear.

Finally, some numerical simulations of the Southern Ocean sea-ice are presented.

Recent Sea Ice Ecosystem in the Central Arctic Ocean

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Recent global warming in the Arctic Ocean predicts shifting of ice-edge to the north, decreasing of sea-ice thickness and surface, and increasing of ice-open areas. This scenario suggests increasing of biological productivity and duration of vegetation period, and intensification of regeneration processes in the sea ice-upper ocean system. However, at present the evidence of impacts of global change on the sea ice ecosystem is sparse or uncertain, though there are fragmentary indications of recent changes. As established now, the biological community response to global change is most likely in the regions, where the sea ice retreat is rather remarkable, e.g., in the region of Beaufort Gyre (Melnikov, 2000; Melnikov and Kolosova, 2001; Melnikov et al., 2001, 2002; Melnikov, 2004). Assessment of the recent sea-ice ecosystem dynamic and modeling its potential changes in the Central Arctic Ocean will allow estimating and forecasting potential changes within the sea ice-upper water system and consequent ecological effects on higher trophic levels including birds, marine mammals and benthic organisms. At meeting lecture it will be presented sea ice-associated biology results obtained in the vicinity of the North Pole area during the PanArctic Ice Camp Expedition, April 2007, under umbrella of the IPY (www.paicex.ru).

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Mesoscale atmospheric vortices in the Okhotsk and Bering Seas: Results of satellite multisensor study

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Winter mesoscale cyclones (MCs) have the size of 100-1000 km and lifetime of 1-3 days. They are often associated with locally heavy precipitation, high winds causing ice drift and serious disturbance in fishery and transport operation at the sea. Climatological occurrence of mesoscale vortices is still poorly understood. They were investigated mainly in the Northern Atlantic Ocean, as well as in Gulf of Alaska and the Japan Sea in the Pacific Ocean. A number of case studies and publications on MCs in the Beaufort, Kara, Laptev and Chuckchi Seas is small. They are frequently observed on satellite images of the Bering and Okhotsk Seas and to the east of Kamchatka where there are favorable conditions for their development, however, up to now the published information on MCs in these areas is too limited. Mesocyclones are difficult to forecast because of their rapid evolution and movement. Additional problem for the Bering and Okhotsk Seas is the sparse conventional network. Thus the main sources of quantitative spatial data to examine these systems were satellite observations and fields of geophysical parameters retrieved from measurements conducted by various satellite sensors. A wide swath Envisat Advanced Synthetic Aperture Radar (ASAR) is an important tool for the study of MCs over the ocean since it can contribute the high-resolution near-surface wind field. Promising sources of regularly available remotely sensed data (as opposite to occasional ASAR images) are the QuikSCAT Seawinds scatterometer, the Aqua Advanced Microwave Scanning Radiometer (AMSR-E), and Terra and Aqua MODIS spectroradiometer. All these sensors are characterized by a wide swath and possess improved spatial resolution and/or have additional spectral channels compare to such sensors as the SSM/I, AMSU, AVHRR, etc. The MCs were detected by screening archive ASAR quick look images acquired over the Northwest Pacific Ocean in 2002-2007. The main attention was given to the intense mesoscale cyclones or polar lows. They occur poleward of the polar front usually during winter season and have winds in excess of gale force. High-resolution ASAR images of selected MCs were compared to corresponding MODIS and NOAA AVHRR visible and infrared imagery, QuikSCAT-derived wind fields, surface analysis and upper-air analysis. Additionally, fields of total atmospheric water vapor content V, total cloud liquid water content Q and wind speed W in the MC area were retrieved from AMSR-E brightness temperatures. Incorporating data from multiple satellite platforms improved the temporal resolution through employment of a greater number of satellites and increases the amount and kind of information collected. Detailed quantitative analysis of structure and parameters of MCs was carried out for several cases. Accurate location of the atmospheric fronts and the MC center at the sea surface as well as the small-scale organized variations of surface wind were revealed on Envisat ASAR images. AMSR-E retrievals showed the distinct features in the fields of V, Q and W. The MC areas were characterized by the higher V values and by appearance of water clouds with Q values as high as 0.1-0.25 kg/m^2. The frontal structure of the most intense MCs was depicted by high V gradients, position of maximum Q values near frontal boundaries and a large near-surface wind shear. Remarkable degree of similarity between ASAR, visible/infrared and 89-GHz brightness temperatures was found over a wide range of scales including the scales of convective cells and rolls in the marine boundary layer of the atmosphere. Individual ASAR images and time series of visible/infrared images, microwave radiometer and scatterometer measurements allowed to trace the life cycle of several MCs. The tendency for MCs to cluster spatially and temporally increases their role in the climate dynamic of the atmosphere and the ocean and should be studied further. Individual polar lows can have fluxes of heat of up to 1,000 W/m^2. MCs likely enhance the formation of cold deep water which is important for global-sale climate changes. Greatest insight into polar lows can be obtained from high resolution model runs, which can also contribute to forecasting of the lows.

