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A special issue of GES Journal dedicated to the PEEX session of the IGU Conference 2015, Moscow, Russia

PREFACE

"Pan-Eurasian Experiment" is a multidisciplinary climate change, air quality, environment and research infrastructure program focused on the Northern Eurasian particularly arctic and boreal regions. It is a bottom up initiative by several European, Russian and Chinese research organizations and institutes. The overall goal of PEEX is to solve interlinked global challenges like climate change, air quality, biodiversity loss, chemicalisation, food supply, energy production and fresh water in integrative way recognizing the increasing role of the arctic and northern boreal forests in the context of global change. PEEX started in 2012 and set for the years 2013–2033 (–2100) as a long-term continuing activity. PEEX involves research communities representing 80 institutions from 20 different countries.

One of the sections of the International Geographical Union (IGU) Regional Conference held in Moscow in August 2015 was devoted to the PEEX program. The section hosted 34 oral and 16 poster presentations from the Russian Federation, Finland, Belarus, Norway, Greece, and China.

The current issue of GES journal contains several full papers from the IGU PEEX session; some other papers will be published in the upcoming issues of the journal.

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PAN-EURASIAN EXPERIMENT (PEEX) PROGRAM: GRAND CHALLENGES IN THE ARCTIC-BOREAL CONTEXT

ABSTRACT. The role of arctic and boreal area is crucial in understanding rapidly changing global climate. The climate change itself has an enhanced effect in arctic and boreal areas. On the other hand, several feedback loops and mechanisms could either enhance or decelerate climate change. Besides these interlinks, the territory has enormous natural resources and the way they are utilised in future gives us a direction how to meet global grand challenges and regional impacts. Regionally, effective early warning systems and comprehensive monitoring will guide in reducing emissions in practise and save natural resources. Here we give insight into these issues, introduce the SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) concept applicable to the PEEX network, and give a roadmap from deep understanding to practical solutions.

KEY WORDS: Grand Challenges, climate change, early warning systems, weather forecasting, arctic, boreal, research infrastructure, SMEAR concept, in situ observations, station network, WMO-GAW, data systems, GEOSS

BACKGROUND

Earth's system is facing several environmental challenges on a global scale, called "Grand Challenges". The growing population needs more fresh water, food and energy, which will affect our climate, air quality, ocean acidification, loss of biodiversity and shortages of fresh water and food supplies. Grand Challenges are the main factors controlling human well-being and security as well as the stabilities of future societies. Since the Grand Challenges are highly connected and interlinked, they cannot be solved separately. Therefore, a framework is needed in which a multidisciplinary scientific approach has the required critical mass and is strongly connected to fast-tracked policy making. The potential solutions are typically tightly coupled with each other (e.g. [Kulmala et al., 2015a]). To meet this requirement, a deep understanding based on new scientific knowledge is needed.

In order to avoid the collapse of the Earth system, one may estimate that the mankind has approximately a 40-year window of opportunity to find a common mind-set and practical solutions to answer the Grand Challenges. This estimate is based on the observed concentrations of CO_2. This year the maximum monhtly mean observed in May at the WMO GAW station Mauna Loa was 404 ppm (NOAA 2015 data: ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt), corresponding the global atmospheric CO_2 concentration. If global CO_2 emissions continue increasing at the same rate as they have done, within 40 years the CO_2 concentration overpasses 500 ppm.

The atmosphere forms a major part of the environment to which life on Earth is sensitively responsive. The atmosphere closely interacts with the biosphere, hydrosphere, cryosphere, pedosphere and lithosphere as well as urban surfaces on time scales from seconds to millennia [Wanner et al., 2008]. Changes in one of these components are directly or indirectly communicated to the others via intricately-linked processes and feedbacks. In recent years, a lot of research has been motivated by the importance of atmospheric aerosols on the global radiation budget, cloud formation and human health. Concentrations of reactive gases, greenhouse gases (GHGs) and atmospheric aerosol particles are tightly connected with each other via physical, chemical and biological processes occurring in the atmosphere, biosphere and at their interface [Arneth et al. 2010, Stocker et al., 2013; Kulmala et al., 2014a; Unger et al., 2014]. Human and societal actions, such as emission policy, urbanization, forest management and land use change, as well as various natural feedback mechanisms involving the biosphere and atmosphere, have substantial impacts on the complicated couplings between atmospheric aerosols, trace gases, GHG, air quality and climate [Raes et al. 2010; Shindell et al. 2012; Stocker et al., 2013; Baklanov et al., 2015].

Northern regions (>45°N) will undergo substantial changes during the next 40 years (e.g. [Smith 2010]]. The arctic boreal Northern Eurasian region, and especially the arctic coastal lines and Siberian region of the Russian territory, is extremely crucial for global climate (see also [Kulmala et al., 2015a]]. Permafrost thawing together with the Arctic sea ice changes will have multiple environmental (greenhouse gas emissions, air quality), economic (energy production, use of mineral, traffic and shipping and infrastructures) and societal (urbanization, cultural changes) consequences. Complex assessment of such consequences could be done using atlas systems. In Russia the National Atlas of Arctic is based on this conception [Kasimov et al., 2015].

Pan-Eurasian Experiment (PEEX) is an Arctic-boreal multi-scale, multi-dimensional and multi-disciplinary program that started in 2012 and aims at resolving the major uncertainties in the Earth system science and global sustainability questions focusing on Northern Eurasian regions [Kulmala et al., 2011; Kulmala et al., 2015a; Lappalainen et al., 2014;]. PEEX is a bottom up initiative by European, Russian and Chinese research communities involving also scientists from other countries. The program is divided into four pillars: research approach, research infrastructure, impact on society and capacity building / knowledge transfer. The 1st pillar is aimed to form holistic understanding of the dominating feedbacks and triggers of the land-atmosphere-aquatic systems and human activities relevant to the arctic-boreal region. The 2nd pillar is designed to establish coherent, coordinated in-situ ground based observations systems [Hari et al., 2015] together with the remote sensing applications across Northern Eurasian region and a multiscale modelling platform. The 3rdpillar is optimizing the impact of the research results for the use of Northern societies and connecting scientific assesment to fast-tracked policy making. The 4thpillar is oriented on capacity building and to educate the next generation of scientists, engineers and technical staff to carry out and continue the approach of the first 3 pillars. In this paper we focus on the 2nd pillar, the PEEX research infrastructure framework. We give insight on the SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) concept, PEEX infrastructure framework and provide a roadmap from deep understanding to practical solutions of PEEX program [Lappalainen et al., 2014].

PEEX NICHE IN A FRAME OF INTERNATIONAL RESEARCH INFRASTRUCTURE LANDSCAPE

PEEX research is based on inter-disciplinary, multi-scale approach which mobilizes a diverse range of scientific and technological expertise, including chemistry, physics, biology, meteorology, engineering sciences, environmental sciences, economics and social sciences.The implementation of the research agenda is built on a novel research infrastructure structure and involves laboratory studies, ground, ship and airborne field studies, satellite remote-sensing as well as numerical modelling studies ranging from the molecular *ab initio* molecular level to the global-scale Earth system models. The backbone of the research infrastructures is a network of continuous, comprehensive flagship stations [Hari et al., 2015], obtained by establishing new stations and/or updating existing stations. The regional coverage of stations and the quality of metadata including open access are the key issues for success.

The PEEX program is completing several ongoing or newly launched initiatives, programs, actions by European Union Horizon 2020, Belmont Forum, IIASA, WMO GAW and SAON. It provides an integrative approach in-terms of the four-pillar program concept, with all the scales taken into account in the analysis and methods, including a joint analysis of Arctic –boreal geographical domain. The PEEX research agenda is aimed to find solutions to global challenges and answers to PEEX science questions related, for example, the changing Arctic-boreal environments in terms of the greening Arctic (see [Kulmala et al., 2015]).

Furthermore, the PEEX research infrastructure aims to fill in the observational gap of coordinated and coherent *in situ* observations in the Northern Eurasian region. This task contributes to the intensive development of research infrastructure and supporting actions taking place in Europe, US (incl. The National Ecological Observatory, NEON US; ARM Climate Research facility) and other parts of the world, as well as to the ongoing, large-scale coordination of the world research data systems (The Global Earth Observation System of Systems, GEOSS; Global Atmosphere Watch GAW-WMO).

SMEAR CONCEPT AS APPLIED TO PEEX OBSERVATION SYSTEM

One of the first tasks of the PEEX infra pillar is to establish a process towards high-level Northern Eurasian Observation Networks. Particularly the Siberian region is currently lacking a coordinated and coherent ground-based atmosphere-ecosystem measurement network crucial for observing and predicting the effects of climate change in the Northern Pan-Eurasian region. The SMEAR concept provides a state-of-the-art foundation for establishing a PEEX observation system that integrates this system to the global GEOSS data system

SMEAR concept essentials

The SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) concept has been developed by University of Helsinki, Division of Atmospheric Sciences together with Division of Forest Ecology starting from 1995 [Hari & Kulmala 2005; Hari et al., 2005; Hari et al., 2009]. Today the SMEAR stations are facilitated with versatile measurement equipment and are carrying out continuous data flow. This enables to analyse the long-term trends in the aerosol, trace gas and GHG loadings over boreal forests and other surfaces as well as to test novel theories and instrumental techniques under different environmental conditions. The instrumentation of the flagship SMEAR station (SMEAR-II-Hyytiälä) covers over 1000 different measurements from standard weather station parameters to mass spectrometers and cloud radars. The basic idea is to measure the mass and energy transport between the atmosphere and surface, in order to understand processes, interactions and feedbacks. The core measurements of SMEAR stations cover meteorological parameters, such as the temperature, relative humidity, wind, precipitation and radiation, as well as atmospheric composition and biological activity (incl. aerosols, clouds, atmospheric chemistry, greenhouse gases, CO, O_3, NO_x, SO_2, VOCs, CH_4, NH_3, H_2SO_4, HONO, HNO_3, ions, external radiation, radon, photosynthesis, soil profiles and chemistry). These measurements include both concentrations and fluxes.

In Finland, SMEAR-type measurements are currently conducted at six stations located in forests, peatlands and lakes (atmosphere-biosphere interface), and in urban (urban surface) and marine/coastal environments. The core measurements in each station are the same, in addition to which specific measurements characteristic for different environments are carried out. Globally, the concept provides a unique basis to diversify the aerosol, trace gas and GHG measurements into different environments providing crucial information for global climate models and regional air quality models [Ghan et al., 2012; Zhang et al., 2012; Schutgens and Stier, 2014]. A fundamental part of the SMEAR measurement concept is to connect *in situ* measurements to satellite based information [Kulmala et al., 2011]. In order to cover the whole globe and be able to establish a Global SMEAR network, new proxies based on satellite data need to be developed as well [Bondur, 2011, 2014].

Technical elements of the SMEAR concept

The SMEAR concept consists of elements like the technical description of the SMEAR station prototypes at different hierarchy levels, SMEAR data system and plan of a global SMEAR station network. These main elements of the SMEAR concept are applicable to developing the existing stations, building new stations at once or to be uprated gradually towards a flagship station. For example, in Russia we have already mapped 206 potential atmospheric or ecosystem stations that could be a part of the PEEX-Russia observation network [Alekseychik et al., 2016]. Furthermore, we have already selected stations which could provide a pilot approach together with most advanced station in Russia and be integrated towards SMEAR measurement concept (Fig. 1).

The SMEAR station prototype description includes determination of the measurement parameters together with the instrument setups. A prototype description describes the station facility requirements (electricity, computer power, net connections, data flows & storage, towers, buildings, roads) and technical staff (man hours) requirements. A science plan can be tailored to each station in order to maximise the setup's scientific outcome and utilization of the measurements capacity of the whole network.

The SMEAR data description covers several aspects of data systems: data policy, data formats together with the description of a higher level data products, data delivery with a user interface, open data access and data quality assurance procedures (calibration laboratory, traceable calibrations). The SMEAR data products enhance scientific exchange also with user communities working on models, satellite retrievals and forecast systems. The near-real-time (NRT) data streams can be linked the European

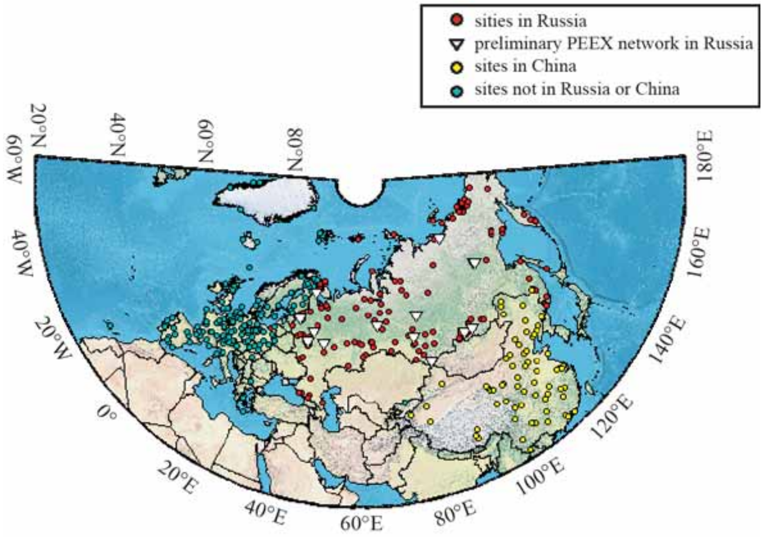

Fig. 1. Locations of permanent ground-based observation stations in the PEEX domain (Lappalainen et al. 2016, manuscript in preparation). The stations in Russia could provide a PEEX network pilot approach and be integrated to the SMEAR measurement concept.

Copernicus (former GMES) and WMO Global Atmosphere Watch (GAW) systems. The SMEAR data system uses automatic operation and remote control procedures which enable interoperability with the ICOS (carbon observations), ACTRIS (aerosols, trace gases, clouds) and ANAEE (experimental ecosystem measurements) stations. Optimal format and procedures for NRT data for each variable are defined including the initial and second level quality assurance (QA) for the incoming NRT data. The sustained SMEAR data streams for NRT reporting include station diagnosis and interoperability between local data center as well as data stream integration in other networks data centers.Dissemination of the data products can be connected to SMART-SMEAR web-interface [Junninen et al., 2009].