The Recent Arctic Tipping Point and Biological Consequences

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As the result of the major loss of multi-year sea ice in the Arctic over the last two decades, likely due to the positive phase of the Arctic Oscillation (AO) climate pattern in the 1990s followed by a meridional (trans-Arctic) wind pattern in the 2000s, it appears that the real world is on a fast trajectory of sea ice loss relative to the expected value of ice loss from IPCC model projections. This fast track results from the combination of a weak global warming signal, fortuitous sequencing of large intrinsic natural variability, and a strong positive ice/ocean feedback. As the AO and meridional patterns persisted for multiple years, they allowed for cumulative shifts in ocean and sea ice conditions. The catastrophic 2007 minimum sea ice extent in the Arctic was 40 % below climatology, and 23 % below the previous record minimum of 2005. Many scientists consider that this magnitude of sea ice loss in one year is a surprise. The proximate loss of sea ice in 2007 was a result of an unusual high pressure/southerly wind pattern from June-August 2007, which increased downward long and short wave radiation and provided for direct ice transport across the central Arctic toward the Atlantic. But this rare event followed the steady preconditioning of sea ice loss over the previous two decades.

In many previous years positive Arctic temperature anomalies were observed in springtime, but the shift to an extreme observed temperature anomaly in fall 2007, of greater than +10° C following the summer sea ice minimum, is now consistent with IPCC model projections for future greenhouse gas influences with potential memory into the following summer. While we would not claim that the physics of the NCAR climate model match that of the 2007 sea ice minimum, large intrinsic climate variability and ice/ocean feedbacks are features of both the model and the 2007 sea ice event. Modeled sea ice projections show sharp one year decreases, which rebound in subsequent years but never recover to earlier extents. While uncertainties and surprises will always be with us in considering future polar climates, given the major loss of multiyear sea ice and the statistics of intrinsic climate patterns, it will be nearly impossible for Arctic sea ice to return to the previous states of the1980s and before.

Sea ice declines are influencing the pollock fishery and the phenology of gray whales, ringed seals and walruses in Alaskan waters. Decade long warm temperatures and reduced sea ice cover has shifted the Bering Sea from primarily an Arctic sea-ice based ecosystem to a sub-Arctic pelagic ecosystem and altered more northerly ecosystems sufficient to impact top predators. Pollock have expanded their range northward adding to their population stability, while cold water and benthic species are in decline. A 17-fold reduction in gray whale sighting rate in the northern Bering Sea and acoustic evidence for whales over-wintering in the Beaufort Sea suggest that whales are foraging in the Chukchi/Beaufort and remaining there longer. Ringed seals, the food for polar bears, are influenced by early snow melt as well as loss of sea ice cover. For walrus, the retreat of sea ice rafts them beyond productive Chukchi shelf waters. Responses to new ranges of ice edge retreats have included pup separation and increased stress from hauling out on land along the northwestern Alaskan and eastern Siberian coasts.