Global SMEAR

The Global SMEAR network plan introduces an optimal geographical coverage of a network, with a hierarchy structure of stations, investment plan, and how to find synergy with the existing research infrastructures and the connections with satellites and data systems. The global network will utilize existing knowledge of recommendations and guidelines for establishing a long-term, highly-standardized network system of the WMO-GAW (2009; 2014). GEOSS together with the European Union Environmental Infrastructures of ESFRI, the European Strategy Forum on Research Infrastructuresand Horizon 2020 RI-projects provide the framework for the harmonized data products development and calibration of network measurements with international standards. ESA's Climate Change Initiative (CCI) programme provides validated and improved satellite observations of atmospheric, land and ocean parameters.

PEEX INFRASTRUCTURE FRAMEWORK

The PEEX research infrastructure development is a back bone for performing the PEEX research agenda. It is important to understand that novel infrastructure and data are not only the basis for scientific breakthroughs but have also direct impacts on several other sectors of interest. A novel RI is useful for different type of end-users, including climate and air quality policy makers at regional and global scales, regional operational services and people developing new observation techniques and innovations for global markets (Fig. 2).

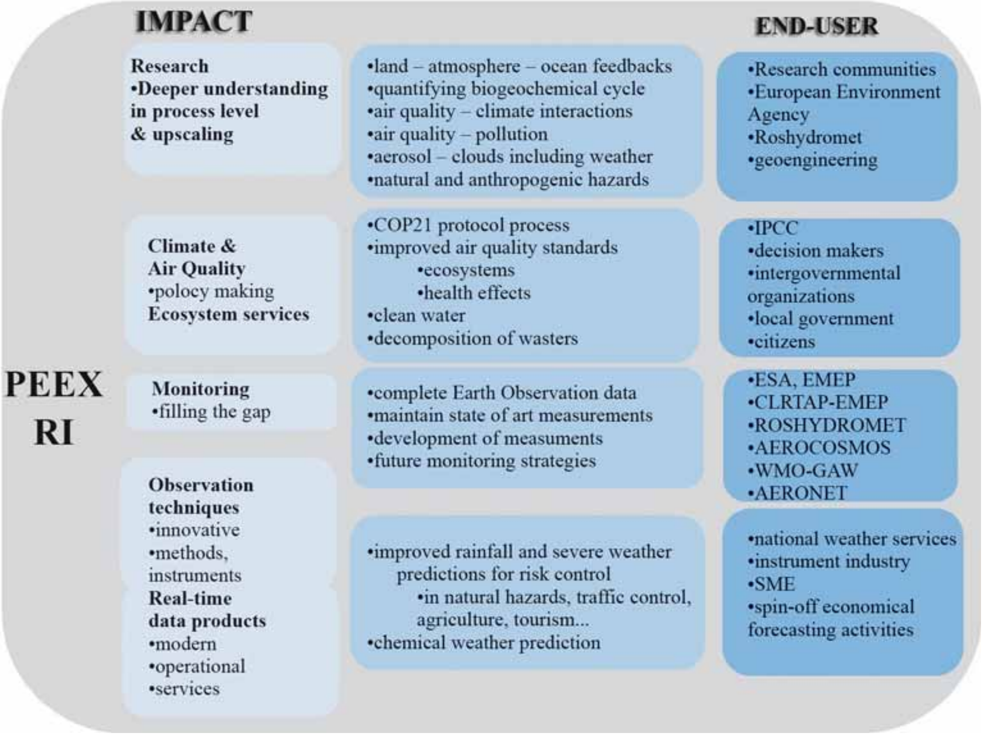

Fig. 2. The potential impact sectors and end-user groups of the PEEX Research Infrastructure (RI). Similar type of impact and end-user approach was applied in a frame of developing ACTRIS infrastructure in Europe.

PEEX Research Infrastructure (RI) contributing scientific breakthroughs in system understanding

We need comprehensive data from the Pan-Eurasian region for not only answering the most urgent science questions but also solving the air quality dynamics of megacities like Moscow and other megacities [Kulmala et al. 2015b; Zilitinkevich et al., 2015]. The PEEX research agenda introduces large-scale research questions and topics relevant to Arctic-boreal region [Kulmala et al., 2015a; Lappalainen et al., 2016]. The new understanding of feedbacks, atmospheric interactions of greenhouse gases, aerosols and trace gases and their connection to the biosphere and anthropogenic activities need to be implemented into large-scale climate models, regional models and atmospheric chemistry models. At the moment the existing observation networks do not deliver information with sufficient accuracy to understand feedback loops, interactions and processes in the land-atmospheric-ocean continuum. As a whole, connected measurements provide a potential for scientific breakthroughs.

Greenhouse gases like CO_2 are relatively well-mixed worldwide, in strong contrast to, for example, aerosols that are highly spatially inhomogeneous depending on the development level of different regions. More data are needed to improve the process understanding and model quality. The PEEX RI aims to provide climate components needed for understanding how the intensity of anthropogenic actions, ecosystem biological activity and water cycle are inter-linked with the climate system. Trace gases and atmospheric aerosols are tightly connected with each other via physical, chemical, meteorological and biological processes occurring in the atmosphere and at the atmosphere – biosphere – water cycle interfaces. For example, the precipitation response and thus the hydrological sensitivity differ strongly for greenhouse gas forcing and aerosol forcing. Decreasing aerosol emissions in the future can lead to an even stronger increase in precipitation as can be expected from GHG forcing alone [Westervelt et al., 2015].

PEEX RI contributing to Climate and Air Quality Policy at regional and global scale

PEEX also aims to provide policy-relevant understanding of the Arctic-boreal environments as a whole to supervise and contribute to the United Nations Framework Convention on Climate Change, the Conference of the Parties (COP) and Subsidiary Body for Scientific and Technological Advice (SBSTA) approach and implementation.The EU Commission has proposed in January 2014 a greenhouse gas (GHG) reduction target of 40 % for 2030. The latest UN Climate Change Conference was held in Paris, in December 2015. In the global climate context, IPCC forum is one of the most import end-user and collaborators of PEEX approach.

Health effects due to air pollution and potential damage from climate change are among the most important environmental problems facing megacities like Moscow and Beijingor other urbanized territories [Baklanov et al., 2012, Kasimov et al., 2014, Guo 2014, Kulmala 2015b, Petäjä et al., 2015]. Quantification of contributions from different anthropogenic and natural sources to the trace gas and aerosol particle load is needed, along with improved source apportionment. Data from Northern Eurasian regions is urgently needed to be linked to the European databanks (incl. EMEP http://www.emep.int/, EBAS databases http://ebas.nilu.no/), in order to collect new information on regional GHG, trace gas and aerosol loadings, estimates on hygroscopicity (related to dose of the population from the loadings) and composition (related to toxicity of the particles) and estimates of how much of the loading is due to the long range transport.

The social benefits are optimal when timely, high-quality and long-term observational data and modeling data are available to aid air quality decision-makers at every level – from intergovernmental organizations to local government and then to citizens. World Health Organization (WHO) has estimated that in 2012 7 million premature deaths world-wide attributed to air pollution, which makes it the single largest cause of death in the world (WMO 2015).

Long-term information on trends is crucial for understanding the land-atmosphere interactions of urban environments and effectiveness of air quality policies. So far, the best results have been related to the verification of the feedback loops [Kulmala et al., 2004, 2013, 2014], Biogeochemical cycles and atmospheric new particle formation (e.g. [Mäkelä et al., 1997, Kulmala et al., 2013]). By quantifying processes, interactions and feedbacks related to the PEEX objectives. We will be able to identify, for example, the steps that are needed to reduce air pollution levels in megacities by a factor of 3–4, to determine how pollutant emissions in China are affecting arctic and boreal areas, and to find out how these effects will be changed due to future emission reductions in Russia and China.

Novel measurement data can also be used for a cost-benefit analysis relevant to different actions to improve air quality, fresh water and food supply, environmentally and economically sustainable use of natural resources including energy, and to prevent further climate change. Such activity would be linked to continuous and comprehensive research, atmospheric and emission modelling, and the process level understanding at regional scale. For example, the factors controlling the air quality in mega-cities need to be quantified and recognized, and the solutions need to be found in collaboration with the private sector, the local government and the national government levels [Zilitinkevich et al., 2015]. It is also important to investigate application of active remote sensing instruments, such as ceilometers and weather radars, to diagnose weather conditions leading to severe air pollution episodes.

PEEX RI contribution to operational services at regional scale

There will be large regional differences in warming due to the changing surface conditions and permanent changes in circulation or precipitation patterns (IPCC). Refer to European ACTRIS-I3-RI Roadmap regional monitoring of climate change is important to documenting to what extent the predicted climate change will actually occur and to take it into account in the development of weather forecast and climate models. National weather services need well-measured climatic components for testing improved physical parameterizations in weather forecast models predicting hazardous weather events. Weather services also need to evaluate cloud-aerosol and other air-pollutant schemes in forecast models. Near-real-time applications are also needed for chemical weather prediction to be delivered to policy makers at all levels and to the general public. To be able to respond to these requirements, the most climatic regions of Northern Eurasia should be represented by at least one PEEX core station for high resolution observations.

Current operational weather forecast models have maximal horizontal resolution of 1km or so and cannot resolve microphysical processes; instead, these are to be parameterized in terms of bulk variables held in the mode, typically at about 1-km scale. Concrete formulations of major parameterization schemes cause much uncertainty in the forecasts, and are the area of active research. Improvement can only take place if we have a number of well-provided atmospheric observatories equipped with Doppler cloud radars and advanced lidars, providing continuous vertical profiles, aerosols, cloud particles and their phase (liquid or ice) across the atmosphere as addressed by the ACTRIS-I3-Roadmap. Such stations, covering the climates of Northern Eurasia will, firstly, provide data for evaluating the performance of current weather forecasting models, and, secondly, suggest improved parameterization schemes to improve the forecast performance.

Similar to the European ENVRI (ACTRIS, ICOS, etc.) approach, the PEEX approach aims to harmonize the on-line, trace level gaseous air pollutant measurements, and yield reliable concentration fields and trends over Russia. This would help to quantify the relative contribution of anthropogenic sources and improve air pollution abatement strategies. Furthermore, this would support reliable monitoring of particulate and gaseous air pollutants at high time-resolution in a standardized way across the Northern Eurasia region and is of interest for the climate and air quality modeling community, and political entities and general public.

New observation techniques and innovations having global markets

New observation technologies will be an outcome applicable to different commercial sectors, such as bio-economy, Clean-tech and digitalization. New technologies can be implemented at locations in different climate regions and will enable local governments to base their policy on more accurate expectations of regional climate change, and local industry to develop appropriate products and technologies to counteract or adapt to local climate change. This is an important development, especially in light of the future climate change and its consequences. Climate monitoring will increasingly become vital for future societies. Many spin-off economical activities, based on improved rainfall and severe weather predictions, are to be expected; e.g. in natural hazards, in (air) traffic control, in agriculture and tourism. Development of new methods and instrumentation will also have important impacts on small and medium-sized enterprises (SMEs), innovation, market etc.

The new emerging area of technical innovations is called a global change geoengineering or climate change engineering, also introduced by the PEEX 4thpillar: the society impact [Lappalainen et al., 2014]. The term "climate engineering" covers a number of different technologies which aim to achieve large-scale technical intervention in the climate system, but which, at the same time, differ substantially with regard to the associated risks, effectiveness, side-effects and cost of deployment. The climate change engineering is designed to affect the Earth's radiation budget in two ways: altering the Earth's radiation budget without reducing greenhouse gas concentrations or reducing the greenhouse gas concentrations so that to change the Earth's radiation budget.

FUTURE OUTLOOK AND ROADMAP

The PEEX network is needed for ensuring the utilization of natural resources in an effective, yet sustainable way. The network would have a capacity to act as a backbone for Early Warning System and improved weather prediction. It would fill in the current observational gap in the Siberian region and bring the observation setup into international context with standardized or comparable procedures. The starting point on the way to sustainable solutions in Northern Eurasian region is to establish flagship stations for continuous and comprehensive observations as a part of the GLOBAL SMEAR network and the Global Atmosphere Watch Programme. The SMEAR flagship stations would cover a full suite of instruments and data systems for monitoring the material and energy flows in the land–atmosphere continuum, whereas some stations would have a targeted instrumentation for a specific topics and/or regions for providing spatial variance of the parameters.

As a summary we propose the following roadmap:

1. Establishment of a continuous, comprehensive measurements network (Global SMEAR network) for global observations, including PEEX ground based in situ observations (supersites) completing the satellite remote sensing observations.

2. Establishment of open data flows and joint data analyses including: open access to observational data and metadata, modelling platforms, emission source analyses, and integration of all scale experimental and modelling results. Via novel data and modelling platforms, PEEX will make it possible to quantify airquality-climate interactions and feedbacks, particularly for megacities in Russia and China, and to analyse the biosphere-trace gas-aerosol-cloud interactions and feedbacks in the Northern Eurasian area, in order to determine past and present conditions and to predict future conditions of the continental planetary boundary layer, as well as boundary-layer climates, and development of arctic greening.

3. Performing economically effective structural changes and constructing reliable early warning systems, based on the data and holistic analysis sustainable solutions and decisions.

PEEX implements strategic tasks of the Sustainable Earth System Manifesto (Kulmala et al.) in the Northern Eurasian region. The latter addresses the urgent need for observations of critical environmental parameters worldwide, evoking a political consensus to overcome various geopolitical interests and prioritize the sustainable living conditions in different parts of the world, and providing sustainable technological solutions for the Grand Challenges aimed at efficient moderation of environmental changes. The PEEX agenda contributes to the Manifesto by providing conceptual design of the land-atmosphere observation network for the Northern regions, in particular, for Russia. Furthermore, PEEX contributes to the global agenda by acting as a Future Earth Arctic-boreal hub in frames of coordination of the Earth System research, and belongs to the key initiatives of GEOSS Cold Region activities.

PEEX will actively seek for long-term funding in order to establish new SMEAR-concept stations and to make their continuous operation possible. All this should be based on national, bilateral, Nordic and all-European funding with matching funding concepts in Russia and China. Estimated building cost is approximately 15–20 million Euros per one flagship station. Such stations can be grown up from integrative blocks (1 million Euros per block). The annual operation costs are ca 10 % of the investment costs.