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A Coherency Between the North Atlantic Temperature Nonlinear Trend, the Eastern Arctic Ice Extent Drift and Change in the Atmospheric Circulation Regimes over the Northern Eurasia

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Atlantic Multidecadal Oscillation (AMO) monthly time series (*Ernfield, et al, 2001*) were investigated for last 150 years by implementation of a comprehensive smoothing technique controlled by cross-validation procedure, which provided more statistically significant trend evaluation than moving average or linear trend techniques. It was found that there is a winter sea surface temperature (SST) oscillation of around the 64-69 year scale behind a known SST fluctuation of decadal scale for winter months. The AMO trend demonstrates waters warming in the first part of twentieth century, cooling period in 50-th and 60-th, and warming in 80-th – 90-th years. This result confirms the global ocean conveyer theory of Broker (*Broecker, 1991*). Weak AMO linear trend respond to the greenhouse warming effect related to carbon dioxide concentration increasing (*Pokrovsky, 2007*). It demonstrates a slow warming behind a more strong (in amplitude) oscillation responded to still not well understood world ocean properties. This result was confirmed by independent research based on wavelet analysis of the same time series. Decadal and multidecadal scales were detected at wavelet power spectrum as a statistically significant with account to 95% probability level. Hurrell's data on monthly the North Atlantic Oscillation (NAO) index with account for SST since 1856 were also used and provided very close conclusions with respect to decadal and multidecadal oscillations and its phases. Similar study was carried out for the 20-th century ice extent (IE) time series obtained in Arctic and Antarctic Research Institute (St. Petersburg) for Russian margin seas: Kara, Laptev and East-Siberian during late summer and early autumn (*Polyakov, et al, 2002*). The IE smoothed curve in Barents and Kara Seas shows a coherent behavior: two minimums (in 20-th –30-th and in 80-th – 90-th) and one maximum in the middle of 20-th century (*Rayner, et al: 2003*). Wavelet analysis provided similar anomalies in power spectrum. It turned out that the atmospheric sea level pressure (SLP) climate series for Northern Siberia demonstrated fluctuations of decadal and multidecadal scales. The surface atmosphere temperature (SAT) series for North Asia sites displayed analogical time and spectral structures. Most exiting are results obtained for Central England surface atmosphere temperature time series since 1659 to 2007. It was found a positive phase in its strongest form in 17-18 centuries similar to those started in middle seventies of twentieth century. Coherency of the AMO/NAO/IE trends, on one hand, and SLP/SAT trends, on other hand, proved a close relationship existed in various modules of the climate system (atmosphere-ocean-glacial cover) in the Northern Hemisphere. Another issue of this study was an investigation of the phase delay detected under analysis of the smoothed curve signatures responded to above climate parameters. Considered phase delays in decadal and multidecadal oscillations were also explored by means of a cross wavelet analysis tool. To quantitative evaluate a linkage between above parameters we carried out a cross wavelet analysis (*Grinsted, et al, 2004*) and revealed some ranges in power spectrum, which are statistically significant with account for 95% probability level.

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Observing, simulating and interpreting the seasonal variability of the oceanographic fluxes passing through Lancaster Sound of the Canadain Arctic Archipelago.

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As part of the Arctic, Sub-Arctic Ocean Flux (ASOF) and the International Polar Year programs, a research project consisting of mooring and modelling work since 1998 has monitored the ocean and sea ice fluxes passing through Lancaster Sound, one of the three main pathways through the Canadian Arctic Archipelago (CAA). The aim is to understand the variability in ocean and sea ice volume, heat and freshwater fluxes passing through the CAA to determine their relationship to the ocean and ice budgets of the Arctic Ocean itself and to the circulation and vertical ventilation of the North Atlantic.