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Pan-Eurasian Experiment (PEEX) is a bottom up initiative by several European, Russian, Chinese and North American research organizations and institutes. PEEX started in 2012 and set for the years 2013–2033 (–2100) as a long-term continuing activity. PEEX involves research communities representing 80 institutions from 20 different countries.

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FIELD AND NUMERICAL STUDY OF THE WIND-WAVE REGIME ON THE GORKY RESERVOIR

ABSTRACT. The paper describes the study of wind-wave regime at the Gorky reservoir. A series of field experiments (carried out from May to October in 2012–2015) showed that the values of the drag coefficient C_D for a middle-sized reservoir in the range of moderate and strong winds are approximately 50 % lower than its values typical of the ocean conditions. The obtained parameterization of C_D was implemented in the wave model WAVEWATCH III to receive the correct wave forecasts for a middle-sized reservoir. Statistical distribution of the wind speeds and directions called for consideration of wind field heterogeneity over the Gorky reservoir. It was incorporated using the wind forcing from atmospheric model WRF to WAVEWATCH III. Homogeneous wind forcing from the experimental data was compared with heterogeneous wind forcing from WRF. The need for further improvement of the quality of wind and wave prediction is discussed.

KEY WORDS: reservoir, field experiment, simulation, wind-wave interaction, WAVEWATCH III, WRF

INTRODUCTION

The study and the prediction of the wave regime in middle-sized reservoirs has both scientific and practical importance. First of all, waves on the water are a major source of erosion of the banks of reservoirs. A correct wave prediction determines the safety of inland navigation. In addition, the processes of momentum and heat and moisture exchange over the reservoir define microclimate of the adjacent areas.

The study of the wave regime of middle-sized reservoirs (with a linear size of 10–100 km) is also relevant because of the lack of the experimental data. Rare examples of these experiments are presented in [Atakturk and Katsaros, 1999; Babanin and Makin, 2008]. In this paper we describe a series of the field experiments carried out by our research group on the Gorky Reservoir. The results of the field experiments demonstrated the need to consider a number of specific characteristics of the wave regime of middle-sized reservoirs that should be taken into account in the high-quality wave forecasts.

Usually, the numerical description of the waves on the middle-sized lakes and reservoirs is based on the empirical models: for example, in [Poddubnyi, Sukhova, 2002] there is a block for the numerical description of the surface waves in the Rybinsk and Ivankovo reservoirs based on the empirical formulas, and in [Sutyrina, 2011], the wave regime on the Bratsk reservoir was also studied using the empirical relationships. But the empirical relationships are based on the averaged characteristics, which can not be used for the prediction of the extreme wave conditions that are highly important for the operational meteorology. Therefore, it is necessary to use modern numerical wave forecast models. They are based on the numerical solution of spectra action balance equation. The models are classified by their treatment of the source terms (physical processes). Outdated first- and second-generation models use observed spectral shapes and sustained spectral energy levels to infer effects of physical processes. Modern third-generation models (WAVEWATCH III [Tolman et al., 2014], WAM [Gunter et al., 1992], SWAN [SWAN team, 2006]) parameterize all physical processes explicitly, without imposing spectral shapes or energy levels. These models describe the evolution of a 2D wave spectrum under the impact of wind-wave interactions, dissipation, nonlinear wave-wave interactions, and in the case of shallow water, some of them also take into account the influence of the bottom friction, depth-induced breaking and triad wave-wave interactions.

It should be noted that the third-generation numerical models are adapted to the ocean conditions. However, the wave models were used successfully on large lakes. WAVEWATCH III was successfully used for the wave forecasts on the Great Lakes in the USA [Alves et al., 2011]. In addition, WAVEWATCH III and SWAN were applied successfully to the Caspian Sea and Lake Ladoga for wind and waves hindcast [Lopatoukhin et al., 2004]. Recently, the first results of the use of WAM to predict the surface waves in a middle-sized water body were obtained [Hesser, 2013]. We have chosen WAVEWATCH III model for the simulation of surface waves on middle-sized reservoirs, because this model considers the largest number of interactions available in the current model versions.

Thus, for the WAVEWATCH III application to the conditions of the middle-sized reservoir, the tuning of the model is required. The tuning should be carried out in two steps: the adjusting of the wind input source term and the adjusting of the "collision integral." This adjusting is caused by the specific characteristics of the waves at small fetches of a middle-sized reservoir: the wind input, which is proportional to the relation of the friction velocity (or 10 m wind speed) to the phase wave velocity [Tolman et al., 2014] is more intense, as well as a stronger non-linearity is caused by steeper waves. The dissipation due to wave breaking remains unchanged. The first step of the tuning was implemented in [Kuznetsova et al., 2016 a].

In this work, the tuning implemented in [Kuznetsova et al., 2016 a] was used to study the ways to set the wind forcing. In the previous works [Kuznetsova et al., 2016 a, b], the wind speed was assumed to be homogeneous over the entire area of the reservoir due to the lack of the sufficient experimental data, and was obtained from the experimental measurements that consider temporal variability. This assumption is a source of possible errors in the numerical experiment. Consideration of the high spatial variability is a challenging task. To solve it, it is possible to use atmospheric models of high spatial resolution, for example, atmospheric model Weather Research & Forecasting (WRF). This method of the wind forcing characterization was realized, for example, in [Alves, 2014]. This paper presents the use of the wind forcing from WRF to WAVEWATCH III for middle-sized reservoirs.

METHODS OF THE FIELD EXPERIMENT AT THE GORKY RESERVOIR

Field measurements were carried out from May to October in 2012–2015 in the waters of the Gorky reservoir which is formed by the dam of the Nizhny Novgorod hydroelectric station near the town of Gorodets on the Volga River. At the normal water level, it spans 430 km from the Rybinsk dam to the Nizhny Novgorod hydroelectric station dam, and its maximal width is 26 km. The water surface area is 1591 km^2, the total volume

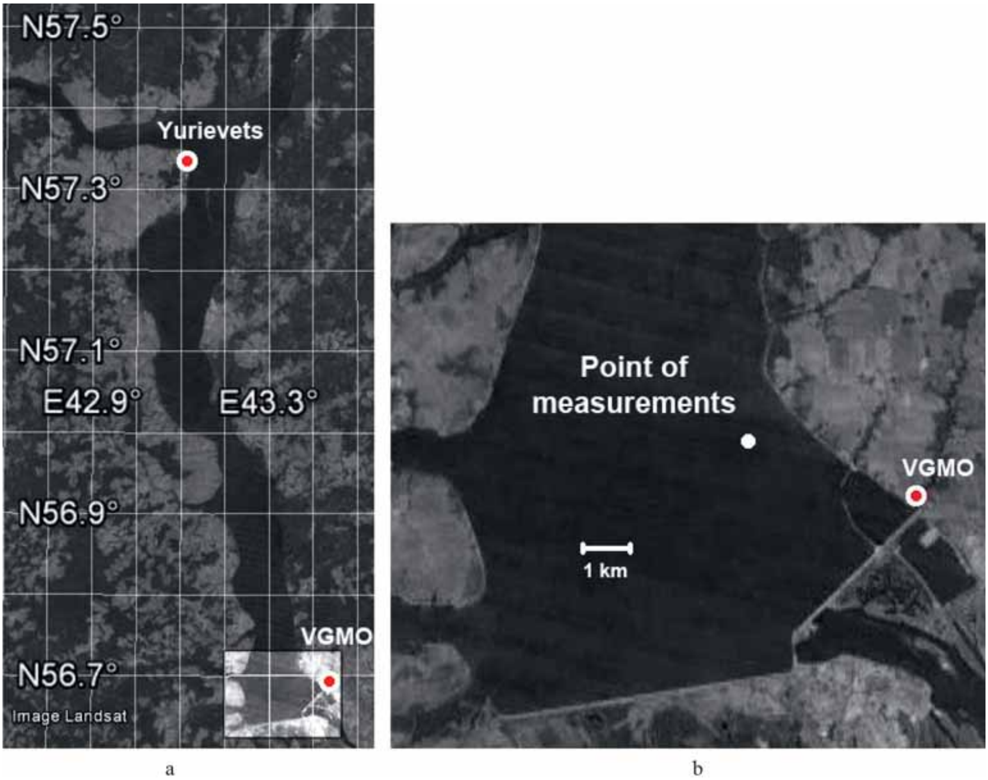
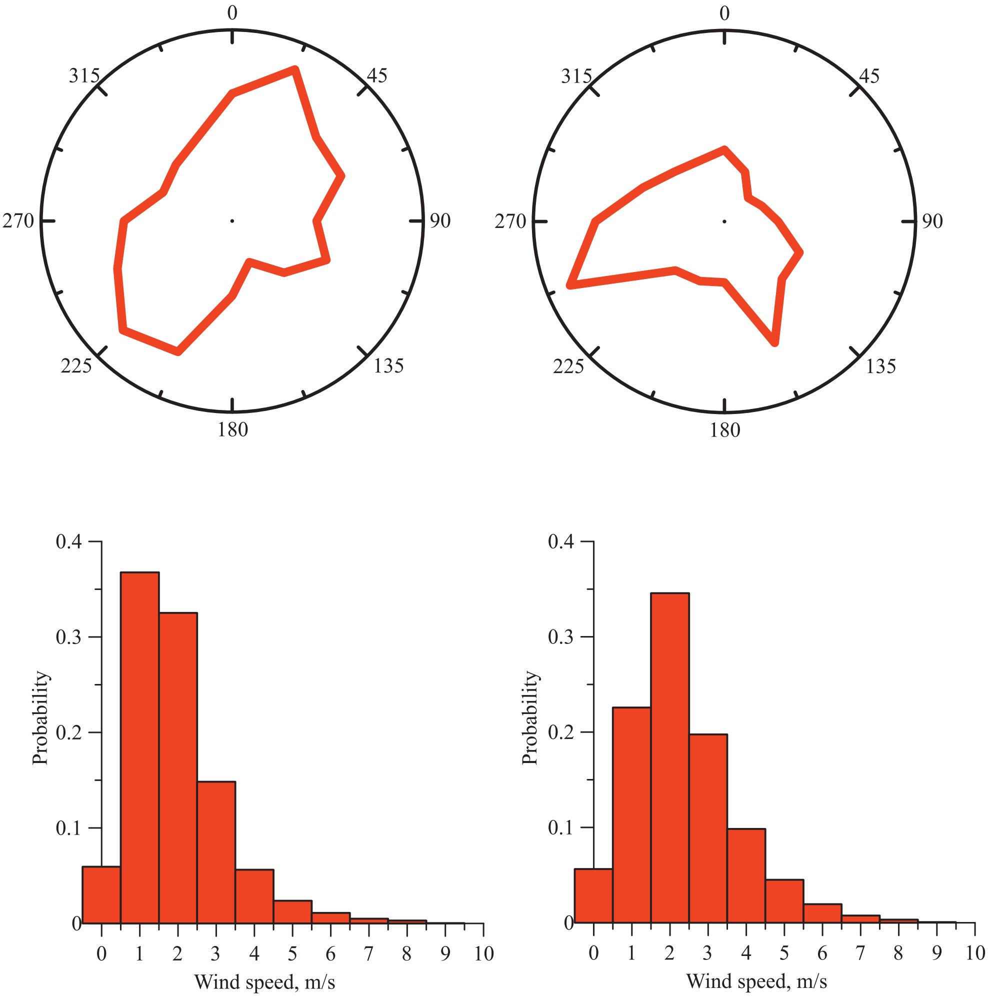


Fig. 1. a) The Gorky reservoir (Google Earth data); b) Zoom view of the measurements area. Red dots in white circles show the weather stations: Volzhskaya (VGMO) and Yurievets.

is 8.8 km^3, the useful volume is 2.8 km^3, and the useful volume of the navigational prism is 0.6 km^3. According to the hydrological regime and navigability, the reservoir is divided into three sections – river, lake, and river and lake. Measurements were carried out in the southern part of the lake area of the reservoir (Fig. 1). The lake area is 97 km from the Elnat River mouth to the Nizhny Novgorod hydroelectric station dam. The width of this part of the reservoir varies from 5 to 14 km, and only near the Puchezh city, it is 3 km. The depths of the main ship channel varies from 4.5 to 20 m, and in the study area, it varies from 9 to 12 m depending on the season and the point of measurement. Throughout the lake part of the reservoir, the right bank is high and sometimes steep. The left bank is low and flat almost everywhere; but near the Sokolskoye village and in the area extending from the city of Chkalovsk to the Nizhny Novgorod hydroelectric station dam, the bank is high and steep.

Fig. 2a shows the distribution of wind speed and direction measured at Volzhskaya weather station (Gorodets) close to the field study area. The distribution was based on the data for the navigational period (May 10 – October 31), 2010–2015. Despite the notable selected wind direction, the range of possible directions is rather wide. The elongated shape of the reservoir allows studying wind and waves of different fetches. Volzhskaya is located on the high bank (about 15 meters above the water level) and the values of the wind velocity at the shore are very different from those over the water area: the wind speed over the water area is up to two times higher. Fig. 2b shows the distribution of wind speed and direction measured at the Yurievets weather station at the same intervals. The difference between the distributions obtained from the two weather stations shows significant spatial inhomogeneity of the wind above the reservoir and, consequently, it is necessary



a

b

Fig. 2. Statistical distribution of the wind directions (top graphs) and wind speeds (low graphs) averaged over 2010–2015 during the navigational period (from May 10 to October 31): a) Volzhskaya, b) Yurievets.

to measure wind and wave characteristics at different points of the reservoir in order to determine the accurate prediction or statistical parameters of wind and waves.

The field studies include measurements of the wind velocity profile, surface waves, profiles of water and air temperature, and current velocity profile (see similar measurements in [Bakhanov et al., 2011]), as well as the measurement of turbulent air flow characteristics (see similar measurements in [Bogatov et al., 2014]) and in the water column. The measurements were carried out from a vessel (Fig. 3 a) using the author's original buoy station (Fig. 3 b, c) based on the oceanographic Froude buoy station.

On the board of the vessel, an ultrasonic profiler of the current velocity ADCP (Teledyne RD Instruments), similar to that used in [Bakhanov et al., 2011], a high-frequency ultrasonic three-gauge wind speed HS-50 (sample rate is 50 Hz) (Gill Instruments) (see [Bogatov et al., 2014]), and CTD-probe (see results in [Ivanov et al., 2015]) were located.

The buoy represents a mast semi-submerged in the water and held in a vertical position by

Fig. 3. a) Vessel on the Gorky reservoir. b) View of the operating state of the Froude buoy. c) Schematics of the Froude buoy.

the float near the surface and by the load at a depth (Fig. 3 b, c). The total length of the mast is 12 m, the length of the topside is 5.3 m. The resonant frequency of vertical oscillations is 0.25 Hz, which corresponds to a wavelength of 25 m. On the buoy's mast, 4 ultrasonic speed sensors WindSonic (Gill Instruments) were located at heights of 0.85 m, 1.3 m 2.27 m, 5.26 m. The fifth sensor was located on the float tracking the waveform for measuring the wind speed in the close proximity to the water surface. The distance from the float to the buoy's mast is 1 m, and the height of the wind speed measurement zone is 10 cm from the water surface. The buoy was also equipped with air temperature sensor (at heights of 0.1 m [float], 0.85 m, 1.3 m), water temperature sensor, and three-channel string wave gauges, which allowed us to retrieve the waves space-time spectra.

WindSonic is a two-component ultrasonic sensor with a 4 % measurement accuracy and velocity resolution of 0.01 m/s. Operating range of wind speed measurements 0–60 m/s includes measurements in calm conditions. Resistive temperature sensors measure the environmental temperature with resolution of 0.01 °C and a 3 % measurement accuracy. The wave gauge consists of three pairs of resistive wire sensors, located at the vertices of an equilateral triangle with a side of 62 mm, the data sampling rate is 100 Hz. The system allows estimating parameters of the wave, which length exceeds the double distance between the sensors $(k_{max} \approx 0{,}5^{-1})$. The algorithm of the processing of the signals received from the devices uses the Fourier transform and is described in detail in [Troitskaya et al., 2012] (a similar algorithm which uses the wavelet transform is described in [Donelan et al., 1996]).

The particular attention in the study was paid to the determination of the dependence of the drag coefficient on the wind speed $C_D(U_{10})$ (see, for example, [Troitskaya et al., 2012]), which defines the momentum flow from the wind to the waves. The dependence $C_D(U_{10})$ is rather well studied for weak and moderate winds in the open ocean, and currently the great attention is paid to the wind-wave interaction under hurricane winds. However, the conditions of small and middle-sized water bodies are substantially different from those of the ocean (small fetches resulting in steep waves, and shielding of wind by the banks), and therefore it is fair to expect different wind-wave regime in these conditions. For example, the results obtained in [Atakturk and Katsaros, 1999; Babanin and Makin, 2008] show features of wind-wave regime in the conditions of inland waters.

RESULTS OF THE FIELD EXPERIMENT

The field study included 44 experiments in a wide range of wind speeds (Fig. 4 a) in the point of measurement. It should be noted that the significant wave height is greatly influenced not only by wind speed, but also by its direction. Due to the small size of the vessel used for the field experiment, the measurements could not be carried out in heavy seas, so the direction of the observed wind speeds U_{10} with values more than 8 m/s is not north. This stipulation has a significant impact on the distribution of the measured waves heights H_S (Fig. 4 b) and of the spectral peaks f_p (Fig. 4 c).

An important feature which sets this study apart from the similar studies (see [Ataturk and Katsaros, 1999; Babanin and Makin, 2008]) is the use of a lower mobile speed sensor tracking the waveforms (see [Kuznetsova et al., 2016 a]). The value of drag coefficient C_D is determined by profiling [Kuznetsova et al., 2016 b], and the impact of the data from different horizons on the resulting approximation of the wind speed profile is analyzed. Fig. 5a shows the comparison of the retrieved relationships $C_D(U_{10})$ for two combinations of speed sensors: with the use of the lower sensor and without it, as well as the results presented in [Atakturk and Katsaros, 1999; Babanin and Makin, 2008], and oceanic parameterization [Fairall et al., 2003]. The values $C_D(U_{10})$ are higher and closer to the results of [Atakturk and Katsaros, 1999; Babanin and Makin, 2008; Fairall et al., 2003] without the use of the lower sensor while the use of the lower sensor demonstrates lower values of the drag coefficient. Fig. 5b shows a comparison of the retrieved dependencies $C_D(U_{10})$ with either two lower only or all five sensors. The use of two sensors only demonstrates significant differences in the retrieving of winds in the range of weak winds.

These results can be interpreted by the deviation of the wind speed profile shape from the logarithmic one. This difference is probably due to the stratification of the atmospheric surface layer as well as to the nonstationary wind, as the lower part of the profile quickly adapts to the changing conditions of the surface waves, wherein the parameters of the air flow determine the momentum transfer from the wind to the waves exactly at the water-air boundary.

Thus, it has been demonstrated that the use of the lower sensor, in particular the use of the two lower sensors only, significantly affects the results of the measurement. To determine the accuracy of the measured dependence $C_D(U_{10})$, it was used in the numerical simulation of wind waves in the framework of WAVEWATCH III. To do this, the experimental data were fitted (Fig. 5b) with the function:

$$C_D = 0.00124U_{10}^{-1} + \\ + 0.00034 + 0.000049U_{10}. \qquad (1)$$

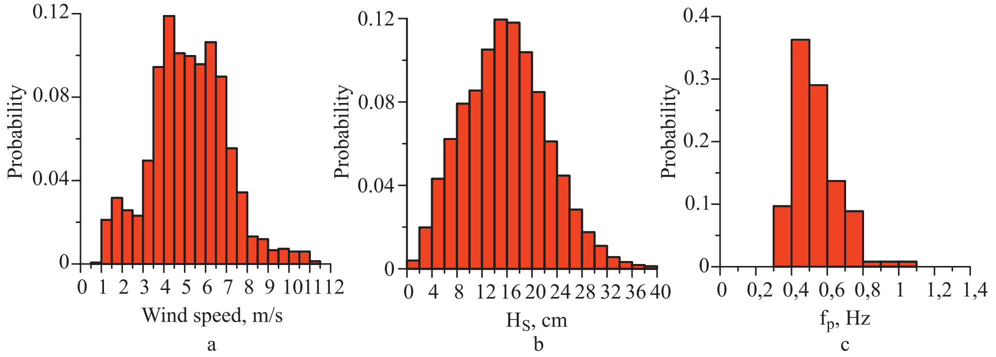
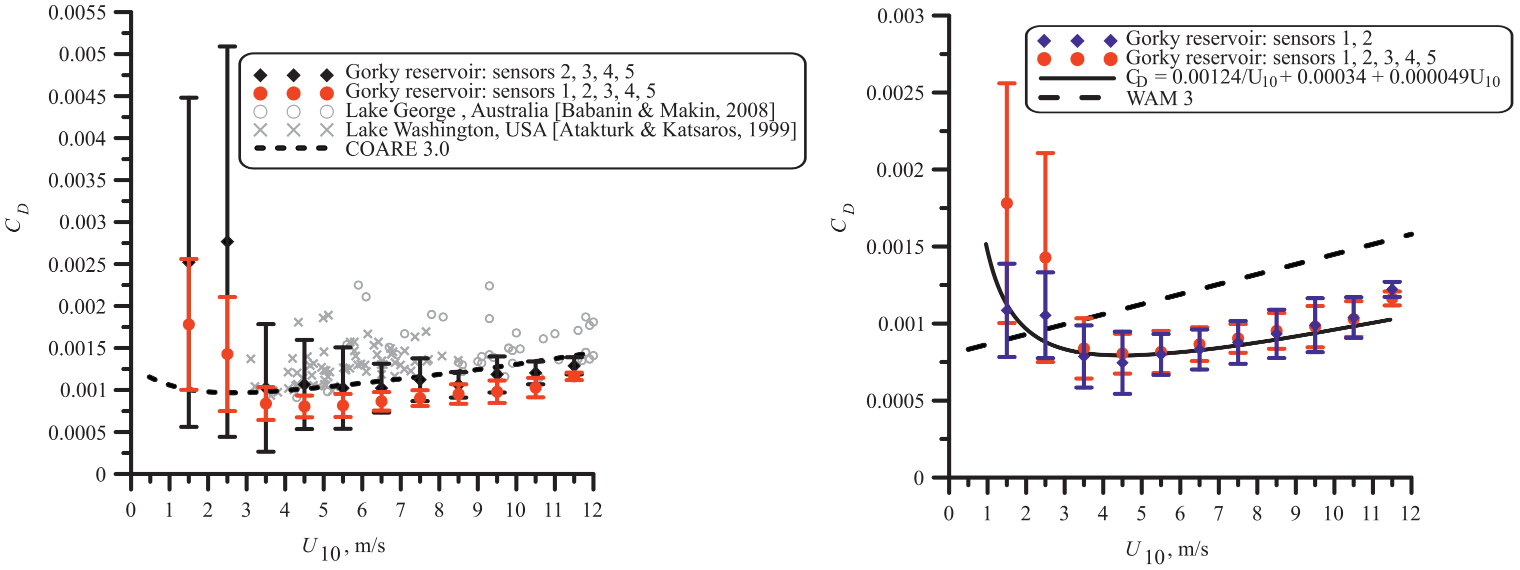


Fig. 4. The statistical distribution of the values measured during the experiment:
a) wind speed, b) significant wave height, c) peak frequency.



a

b

Fig. 5. Comparison of the retrieved dependences $C_D(U_{10})$:

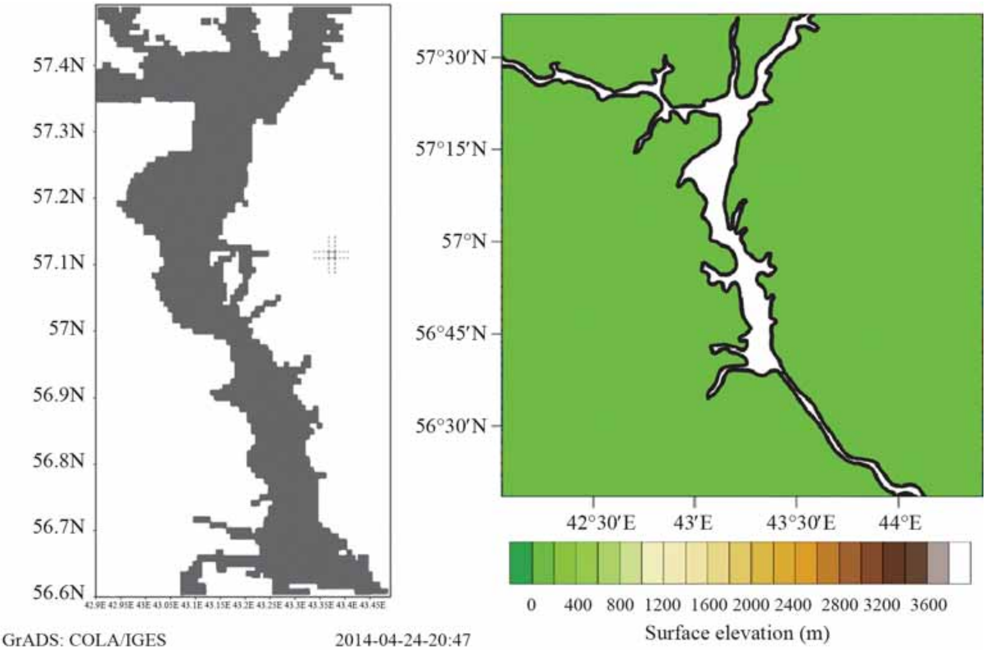
a) with and without the lower sensor: black diamonds denote the binning of data with the lower sensor (with the standard deviation as the error gates), red solid circles denote the binning of the data without the lower sensor (with the standard deviation as the error gates), gray circles are the results of the field experiment [Babanin and Makin, 2008], gray crosses are the results of the field experiment [Atakturk and Katsaros, 1999], dashed line is the empiric ocean parameterization COARE 3.0; b) using two and five sensors: red solid circles are the binning of the five-sensors data (with the standard deviation as the error gates), blue diamonds are the binning of the two-sensors data (with the standard deviation as the error gates, solid line is an approximation of the obtained data by a function $C_D = 0{,}00124 \cdot U_{10}^{-1} + 0{,}00034 + 0{,}000049 \cdot U_{10}$, dashed line is the WAM 3 parameterization [Wu, 1982].

SIMULATION

To apply the wave prediction model WAVEWATCH III to the conditions of a middle-sized reservoir, the tuning of the model was needed. The reasons and steps for the tuning are discussed in detail in the introduction.

In this study, we used the adapted to the conditions of an inland water body WAVEWATCH III model [Kuznetsova et al., 2016 a], where adjustments of the wind input and a number of other modifications in the WAVEWATCH III code were implemented, including: in the open code, the minimal value of a significant wave height H_S was adjusted; then, for the reservoir description, the topographic grid of the Gorky reservoir with dimensions 72×108 and increments of 0.00833° was used. The grid was taken from the NOAA data "Global Land One-Kilometer Base Elevation (GLOBE)" (Fig. 6a). It should be noted that there is no open-source reliable information about the bathymetry of the considered area; the existing navigational maps have not been digitized. This is a subject for another study. Although these navigational maps showed that the depth was sufficient to consider it deep water. In addition, the observed wavelength in the field experiments is less than 4.5 m, and therefore, the exact bathymetry was not considered in calculations, and depth was chosen to be 9 m. The frequency range was changed to 0.2–4 Hz in accordance with the experimentally observed range, which was split in 31 frequencies in the simulation and was modeled by a logarithmic formula for the frequency growth $\sigma_N = (\delta)^{N-1}\sigma_1$, where the growth rate was determined to be $\delta = 1.1$ in accordance with the recommendations of [Tolman et al., 2014]; 30 angular directions of the wave field were considered. The waves in the reservoir were simulated for a given Gaussian initial seeding for different wind input parameterizations using the specified topographic data, wind speed and direction, and water-air temperature difference.

Typical values of wind speeds for the calculations are weak and moderate wind



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a

b

Fig. 6. Topographical grid of the Gorky reservoir in a) WAVEWATCH III, b) WRF. Computational cell with a size of 0.00833° is shown.