Eight years of mooring data have now been analysed and numerical model simulations for the entire CAA and Arctic have been run. The volume, freshwater and heat fluxes exhibit large seasonal and inter-annual variabilities, they are small in fall and winter and reach their maximum in late summer. The seasonal volume flux estimate ranges from a fall low of -0.01Sv in 1998 to a summer max of 1.3Sv in 2000. It has a 8-year mean of 0.65Sv and varies inter-annually by ±0.25Sv. Model simulations indicate that fluxes through Lancaster Sound make up 40-50% of the fluxes through the Canadian Archipelago and are dependent on the sea surface level difference between Beaufort Sea and Baffin Bay that are driven by the wind field in the Beaufort Sea.

Regression analysis with the Arctic Ocean wind field shows that the variability of fluxes in Lancaster Sound are related to the far-field wind forcing in the Beaufort Sea and not the local winds in Lancaster Sound. The N-S winds along the western coast of the Arctic Islands varies the sea level slope along the entire passage through the Arctic Islands causing its variability in flux observations. Numerical models are duplicating this affect.

Marine Microbial Interactions in a Changing Polar Environment

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Marine heterotrophic microbes (i.e. prokaryotic bacteria and eukaryotic protozoa) dominate the fluxes of organic carbon in the upper ocean, where they typically remineralize >75% of primary production back to CO2. Although these small organisms and their interactions are well studied in low latitudes, there is far less known about their distributions, community structure, activity and food web interactions, and their impact on upper open biogeochemistry in high latitudes. In the present study, we report on a meta-analysis of a large database on heterotrophic microbes from polar oceans. Using the results of the database analyses, and conceptual and analytical models, we examine the influence of predicted changes in the climate in polar regions on microbial activity, their mediation of upper ocean biogeochemistry, and potential feedbacks on the air-sea exchanges of climate active properties.

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Seasonal and Interannual Variability of the Sea Ice Extent in the Barents and Kara Seas

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The Barents and Kara seas are among the most sensitive regions in the Arctic Ocean to climate change. One of the key parameters to follow consequences of the regional climate change is sea ice cover. In 2007, from June to September the record (minimum) sea ice extent was observed in the Arctic. According to the US National Snow and Ice Data Center (NSIDC), on September 16, 2007 it was 24% below the previous record, set in September 2005, and 38% below the average sea ice extent calculated for 1979-2000 (or lower by 2.61 million km^2, an area approximately equal to the size of 10 United Kingdoms). Thus, sea ice extent in the Arctic Ocean dropped to 4.13 million km^2. The summer of 2007 brought an ice-free opening through the Northwest Passage that lasted several weeks, however, the Northeast Passage was not yet open because of a little tongue of ice remained along the Russian coast (Taimyr Peninsula). It is clear that long-term opening of both passages would have global impacts on trade and natural resource use.

The sea ice coverage charts are produced at the National Ice Center (NIC, NOAA) basing on remotely sensed data and observations. RADARSAT, DMSP/OLS, NOAA/TIROS, and DMSP/SSM-I sensors comprised the majority of the sensors used in the analysis and for the production of the charts. We used this data set to investigate seasonal and interannual variability of the sea ice cover in the Barents and Kara seas in 1997-2007. The analysis includes sea ice extent (ice surface), ice margin retreat in the periods of maximum and minimum ice extent, shift of these periods, trends in the sea ice extent, forecast for the sea ice extent, pecularities in different geographic regions, and correlation analysis with some of the meteo parameters aquired at meteo stations located at Bear Island, Svalbard, Franz Josef Land, and Novaya Zemlya. The Advanced Microwave Scanning Radiometer (AMSR-E) instrument onboard the NASA's *Aqua* satellite is also a perfect tool for regular monitoring of the sea ice extent in the Arctic. A comparison between NIC data and NSIDC Sea ice index, and AMSR-E ASI Sea Ice Concentration index from Hamburg Institute of Oceanography will be shown.