($U_{10} = 1 \div 9$ m/s) of different directions. Two types of wind input data were studied. First, wind forcing was set as the value of wind speed measured in the experiments and assumed homogeneous over the entire surface of the Gorky reservoir; variability in time was taken into account. The simulation was held with input data updated every15 minutes, measured in the field experiment: 10 m wind speed and direction, the water-air temperature difference. In practice, to simulate wind waves on the surface of the seas and oceans, the reanalysis data is typically used as a wind forcing. It has a spatial variability that can help to simulate the wave regime more accurately. In the middle-sized inland waters, this approach is not applicable because of its too low spatial resolution (2.5°). In addition, the reanalysis data are more precise the more data assimilation occurs in this area. In the studied area there are only two weather stations (Volzhskaya and Yurievets), but they are on the coast, and the wind speed on the coast is different from that over the waters of the reservoir. In this regard, the use of the reanalysis data in a simple form is not correct. This assumption of the homogeneity of the wind forcing over the pond can be a source of errors in a numerical experiment, because the wind field is expected to be heterogeneous, and such factors as the elongated shape of the reservoir and the high banks can lead to a significant spatial variability of the wind field. The heterogeneity of the wind field over the reservoir was supported by the field study of wind conditions over the entire water area (see Fig. 2). Thus, the second method of the wind forcing setting in the simulation was used. It was realized taking considering the spatial variability of the wind field using the wind forcing from the atmospheric model WRF.

To apply WRF to the calculation of the wind field over the Gorky reservoir, the following steps were undertaken. In WRF preprocessing system, the preprocessing of the data to prepare the input to the real program for real-data simulations was realized. For the geogrid module, the recommended geographical data for the lakes description "modis_lakes" for four nested domains in the studied region was used. The minimal cell size of the fourth nested domain was 30 arcseconds (it is equivalent to the cell size of the topographical data used in WAVEWATCH III 0.00833°) (Fig. 6b). These data were used to describe the domains and to interpolate the static geographical information for the given grid. To describe the current weather situation, the meteorological data "NCEP Final Analysis (FNL from GFS) (ds083.2)" with 1 degree resolution was loaded. It was updated every 6 hours and was extracted from the GRIB format using the ungrib program. Metgrid program produced a horizontal interpolation of the extracted meteorological data on the domains grid. The simulations were conducted on the Yellowstone supercomputer, Boulder, USA [Computational and Information Systems Laboratory, 2012].

Simulation was carried out in two ways: firstly, in the framework of the ocean parameterization WAM 3, which uses a linear dependence of the C_D on U_{10} [Wu, 1982], and secondly, with our proposed parameterization of C_D(1) in the wind input source term WAM 3. The difference of parameterizations $C_D(U_{10})$ is shown in Fig. 5b. For the wind speeds of up to 2.5 m/s, the C_D values from the field experiment lie above the C_D values given by the ocean parameterization, and for the wind speeds greater than 3 m/s, they lie below.

RESULTS OF THE SIMULATION AND DISCUSSION

The comparison is made for the following WAVEWATCH III output: significant wave heights and mean wave periods. Both in the model and in the processing of the experimental results, the calculation of H_S was performed by the formula:

$$H_s = 4\sqrt{E}. \tag{2}$$

The calculation of mean wave period T_m was performed by the formula:

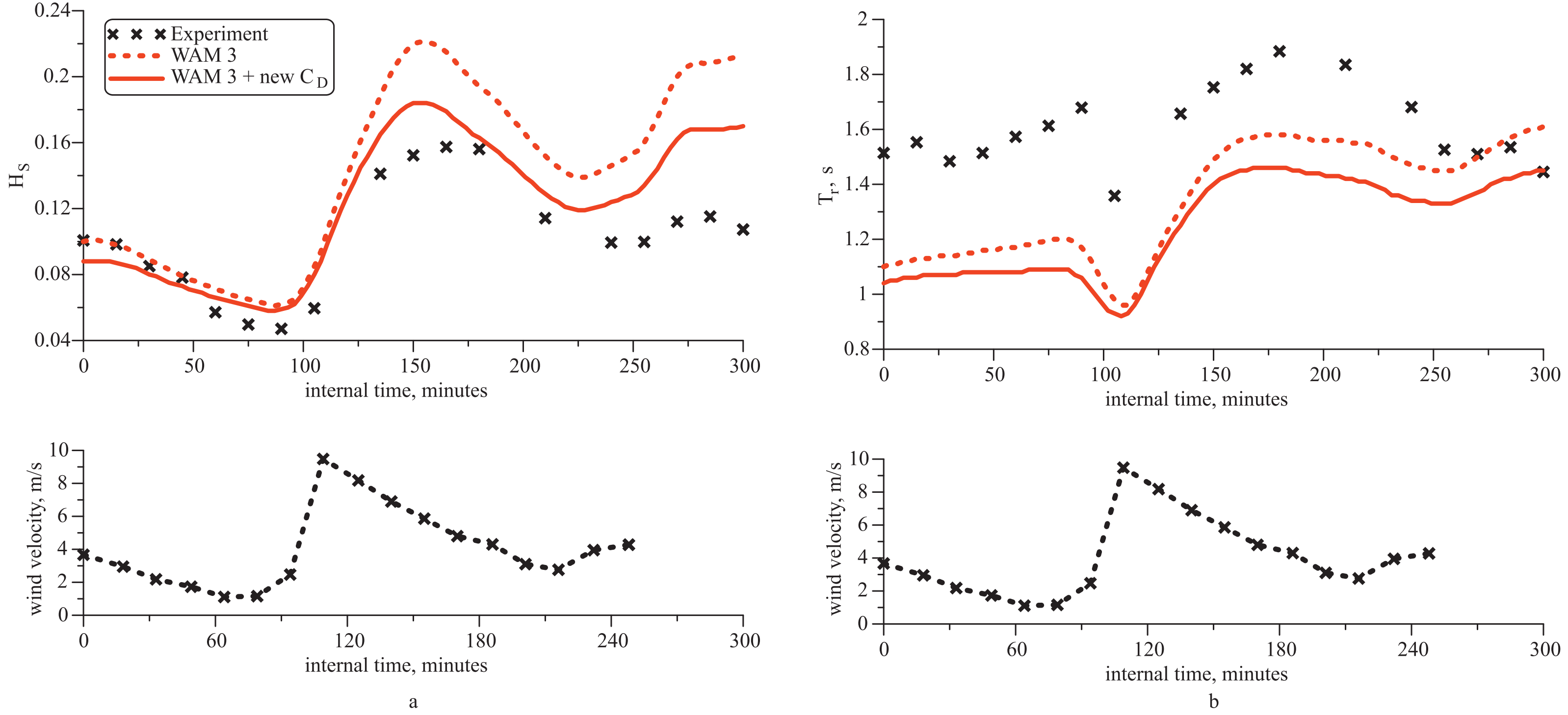

Fig. 7. On the top plots: the retrieved values of a) H_S and b)T_m obtained both from the field experiment (crosses) and from the numerical experiment (red dashed line for the WAM 3 parameterization, red solid line for the WAM 3 parameterization with new $C_D(U_{10})$). On the lower plots: the measured values of the wind used in the simulation.

$$T_m = T_{m0,-1}\left(\int_{F_{\min}}^{f_r} E(f)df\right)^{-1}\int_{f_{\min}}^{f_r} E(f)f^{-1}df. \quad (3)$$

All the data were obtained at the point corresponding to the point of the observations.

Wind forcing from the experimental data

When the wind forcing is set as the constant value of the wind speed measured in the experiment, the output data from the simulation were averaged over the interval of 15 minutes to correspond with the similarly averaged data from the field experiment.

Fig. 7 shows the results of the modeling and field measurements for the test day 13.06.13 using the ocean model WAM 3 and new parameterization $C_D(U_{10})$ within WAM 3. The lower plots show the measured values of the wind used in the simulation, the plot on the top shows a change for the retrieved values of H_S and T_m, obtained both from the field and numerical experiments. As it can be seen from Fig. 7, usually the values of the significant wave height in simulations with WAM 3 parameterizations are overestimated. The use of the proposed parameterization $C_D(U_{10})$ reduces the standard deviation of H_S for WAM 3 parameterization compared to the field experiment. This is the expected result, as in the numerical experiment with the use of new parameterization of C_D, the wave growth rate was defined more precisely, which means that the amount of energy entering the system was simulated more accurately.

However, the top graphs of Fig. 7b show that the prediction of mean wave periods has a significant discrepancy with the measured ones, and the use of the new parameterization of $C_D(U_{10})$ does not have a sufficient impact. Perhaps, this is due to the fact that the tuning of WAVEWATCH III to marine environment was reflected not only in the function of the wind input, but also in taking into account the specific parameters of numerical nonlinear scheme DIA [Hasselmann and Hasselmann, 1985; Hasselmann et al., 1985], because nonlinear processes are responsible for the redistribution of the energy received from the wind in the spectrum. WAVEWATCH III considers the wave characteristics of marine and ocean conditions, which have a lower slope compared to the waves on the middle-sized inland waters. The coefficients of proportionality in the scheme DIA were adjusted to the sea conditions. Steeper waves of a middle-sized reservoir may require a different adjustment of parameters corresponding to a situation with stronger non-linearity, which should lead to a more rapid frequencies downshift. Consequently, mean wave periods will decrease. At the same time, we can expect that such a tuning of the numerical nonlinear scheme should not affect the quality of the predictions of H_S, which indicates the amount of energy received by the system, but should lead to a better prediction of mean wave periods. This hypothesis will be tested in the subsequent numerical experiments.

The advantages of the use of the proposed parameterization $C_D(U_{10})$ are described in detail in [Kuznetsova et al., 2016 a].

Wind forcing from WRF

The use of WRF wind forcing was the next step in improving the wave forecast and eliminating the possible causes of errors in the numerical experiment. The WRF application to the area containing the Gorky reservoir showed the significant spatial variability of the wind over the water area. The results obtained in the simulation for the test day 13.06.13 are presented in Fig. 8.

The distribution of the wind over the water area of the Gorky reservoir (Fig. 8) is heterogeneous both in the value (indicated by color), and in the direction (indicated by the direction of the segment). However, the values of the wind speed are much lower than those measured in the field experiment in the test day 13.06.13. This is also supported by the lower graphs in Fig. 9, which show the value of the wind measured in the experiment

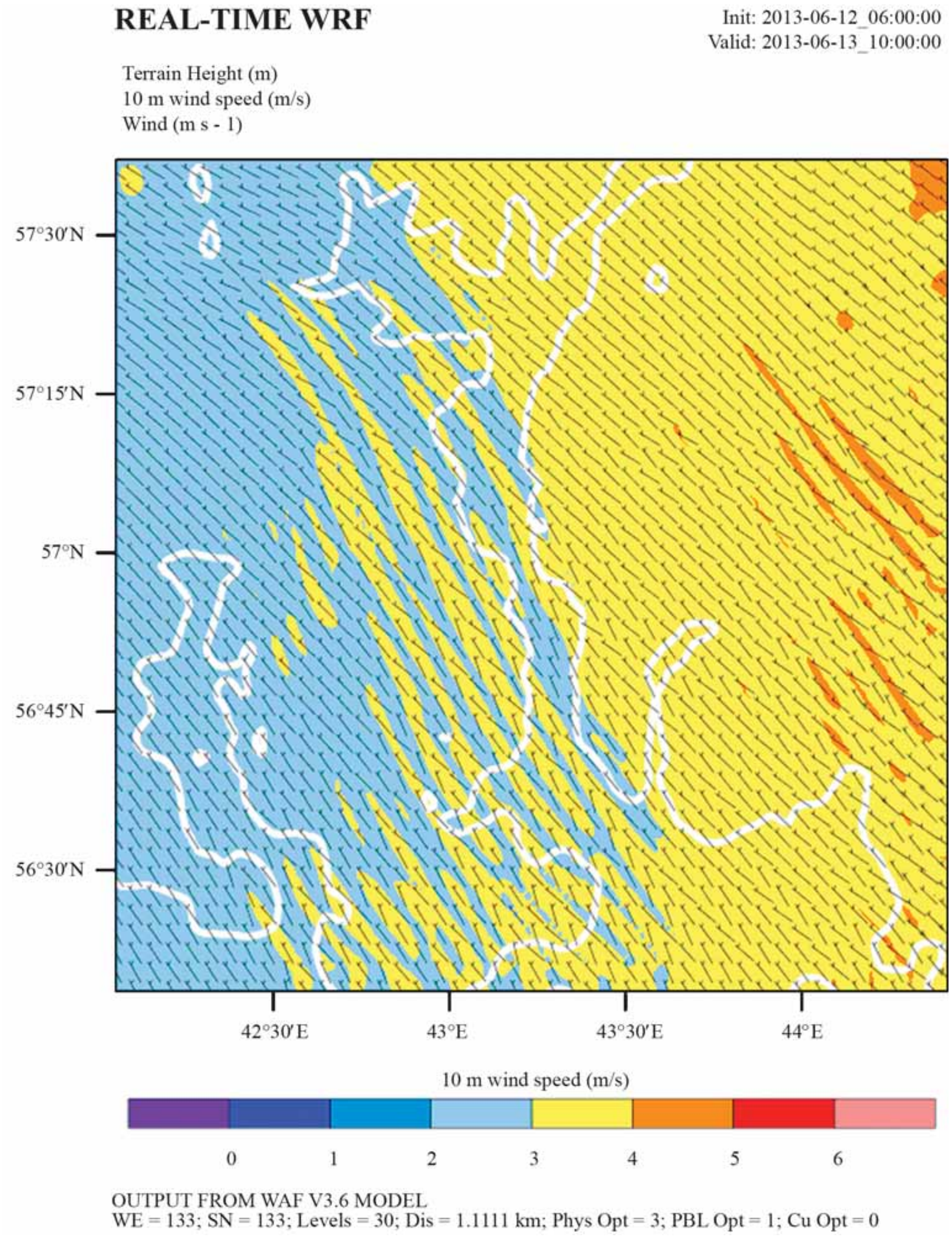

Fig. 8. The distribution of the wind over the water area of the Gorky reservoir in the test day 13.06.13, WRF simulation.

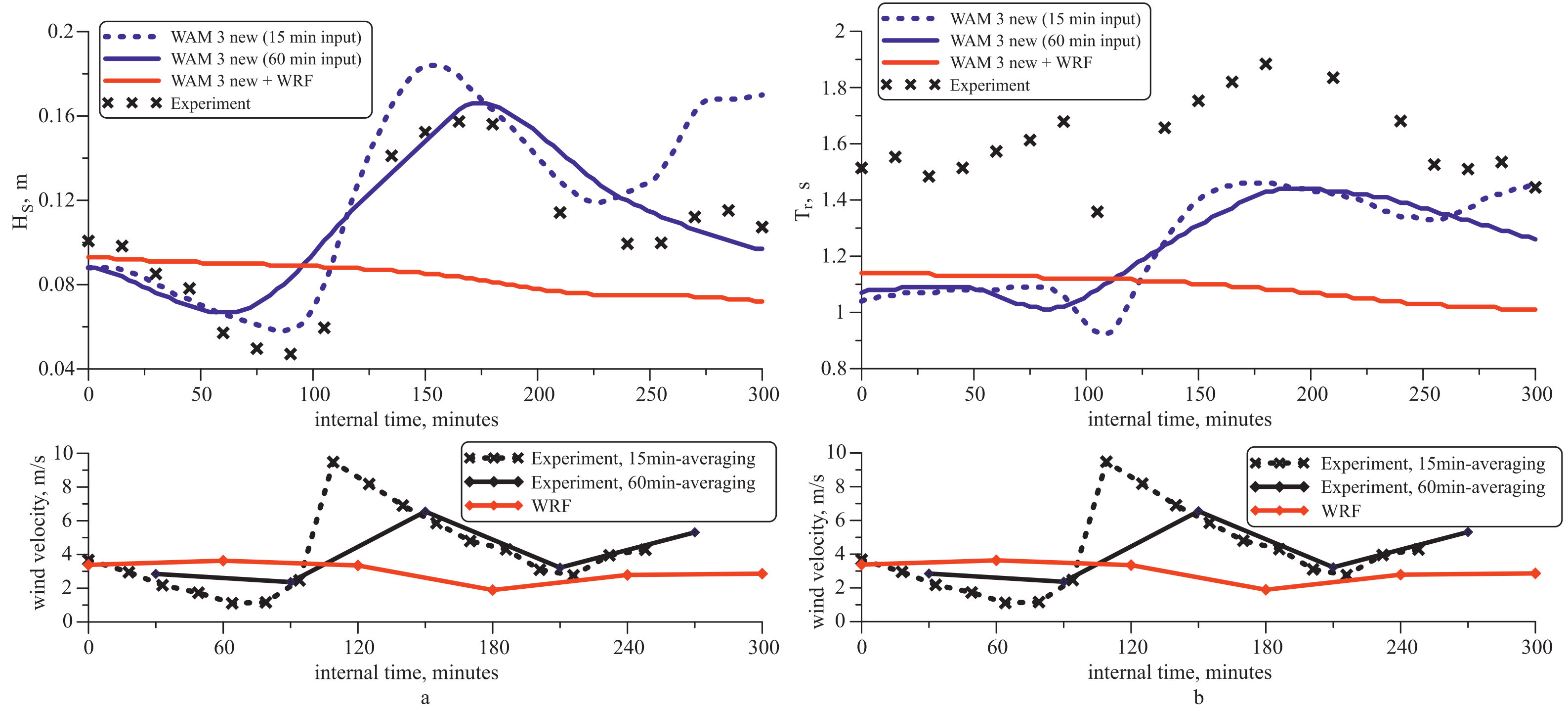

Fig. 9. Top plots: a) H_S and b) T_m for: WAM 3 with new $C_D(U_{10})$ with wind forcing from the experiment averaged over 15 minutes (blue dashed line), WAM 3 with new $C_D(U_{10})$ with wind forcing from the experiment averaged over 60 minutes (blue solid line),WAM 3 with new $C_D(U_{10})$ with WRF wind forcing (red solid line). Lower plots: wind measured in the experiment and averaged over 15 minutes (dashed black line), wind measured in the experiment and averaged over 60 minutes (black line), wind from WRF, averaged over 60 minutes (red line).

and averaged over 15 minutes (dashed black line) and over 60 minutes (black line) for the convenience of the comparison with the wind from WRF, which was also averaged over 60 minutes (red line).

We associate this inaccuracy of wind prediction in WRF model with several factors. First, with a small amount of data assimilated in the test area. As it was discussed in section "Simulation," there are only two weather stations (Volzhskaya and Yurievets) in the study area, and they are located on the coast, where the wind speed is significantly different from that over the waters of the reservoir. Consequently, the data from the additional sources (e.g., private weather stations) along the perimeter of the pond is needed. Installation of the private weather stations is part of the future study.

Second, we associate this inaccuracy with the insufficient precision of the geographical data resolution. With the increase of the precision, the inclusion of the Large Eddy Simulation (LES) unit will be possible, and this unit will help to create highly accurate forecasts incorporating the calculation of turbulent flows.

Fig. 9 shows that the change of the wind averaging from experimental data over 15 minutes and over 60 minutes, of course, affects the dependence of the wind on time. However, on average, the wind given by the experiment was higher than the wind, given by WRF. In addition, the WRF simulation does not reflect the local increase of wind speed. Consequently, the resulting dependence of $H_S(t)$ with wind forcing from WRF is, on average, lower than that with the wind from the experimental data, and it also does not indicate the peaks. We suppose that the discussed above data assimilation and the LES unit inclusion impact the quality of the WRF output. The same situation as in the case of setting the wind forcing from the experiment is realized for the prediction of the mean wave periods. The solution for the mean wave period prediction should become the next step of the WAVEWATCH III tuning that includes adjustment to the non-linearity model discussed in subsection "Wind forcing from the experimental data."

CONCLUSIONS

This paper describes a study of wind-wave regime at the Gorky reservoir. In a series of field experiments, the statistics parameters of wind waves (such as wind speed and direction, temperature stratification of the atmospheric surface layer and of the water column) in the southern part of the reservoir in a wide range of meteorological and hydrological conditions were collected over a four-year period. The basic research of wind flow above the reservoir showed that the values of the drag coefficient C_D in the range of moderate and strong winds were approximately 50 % lower than its values typical of the ocean conditions. The strong dependence of the retrieved values of the statistical parameters of the wind speed on the height of the wind speed sensors was also shown. In particular, the use of two speed sensors only (the one tracking surface and the adjacent fixed) reduced the scatter in the experimental data significantly, and also rendered lower values. This is due to the specific features of air flow in the reservoir conditions: wind gustiness, stratification of the surface layer, and shielding of wind by banks.

The simulation of surface wind waves on the Gorky reservoir was performed. The wave process was simulated within the tuned WAVEWATCH III model and was calculated both under the influence of unsteady uniform wind field based on the data from the field experiment, and under the wind given by WRF. In the tuned WAVEWATCH III, the new proposed parameterization $C_D(U_{10})$ suitable for the conditions of a middle-sized reservoir obtained from the series of field experiments was used. The results of the numerical experiments were compared with the results obtained in the field experiments on the Gorky reservoir.

The uniform unsteady wind speed over the entire water area of the reservoir taken from the field experiment, was in a fairly good agreement with the experiment, but did not describe accurately the case of a highly inhomogeneous wind. Moreover, in the practical prediction of wind and waves, it is necessary to use the numerical models. The accounting for the spatial variability was implemented using WRF. It should be noted, however, that the results should be used with caution, since the horizontal spatial resolution used in the model was the so-called "gray zone", i.e., the scales which are neither fully sub-grid nor resolved. Under such circumstances, the appearance of artificial large-scale motions resembling convective cells in a real turbulent boundary layer is observed. In [Zilitinkevich et al., 2015] this situation relates to the drawbacks in the simulation of turbulence in the stratified atmosphere (see [Zilitinkevich et al., 2006; Zilitinkevich et al., 2013]).

The results of the WRF application in WAVEWATCH III wind forcing demonstrated the need to improve the simulation within WRF, because the results of the simulation underestimate the value of the wind speed in the considered area and, as a consequence, significant wave height. We suppose that this is due to insufficient accuracy in the topography (≈ 1 km). The wind speed field of ultrahigh spatial resolution can be obtained by incorporating a detailed topography and inclusion of the LES unit, and by the data assimilation from the experiments and from private weather stations in this area. The prediction of the mean wave periods will be improved with the implementation of the next step of the WAVEWATCH III tuning that includes the adjustment to the non-linearity model.

In addition to the assumptions made in the calculations, the deep water assumption was made. Accounting for the real bathymetry of the Gorky reservoir, as well as the inclusion of the source terms in WAVEWATCH III associated with the transition to shallow water, can make a positive impact on the results.

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INTEGRATED PROJECTION FOR RUNOFF CHANGES IN LARGE RUSSIAN RIVER BASINS IN THE XXI CENTURY

ABSTRACT. The paper discusses an approach to a long-term forecast of river runoff changes for Russian large river basins in the first third of the XXI century caused by climate warming and social-economic changes. The approach considers runoff changes under a range of possible climate warming effects. This range is chosen by generalizing the calculation results obtained by using an ensemble of global climate models within CMIP 3 and CMIP 5 experiments for two contrasting scenarios (A2/RCP 8.5 and B1/RCP 2.6) of globally averaged air temperature rises. The approach also utilizes a method for alternative scenario for water consumption related to socio-economic changes. The obtained scenario estimates show that expected changes in the Volga and Don annual river runoff and its intra-annual distribution in the first third of this century can be relatively small, while changes in water use characteristics may be extremely negative in some scenarios, especially in the Don River basin.

KEY WORDS: large river basins, scenarios of river runoff changes, global climate warming, socio-economic changes, water consumption

INTRODUCTION

Global climate warming and socio-economic changes are the leading factors in determining the future state of large river basin water systems that play an important role in the economic development of Russia. For this reason, it is necessary to generate integrated scenarios of river runoff changes within the large river basins, which would take into account the long-term potential changes in the two factors. Such scenarios should provide the basis for an ecologically safe management of water systems in the future.

Because the long-term trends and rate of changes in climate and social and economic development are rather uncertain, it is important to use their alternative scenarios in the forecast. Thus a great deal of attention is given to the development of long-term scenario forecasting the hydrological effects of global climate change and the water management system transformation in large Russian river basins.

In recent years, the authors have developed a methodology for long-term scenario projections of river runoff changes, which includes a water balance model and methods for utilization of global climate warming scenarios, methods for the scenario estimates of the water management system transformation, and GIS technologies [Georgiadi et al., 2011; Georgiadi et al., 2014].

RESEARCH METHODOLOGY

The approach taken to create a long-term scenario projection of river runoff changes in large Russian river basins in the

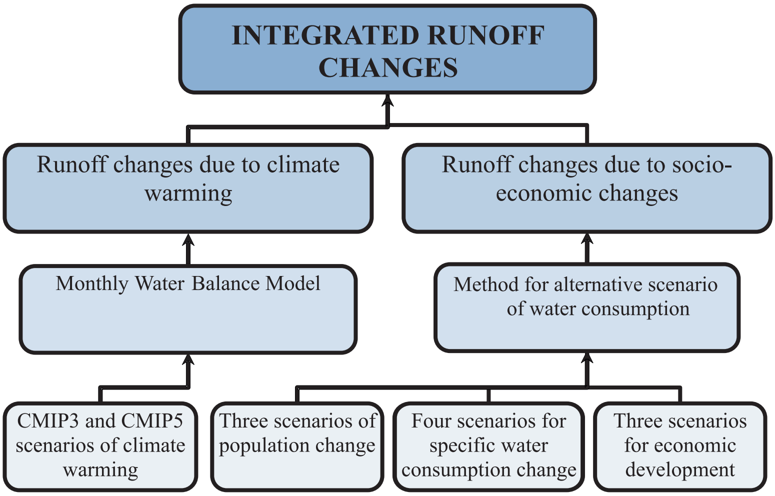

Fig. 1. Flowchart of the estimation.

first third of the XXI century includes two methods: (1) a method generating scenario estimations of runoff changes for a range of potential climate warming scenarios based on the generalization of calculated results obtained by using an ensemble of global climate models and (2) a method for alternative scenario estimations for the water management system transformation caused by socio-economic changes and their impact on the river runoff. The estimation flowchart is shown in Fig. 1.

Monthly water budget model

The model and its application to the largest river basins of the Russian Plain are considered in detail in the following publications: Georgiadi & Milyukova [2002] and Georgiadi et al. [2010, 2011]. This model can be categorized as one of a number of macro-scale hydrological models that have been developed in recent years [Willmott et al., 1985; WATCH, 2008]. The model is based on the conservation equation for the long-term monthly average water balance of river watersheds. It simulates the following processes: infiltration and moisture accumulation in the soil; evaporation (based on a modified Thornthwaite's method [Willmott et al., 1985]); water accumulation in the snow cover and snow melting (based on V.D. Komarov's method 'Manual on Hydrological Forecasts,' 1989); movement of the freezing front calculated from a simplified solution for classical single-front Stefan problem [Bel'chikov & Koren', 1979; Pavlov, 1979]; formation of surface, subsurface, and groundwater flow in the rivers and full river runoff. In the monthly water balance model, the changes in the river runoff and other water balance elements are estimated in the cells of a regular grid, which facilitates the coupling of the model and climate model simulations.

The range of probable climatic changes, which is estimated by calculating mean annual deviations of climatic elements for the 2010–2039 (conventionally referred to as 2025) from their recent values, is used as a climatic scenario. The calculations in water balance model are made for the two scenarios using the most (A2 and RCP 8.5) and the least (B1 and RCP 2.6) intensive rises of globally averaged air temperatures. Calculation results obtained by using ten global climate models for CMIP3 scenarios [Meehl et al., 2007] and about 30 global climate models for CMIP5 scenarios (http://cmip-pcmdi.llnl.gov/cmip5/) were incorporated. The ten "best" climate models, which were chosen by A.V. Kislov with co-authors [Kislov et al., 2008] from 23 climate models by comparing the present-day observed climatic conditions with the simulated ones in case of CMIP 3, while to estimate the runoff changes by the CMIP 5 scenarios, the results obtained from all climate models included in this program are used. The range of scenario deviations of mean monthly air temperatures and precipitation totals is determined for each of the scenario ensemble mentioned by averaging the calculated results obtained from each of the climate model chosen.