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The role of light, vertical stability and nutrient supply on the productivity of Arctic waters: a perspective on climate change

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Assessing the current and future productivity of the marine ecosystem is a major challenge of Arctic oceanography. A previous analysis at the pan-arctic scale suggests that annual, pelagic primary production is related linearly to the duration of the ice-free period through cumulative exposure to sunlight. However, the regions characterized by the longest ice-free periods are currently located in peripheral Arctic seas or polynyas where convective or wind-driven mixing between autumn and early spring is extensive. The ensuing replenishment of nutrients drives primary production to levels unattained in the strongly stratified interior of the Arctic Ocean (e.g. the Beaufort Sea), with the exception of localized hotspots and upwelling areas. Here I argue that climatic forcing of vertical nutrient renewal is potentially the primary driver of change in pelagic productivity, whereas irradiance mostly sets the timing and duration of the production pulse(s). In order to develop this hypothesis I will present and discuss the results obtained by the programs NOW, CASES and ArcticNet over the last decade. This analysis shows substantial inter-annual variability in new production despite open-water periods of similar duration. This variability is linked to differences in the vertical extent of mixing although the exact trigger is sometimes unclear. While the ongoing rise in the supply of heat and freshwater to the Arctic Ocean should bolster vertical stability and further curtail the average, upward supply of nutrients, the increased exposure of surface waters to direct eolian forcing might foster a net increase in pelagic productivity.

Causes of recent Arctic sea-ice variability investigated with a large-scale ice-ocean model.

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Recent Arctic sea-ice variability is investigated using OPA9-LIM3, a large-scale ice-ocean model. LIM3 is a C-grid dynamic-thermodynamic model, including the representation of the subgrid scale distributions of ice thickness enthalpy, salinity and age, and includes explicit brine physics. LIM3 is embedded in the ocean modelling system NEMO, using OPA9, a hydrostatic, primitive equation, finite-difference ocean model used in a 2°×2° global configuration.

The control run is a hindcast simulation of the Arctic and Antarctic sea ice variability and changes over the period 1970-2007 driven by the NCEP/NCAR reanalysis daily surface air temperatures and winds. Results from this simulation are thoroughly compared to available in-situ and satellite data and to outputs from other models. The mean seasonal cycle of sea ice is relatively well reproduced in both hemispheres, with snow depths and ice concentrations, thicknesses, salinities and drifts in reasonable agreement with observations. The model is also found to capture the high interannual variability of the Arctic and Antarctic ice packs as well as the strong negative trend in summer ice extent observed.

Several sensitivity runs are performed to analyse the causes of the recent sea-ice variability. First, in order to investigate the role forcing, its different components (temperatures, winds, clouds and oceanic heat flux) are replaced separately by their mean seasonal cycle. In addition, in order to study the role of preconditioning on the recent series of minima, the 2000's sea ice conditions are replaced by what they were in 1990.

Carbon Cycle in the Russian Arctic Seas

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Generalization on carbon cycling in the Arctic Seas of Russia (White, Barents, Kara, Laptev, East-Siberian and Chukchi Seas) has been carried out on the base data bank (particulate matter, bottom sediments, fluxes of matter) created in Shirshov Institute of Oceanology Russian Academy of Sciences, chemical analysis and consideration of results of last expeditions (2004-2007), and published data [*Vetrov and Romankevich, 2004; Stein and Macdonald, 2004; et al.*]. Scales of total organic (TOC) and inorganic carbon supply into Arctic Basin from land have been assessed. Main sources of TOC from land into Arctic Basin are river runoff $30 \cdot 10^6$ t yr^{-1}, including $24.4 \cdot 10^6$ t yr^{-1} through the Arctic Sea of Russia (ASR), and coastal abrasion $6.7 \cdot 10^6$ t yr^{-1}, including $5.6 \cdot 10^6$ t yr^{-1} through ASR. Many less supply are given by underground flows by-passing rivers $2.3 \cdot 10^6$ t yr^{-1} and eolian transfer $1.7 \cdot 10^6$ t yr^{-1}, including $1.8 \cdot 10^6$ t yr^{-1} and $0.8 \cdot 10^6$ t yr^{-1} into ASR respectively. The maps of month and annual distributions of chlorophyll "a", primary production and TOC fluxes to seafloor have been constructed for all ASR on the base CZCS (1978-1986), SeaWiFS (1998-2006), and MODIS (2002–2006) satellite data and field measurements. Primary production in ASR have been estimated at $194 \cdot 10^6$ t C yr^{-1}, including production of phytoplankton $163 \cdot 10^6$ t C yr^{-1}, ice algae $17 \cdot 10^6$ t C yr^{-1}, macro- $0.2 \cdot 10^6$ t C yr^{-1} and microphytobenthos $14 \cdot 10^6$ t C yr^{-1}. Flux of photosynthesized OC to seafloor is assessed at $90 \cdot 10^6$ t C yr^{-1} and total flux including terrigenous supply – at $99 \cdot 10^6$ t C yr^{-1}. About 58% photosynthesized organic matter (OM) is mineralized in water column. Mineralization of OM supplied to the bottom was estimated at $89 \cdot 10^6$ t C yr^{-1} (90%) as difference between OM buried in bottom sediments ($10 \cdot 10^6$ t C yr^{-1}) and OM reached seafloor. Coefficient of fossilization calculated as ratio TOC buried in bottom sediment to primary production has been estimated at 4.9–5.1%.

For purpose to assess a response of primary production to modern climate warming, trends of primary production have been considered at the polygons in the Barents, Kara and Chukchi Seas using satellite and field data. Criterions for choice of size and location of polygons were i) possible long period of open water, ii) a lot of observation for vegetation period, that mainly happens out of cloudiness hiding the sea surface, iii) minimal river supply with humic and particulate matter causing big errors in chlorophyll estimations. Presence of positive and negative trends has been revealed with general tendency of primary production increasing as well as accumulation rate of organic carbon in bottom sediments. Linear trend (1998–2006) shows little rise of primary production (mg of C m^{-2} per day) in the Barents Sea (3.4% yr^{-1}) and its little reduction in the Kara (–5.3%) and Chukchi (–3.3%) Seas compared to mean primary production for this period. Trend 2003–2006 shows reduce of primary production in the Barents Sea (–8% yr^{-1}), Kara (–27%) and Chukchi (–7% yr^{-1}) Seas. Trends (1998–2006) of summary primary production (t C yr^{-1}) at these polygons are positive – in the Barents sea (8% yr^{-1}), Kara (2%) and Chukchi (6%) seas as burial TOC mass in bottom sediments 2.8, 2.7 and 6.3% respectively.

Methods of quantitative estimation of terrigenous OM fraction in the bottom sediments by organic markers: C/N ratio, $\delta^{13}C$, $\delta^{15}N$, and the composition of *n*-alkanes have been considered. Estimation as result of optimal agreement of these markers use has been tasted for the East-Siberian Sea. The fraction of terrigenous OM in the organic matter of the upper layer of the studied sediments in the area devoid of ice in the summer varies from 15 to 95%, at an average value for the sea equal to 62%. The largest values (>80%) occur in the influx areas of the Indigirka and Kolyma rivers, while the lowest values were found in the eastern part of the sea, near the Long Strait, which is affected by Bering Sea waters. The complex estimation of the fraction of terrigenous carbon in the sediments allowed us to elucidate the average values of indicators of autochthonous and allochthonous OM in the East Siberian Sea. The C/N_{ter} ratio was relatively low (13.1). The estimated average isotopic composition of autochthonous carbon $\delta^{13}C = -22$‰ is within the average range of $\delta^{13}C$ varying from −21 to –23‰ for the Arctic Basin. In preliminary estimates, the land flux of suspended organic carbon in the East Siberian Sea ($2.6 \cdot 10^6$ t yr^{-1}) accounts for 17% of autochthonous (marine) production; however, the composition of the bottom sediments is determined mainly by terrigenous influxes containing older and more stable OM.