Method for alternative scenario estimations for water management system transformation

The methodology of estimating the impact of socio-economic changes on river runoff [Koronkevich, 1990; Georgiadi et al., 2008, 2011] is based on the assumptions of different rates of socio-economic development of a country and its regions and on the scenarios built around using different levels of water consumption and the water system protection technologies in place.

Major water consumers (household and industrial water use, irrigation, and rural water supply) are taken into account. Scenarios of household water use changes are recognized with regard to urban and rural population dynamics.

Scenarios of accelerated, moderate, and minimum socio-economic development are considered. The scenarios are based on the current specific level of water consumption and its maximum, average, and minimum decrease. Changes in storage evaporation rates and land use effects are also taken into account.

It is essential to understand that in the past decades, the water consumption dynamics in the Volga and Don river basins are in many respects close to that which was typical for Russia as a whole (Fig. 2a, b). This makes it possible to use economic and water consumption changes recorded/predicted for the whole of Russia when working out basin scenarios. Along with this, the natural and economic features of individual basins should be taken into account in forecast scenarios as well. The general algorithm for the method behind alternative scenario estimations for the water management system transformation takes place in two stages: pre-projection and projection.

The pre-projection stage includes the following steps: general orientation of the method development; analysis of natural conditions and space-time patterns of water resources distribution and water resources quality; analysis of economic activity and its impact on water systems; analysis of water system state dynamics; and selection of operating units.

The projection stage consists of the following steps: consideration of the expected natural hydrological and climatic situation; consideration of predicted population and economic development; estimation of probable changes in water use technology; consideration of the aggregate of anthropogenic and natural climatic factors; and scenario verification from water economy balances.

Estimates of future anthropogenic impacts on water resources for the years 2025–2030 are based on three scenarios for population change (average, maximum, and minimum), three options for economic development (inertia, energy and resource-based, and innovative) and four scenarios of specific water consumption change (the basic levels in 2000–2005, average, maximum, and minimum reduction). According to the official statistical forecast, the 1.05–1.15 times population decline is expected by 2025–2030. The Ministry of Economic Development of The Russian Federation gives the following economic growth rates of economic development for the same period – in industry 3–5 % per year increase, 2–4 % in the sectors of agriculture, and 1–3 % in other industries [The concept of long-term socio-economic development…, 2008; Kuzyk & Yakovets, 2006, etc.].

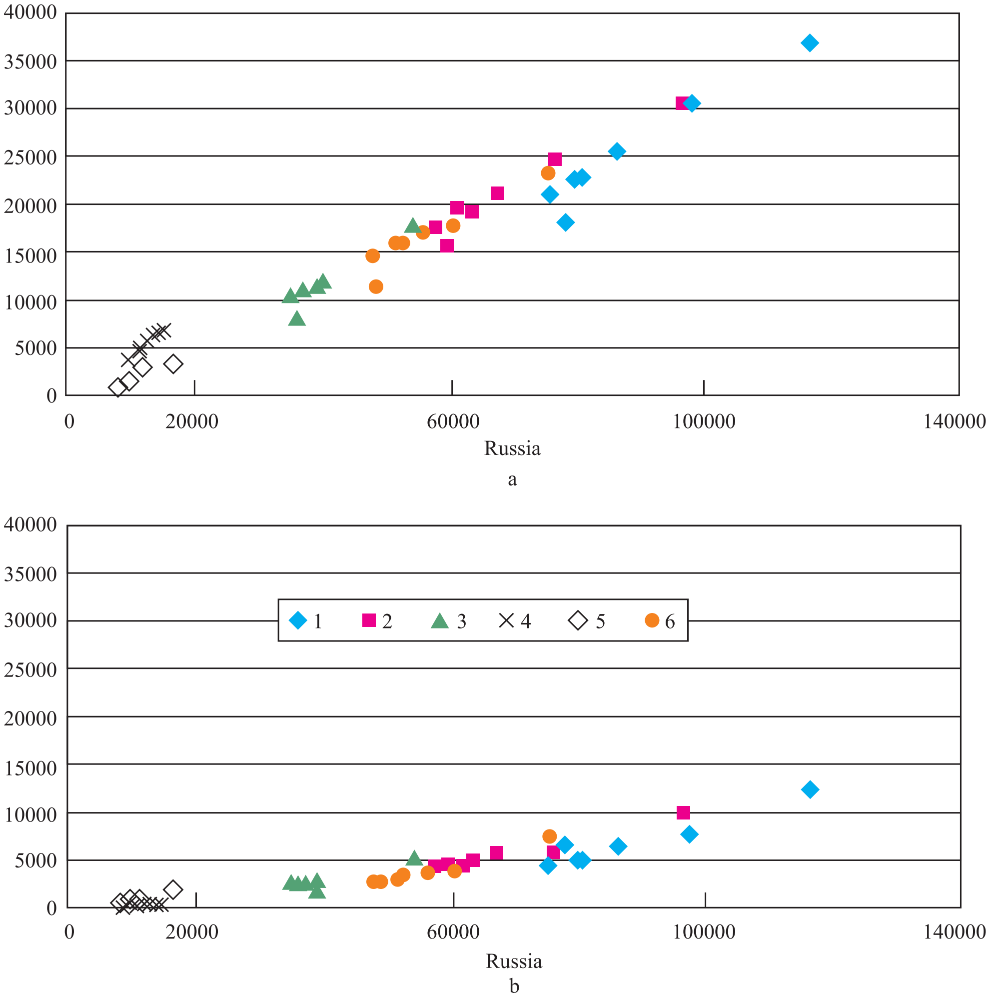

Fig. 2. Water consumption indices in Russia as related to those in the Volga (a) and Don (b) river basins (in mln m^3/yr) in 1990, 1995, 2000, and 2005. 1 – the total water volume abstracted; 2 – the total water volume used; 3 – the water volume used to meet production needs; 4 – the water volume used for domestic water supply; 5 – the water volume used for irrigation; and 6 – the total sewage volume discharged.

Possible improvement in the water use technology provides the opportunity to plan for a 1.2–5 times reduction in delivery waste [Water Resources of Russia..., 2008; Demin, 2005; Laskorin et al, 1981]. There is a 10 % per capita decline expected in domestic water use according to the scenario of the average specific water consumption changes, 20 % – according to the maximum changes, and 5 % – according to the minimum changes. Industrial water use in the Volga and Don basins is projected to decline by 1.7 times according to the scenario of maximum specific water consumption changes; in the medium and minimum scenarios, it is 1.5 and 1.2 times, respectively, which is slightly lower than the average reduction for Russia as a whole, taking into account possible water-intensive industry distribution in the areas rich in water resources. In agriculture, the consumption of water for irrigation will decrease by 1.1–1.5 times. This reduction is less than the average for Russia currently where, for example, in the Volga and Don basins, sprinkling irrigation is used for large areas as a more economical form as opposed to contour ditch irrigation, prevailing in regions like Northern Caucasus.

HYDROCLIMATIC CHANGES IN THE FIRST THREE DECADES OF THE XXIST CENTURY

Specific features of air temperature and atmospheric precipitation changes

In the first three decades of the XXI century, the mean annual air temperature in the Volga and Don river basins is expected to rise by 1.4–2.1 °C and 1.3–2 °C, respectively. Air temperature changes according to CMIP 5 scenario are slightly more notable (by 0.1–0.2). According to the scenarios, the mean annual atmospheric precipitation will increase in the Volga basin by 32–46 mm (the A2 and RCP 8.5 scenarios) and by 24–42 mm (the B1 and RCP 2.6 scenarios) and in the Don basin by 10–31 and 13–26 mm, respectively, which is within the limits of 5–8 % for the Volga and 2–5 % for the Don as it relates to its recent values. Intra-annual distributions of air temperature and atmospheric precipitation scenario changes in the Don basin were quite similar for each scenario; however, the figures for the Volga basin were substantially different.

Main trends for river runoff changes

Relatively close scenario changes of air temperature and atmospheric precipitation in the first third of the XXI century may result in varying character of hydrological consequences in the Volga and Don basins. Annual runoff in the Don basin may be expected to have small changes under the conditions of all considered scenarios. Whereas the Volga runoff most possibly would increase in A2, RCP8.5, and RCP2.6 climatic conditions scenarios by approximately 10 %, but in the B1 scenario changes may be less notable (Fig. 3).

The response of the intra-annual runoff structure to scenario climate changes is also quite different for the Volga and Don basins. A flattening-out of the flood wave can be expected for the Don River, while on the Volga River, on the contrary, in the month of the highest runoff during flood there may be a runoff increase, whereas the runoff of the next month can decrease. The winter runoff

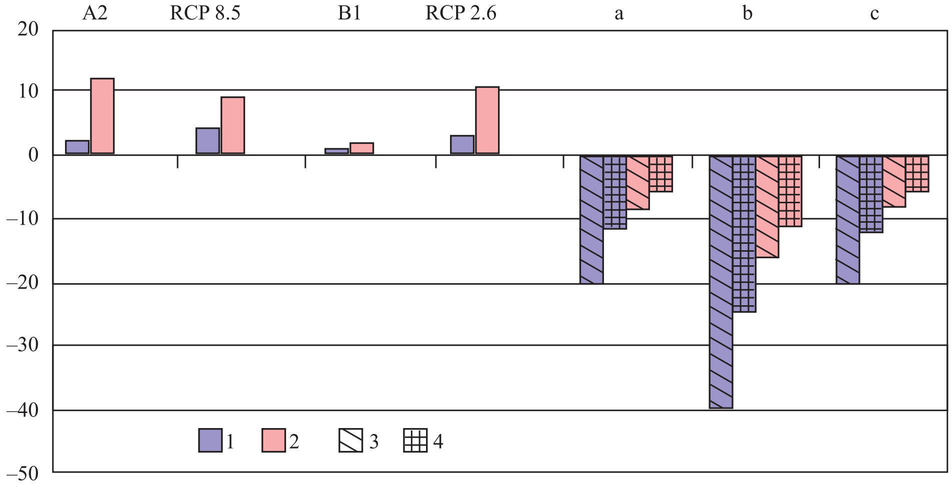

Fig. 3. Observed and expected in future (2025–2030) water abstraction in the Don (1) and Volga (2) river basins, and the projected change in their mean annual river runoff in the third three decades of the XXI century with contrasting scenarios of global climate warming A2/RCP8.5 and B1/RCP2.6 (as a percentage of the mean annual runoff).

a *– the existing situation;* ***b*** *– the most favorable scenario of economic development and the current specific water consumption;* ***c*** *– moderate rates of economic development and reduced specific water consumption; 3 – total water withdrawal; 4 – consumptive water use.*

can increase both on the Volga and on the Don; however, the summer-autumn runoff on the Volga may be lower than the recent runoff; and on the Don it may be higher.

PROJECTED CHANGES IN THE CHARACTERISTICS OF WATER MANAGEMENT SYSTEMS

The long-term forecast for anthropogenic changes in the Volga and Don runoff has been significantly refined compared to the previous one [Georgiadi at al., 2014a, 2014b]. This is due to a number of circumstances that have arisen in the last few years. Among them, the economic crisis, intensive water resources management restructuring associated with the wet industries replacement, and water saving measures. As a result the previously presented indices of economic development and water protection measures are adjusted to fit the almost double-term reduction forecast, and attributed to the modern period (2010–2013).

Refined results of the calculations have shown that keeping the existing specific water consumption rates in the Volga and, in particularly, the Don basins is unacceptable since under any scenario, this imposes an excessive load on the water elements of the environment, mainly on the river runoff.

With the most favorable scenario of economic development and the current specific water consumption, water abstraction, compared to the existing situation, can increase twice on average and reach 17 % of the mean annual runoff in the Volga basin and almost 40 % in the Don basin, which is unacceptable in respect to water economy and ecology. However, a close to the current level water abstraction can be maintained with specific water consumption reduced by a factor of 1.2–1.3 and moderate rates of economic development (Fig. 3).

Reduction in specific water consumption based on the known technological solutions, primarily those intended to avoid non-productive water losses, would result in a substantial decrease in major water consumption indices. Moreover, under one of the scenarios of economic development and the greatest level of introduction of new technology, a decrease in the anthropogenic load on water resources can be achieved to be lower than or approximately equal to the current levels, with a significantly higher standard of living attained.

CONCLUSION

The proposed ensemble approach to the long-term forecast scenario of runoff changes in large river basins, related to the socio-economic transformation and global climate warming, allows for the estimation of a range of runoff changes in the Volga and Don basins that can be expected in the first three decades of the XXI century.

Under the most favorable scenario of economic development and the current specific water consumption, water abstraction can increase by as much as three times compared to the current situation and reach a critical level, which would have an adverse effect on the water management system and the environment. However, the current water abstraction levels can be maintained with specific water consumption reduced by a factor of 1.5 and with moderate rates of economic development. Under global climate warming scenarios, the mean annual Volga river runoff can increase, which, to a certain extent, offsets the negative impacts of water abstraction growth. However, this compensation to the negative impacts would not occur in the Don river basin, where negative effects are expected to take toll on the regional environment.

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THE OXYGEN REGIME OF A SHALLOW LAKE

ABSTRACT. The year-round measurement data of water temperature and dissolved oxygen content in a small boreal Lake Vendyurskoe in 2007–2013 were used to explore the hydrophysical prerequisits of anoxia and accumulation and emission of greenhouse gases. Typically, anoxia appears in the bottom layers of lakes in mid-winter and during the summer stagnation. The thickness of the benthic anaerobic zone (dissolved oxygen concentration <2 mg·l^{-1}) reached one meter in the end of the winter and at the peak of the summer stratification, except for the extremely hot summer of 2010, when it reached five meters. Synoptic conditions had a crucial influence on the formation and destruction of the benthic anaerobic zones in summer. The most favorable oxygen dynamics was observed during the cold summers of 2008, 2009, and 2012, when the repeated full mixings of the water column occurred under conditions of the cyclonic weather. In the winter periods, the early dates of ice season resulted in the most pronounced deficiency of oxygen.