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Investigation of wind-driven, coastal polynya dynamics with a mass and momentum conserving, one-dimensional model

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Sea ice growth in wind-driven, coastal polynyas is believed to be an important mechanism for the formation of dense, intermediate and deep waters in the Arctic Ocean and subarctic seas. Coastal polynyas are typically only a few kilometers wide and so are difficult to resolve in current sea ice-ocean models. For this reason, the dynamics of these polynyas have been often investigated with relatively simple flux models that use the ice continuity, or mass balance, equation to calculate polynya evolution [*Willmott et al*., 2007]. Here we discuss the strengths and weaknesses of the flux model approach and extend it to include conservation of momentum as well as mass. We show that mass and momentum conserving models behave in ways sensibly different from traditional flux polynya models. In particular, while flux models admit polynya solutions that open to a steady state in times scales of hours to days, models that conserve both ice mass and ice momentum tend to create polynyas that open indefinitely.

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Two US Programs during IPY

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The focus on the poles during the IPY has resulted in the initiation of a number of major programs. Two such US programs in which the US National Science Foundation (NSF) is investing are the Arctic Observing Network (AON) and the combined Bering Ecosystem Study (BEST) – Bering Sea Integrated Ecosystem Research Program (BSIERP). AON is conceived to be a system of atmospheric, land- and ocean-based environmental monitoring capabilities that will significantly advance the volume and quality of our observations of Arctic environmental conditions. Data from the AON will enable the Study of Environmental Arctic Change (SEARCH), a U.S. initiative associated with the International Study of Arctic Change (ISAC), to document the manifold significant and rapid changes occurring in the Arctic. BEST –BSIERP is a partnership between NSF and the North Pacific Research Board to characterize the eastern Bering Sea shelf ecosystem and how it might change in response to a climate-induced loss of sea ice. It maintains international ties through the Ecosystem Studies of Sub-Arctic Seas (ESSAS) program. We describe the status and scope of these two programs, as well as plans for future development and opportunities for international collaboration.

SOCIAL, ECONOMIC, LEGAL AND POLITICAL ISSUES OF THE RUSSIAN ARCTICS

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The Arctic zone geopolitically is very important for all Arctic states. And it became such for Russia especially after breakdown of the USSR and reduction of its territory after separation of its southern and western regions because of spatial re-orientation of Russia development and acknowledgement of the role of Arctic in the long-term strategy of economic development. This area gives 95% of gas, 75% of oil, 90% of tin, the greater part of gold and diamond production.

Arctic has enormous economic significance for Russia in view of the prospective development of hydrocarbons. Potential geological resources of oil and gas in Arctic and nearby regions are evaluated at over 200 bill tons and 400 tril cu.m, respectively. However, development of these resources occurring in extreme natural-climatic conditions will demand scale foreign investments. And we should not forget about the issues of their transportation, storage and processing.

Worsening of the economic situation in the region in the period of reforms that was caused by cutting of state financing and mistakes in organizational and management solutions led to deterioration of the living standard of the population. The specific feature of the ethno-demographic situation in the Arctic regions is that its motive force is migration of the population that usually comes here for temporary earnings. And of special significance for economic-social development of Arctic is the correlation of shift and sedentary methods. It should be remembered that the sedentary way of life spurs the wider development of Arctic lands, their preservation and conservation as the places of permanent settlement. So far the issues of survival of the meager aboriginal peoples of the North and their interaction with migrants are addressed, but inadequately.

In the recent years the Arctic sea region turned into a source of international tension due to rivalry in getting access to its natural resources. This is caused, to some extent, by the fact that the legal regime of Arctic has not been determined in full so far.

Installation in late 2007 of the Russian flag on the bottom of the Arctic Sea near the North Pole provoked the beginning of the “Great Northern Game” the stakes in which are extension of a continental shelf for development of natural resources. Already now it can be said with assurance that the 21st century will become the time of struggle for the Arctic expanses and will give rise to ambiguous response from the Arctic countries that is difficult to predict.