KEY WORDS: ice-covered lake, summer stagnation, dissolved oxygen, anoxia, greenhouse gases

INTRODUCTION

Dissolved oxygen (DO) is one of the most important parameters in the lake ecosystem. Oxygen depletion can cause large changes in the population of fish, leading, in extreme cases, to the massive fish kill [Greenbank, 1945; Barica & Mathias, 1979]. The lack of DO leads to the activation of anaerobic processes and to accumulation of harmful greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) in the bottom layers of the water column and upper bottom sediments [Golosov et al., 2007; McGinnis et al., 2015]. The significant emission of such gases can take place after the full mixing of the water column, for example, as a result of the ice breakup or after erosion of the seasonal thermocline at the end of the summer [Lohila et al., 2015]. Anaerobic conditions occur in the bottom layers of mesotrophic and eutrophic boreal lakes during summer thermal stratification due to insufficient aeration of the water column [Efremova et al., 2015]. In the winter periods, the main cause of the oxygen reduction in shallow lakes is the absence of the gas exchange with the atmosphere and the suppression of photosynthesis. The rate of DO reduction is determined by the intensity of its diffusion in sediments and bacterial consumption in the water column [Hargrave, 1972; Boylen & Brock, 1973; Mathias & Barica, 1980; Brekhovskih, 1988]. The amount of organic matter, initial water temperature at the start of the ice season, and heat flux from the sediments are the factors that have the major influence on the rate of oxygen reduction in a lake during winter [Terzhevik et al., 2009]. In addition, hydrodynamic processes, such as geostrophic circulation, non-linear internal waves, seiches, and seiche-induced convection in upper sediments, can have a significant impact on the rate of oxygen reduction [Mackenthun & Stefan, 1998; Baehr & DeGrandpre, 2002; Lorke et al., 2003; Bernhardt et al., 2014].

To date, the seasonal oxygen regime of the shallow boreal lakes is described in general [Golosov et al., 2007, 2012; Terzhevik et al., 2009, 2010; Zdorovennov et al., 2011]; however, many aspects of its dynamics at a finer scale remain poorly understood.

The aim of the current study is to investigate the thermal and oxygen seasonal dynamics of a shallow boreal lake from the standpoint of the development of favourable conditions for the accumulation and release of greenhouse gases, including anoxia in near-bottom waters as a prerequisite.

MATERIALS AND METHODS

A small mesotrophic Lake Vendyurskoe (southern part of Karelia, Russia, 62°10′N, 33°10′E) was chosen as the object of our study. It is a shallow polymictic lake (surface area 10.4 km^2, volume 54.8·10^6 m^3, maximal and mean depths 13.4 and 5.3 m, respectively) (Fig. 1), a typical representative of the lakes of water-glacial origin widespread in North-Western Russia and Fennoscandia [Terzhevik et al., 2010]. Lake Vendyurskoe is a popular site for fishing used for fish farming and recreational purposes.

The climate of the study area can be characterized as temperate continental with some marine features. Winters are long and relatively mild, and summers are short and cool. The weather during the year is highly variable due to the frequent cyclones approaching the area from the west. Cloudy weather occurs on more than half of the days each year. In winter, thawing often occurs, and in spring and sometimes in early summer, short frosty periods are normal.

Previous studies of the oxygen regime of the lake were carried out in 2000-2006 based on the field measurements of DO content made in the vertical sounding regime at 22 stations in April and October. Estimates of winter DO consumption rate were obtained [Terzhevik et al., 2009, 2010]. However, such sporadic surveys could not describe the annual course of DO dynamics.

The year-round measurements with 1-min intervals during 2007–2013 allowed filling this gap. We measured the water temperature and DO content within the water column using chains equipped with sensors TR-1060 (range –5…+35 °C, accuracy ± 0.002 °C, resolution < 0.00005 °C) and DO-1050 (range 0–150 %, accuracy ±1 %FS) (RBR Ltd., Canada), which were spaced on a rope at the intervals of 0.5–1 m, the top sensor being located at the depth of 2.5 m. The rope was stretched between the anchor and the buoy.

RESULTS AND DISCUSSION

The seasonal dynamics of the thermal regime of Lake Vendyurskoe included spring and

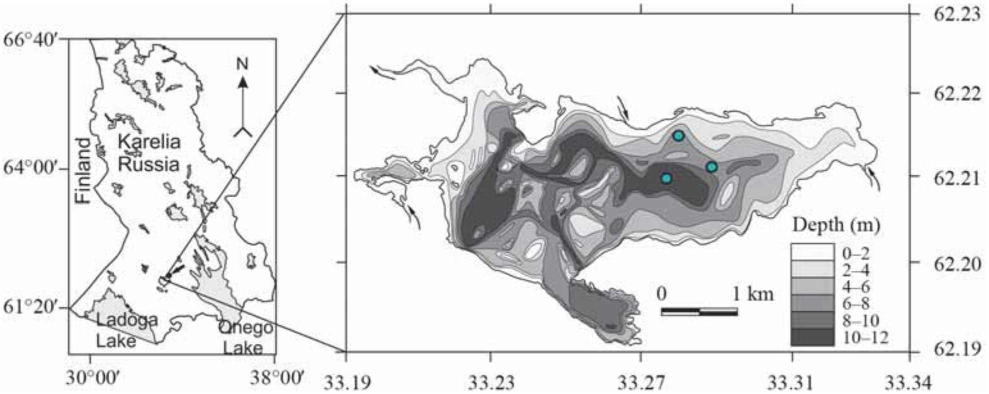

Fig. 1. Scheme of Lake Vendyurskoe with the location of the measurement sites (circles).

summer heating (2.5–3.5 months), autumn cooling (3–4.5 months), winter heating (5–6 months) and spring under-ice convection (one month). The water column was inversely stratified during winter with temperature and density increasing with depth, it was homothermal after the ice breakup and during autumn cooling, and it was unstable or had a mild thermal stratification during summer heating.

Ice season. The period started in mid-November to early December and ended in the first half of May, thus lasting five to six months [Zdorovennov et al., 2013]. The bottom water temperature in the central part of the lake rose to 4.5–5.5 °C by the end of winter [Zdorovennov et al., 2011] due to the heat exchange with bottom sediments and redistribution of heat [Malm, 1998; Palshin et al., 2009]. The reduction of the DO concentration throughout the water column started in the first days of the ice season. The oxygen deficit appeared in the bottom layers of the central basin during the first month. The thickness of the anaerobic zone gradually increased and reached one meter by the end of winter. Maximal thickness of the anaerobic zone was observed in years with early start of the ice-covered period (winters of 2007–2008 and 2010–2011). The data of our field measurements confirmed the results of the numerical modeling [Golosov et al., 2007; Terzhevik et al., 2009]: colder autumns and earlier dates of freeze-up contribute to the earlier formation of the anaerobic zone and an increase in its thickness. Warmer autumns and later dates of freeze-up contribute to the favorable oxygen regime in the lake: anaerobic conditions appear much later, if any, and the thickness of the anaerobic zone is significantly reduced.

Estimates of the total rate of DO consumption γ for the winter seasons of 2007–2013 were calculated in accordance with the approach outlined in [Terzhevik et al., 2010]:

$$\frac{\partial C}{\partial t} = -\gamma C,$$

where C is DO concentration, γ is the total rate of oxygen consumption; $[\gamma] = s^{-1}$, t time. This equation has an analytical solution:

$$C_t = C_0 e^{-\gamma t},$$

where C_0 is the initial DO concentration at the very beginning of the ice season.

Evolution of relation C_t/C_0 shows that DO concentration in the lake decreased by more than one-third during the winter, compared with the initial value (Fig. 2A). The reduction of oxygen concentration lasted from 140 to 170 days every winter. The maximal values of the total rate of oxygen consumption γ reached $0.5–1.5 \cdot 10^{-7}$ s^{-1} in the first week of ice period and then rapidly dropped, not exceeding $0.5 \cdot 10^{-8}$ s^{-1} from the third month until the end of winter (Fig. 2B). The greatest variation in the range of γ was observed in the first month of ice period, while later the rate of oxygen consumption became comparable across different years. As shown previously [Golosov et al., 2007, 2012; Terzhevik et al., 2009, 2010], the rate of oxygen consumption is determined by several factors, i.e. (1) the initial freezing temperature of the lake, (2) the magnitude of the heat flux from the sediments and (3) the amount of the organic matter accumulated in waters of the lake. Our estimates of γ for winters of 2007–2013 are in a good agreement with the estimates done for the winter seasons of 2001–2002 and 2003–2006 [Terzhevik et al., 2010].

Thus, anaerobic conditions may exist in the bottom layers of Lake Vendyurskoe for four-five months of each winter, and the probability of a significant accumulation of greenhouse gases in the bottom layers of the lake at the end of winter is high. A decrease of the ice-covered period leads to the less pronounced deficiency of oxygen in the bottom layers of lakes and a reduced risk of large greenhouse gases emissions after the ice breakup.

Ice breakup lasts for several days accompanied with a complete mixing of the water column and vertical uniform distribution of the water

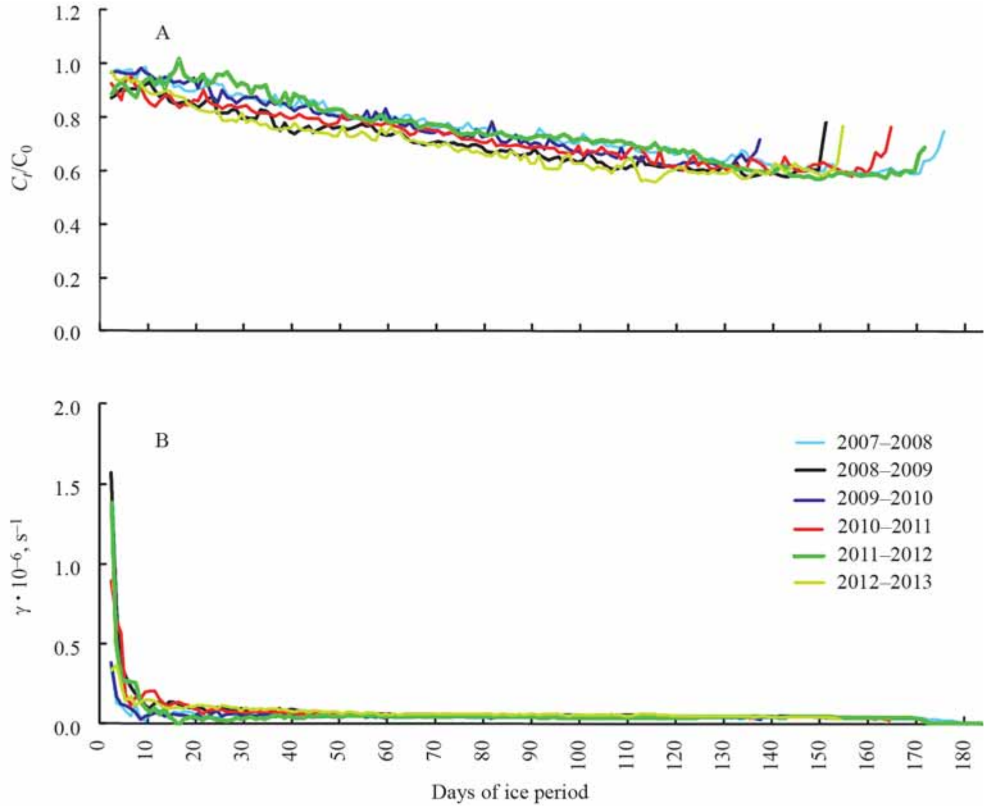

Fig. 2. Evolution of relation C_t/C_0 (A) and γ (B) during the ice season.

temperature and dissolved oxygen content [Gavrilenko et al., 2014]. The near-bottom anaerobic zone usually disappears after the ice breakup; at this moment, a substantial release of greenhouse gases into the atmosphere may occur.

Measurements carried out in small and medium-size boreal lakes show that concentration of greenhouse gases changes significantly during the ice-covered period. Greenhouse gas concentrations change little in the under-ice layer, while in the bottom layers there is rapid growth at the beginning of winter, taking place against the backdrop of a sharp reduction of oxygen [Denfeld et al., 2015]. The sharp increase of greenhouse gases concentration in the surface layer of small boreal lakes in late winter during ice and snow melting may occur due to inputs from the catchment area [Denfeld et al., 2015], and from the bottom layers involved into convective mixing [Huotari et al., 2009; Baehr & DeGrandpre, 2004; Miettinen et al., 2015]. The spring peak in greenhouse gas emissions can reach 30 % of the total annual emissions [Miettinen et al., 2015], but in most cases the autumn peak prevails [Huotari et al., 2011].

Summer heating. After ice breakup, the surface temperature increased due to radiation heating. The concentration of DO increased to 10–11.5 mg·l^{-1} (saturation of 80–90 %) during the first week of open water. The weather in the study area is usually unstable in May and June, and thermal stratification of Lake Vendyurskoe is slight or moderate. The thermocline was observed only in mid-May 2010 following a long period of hot windless weather. The oxygen regime was usually favorable in May and early June as the water column was periodically mixed and phytoplankton bloomed. The saturation of dissolved oxygen in the daytime in the upper layer of the water column often exceeded 100 % (103–106 % – 23–30 May 2009, 105–113 % – 15–22 May 2010) [Gavrilenko et al., 2014]. However, the total oxygen content decreased within the water column along the amplification of thermal stratification due to the increased biochemical oxygen demand and reduced photosynthesis.

The water temperature rose during July [Efremova et al., 2015]. Observational data for six years (2007–2013) show that the DO concentration decreased to 8–9 mg·l^{-1} (80–100 % saturation) in the surface layer with the water temperature increasing to 15–20 °C. With the water temperature above 20 °C, the oxygen concentration dropped to 6–7 mg · l^{-1} (70–80 % saturation).

Weather has a decisive influence on the oxygen regime of the lake in summer. Weak stratification or homothermia was observed in July of 2007–2009 and 2012 due to frequent cyclones. For example, the water column was completely mixed at least five times during May–July 2012. Under those conditions, the oxygen regime of the lake was favorable. A decrease of the oxygen content in the bottom layers of deeper locations was less pronounced than in other years of research

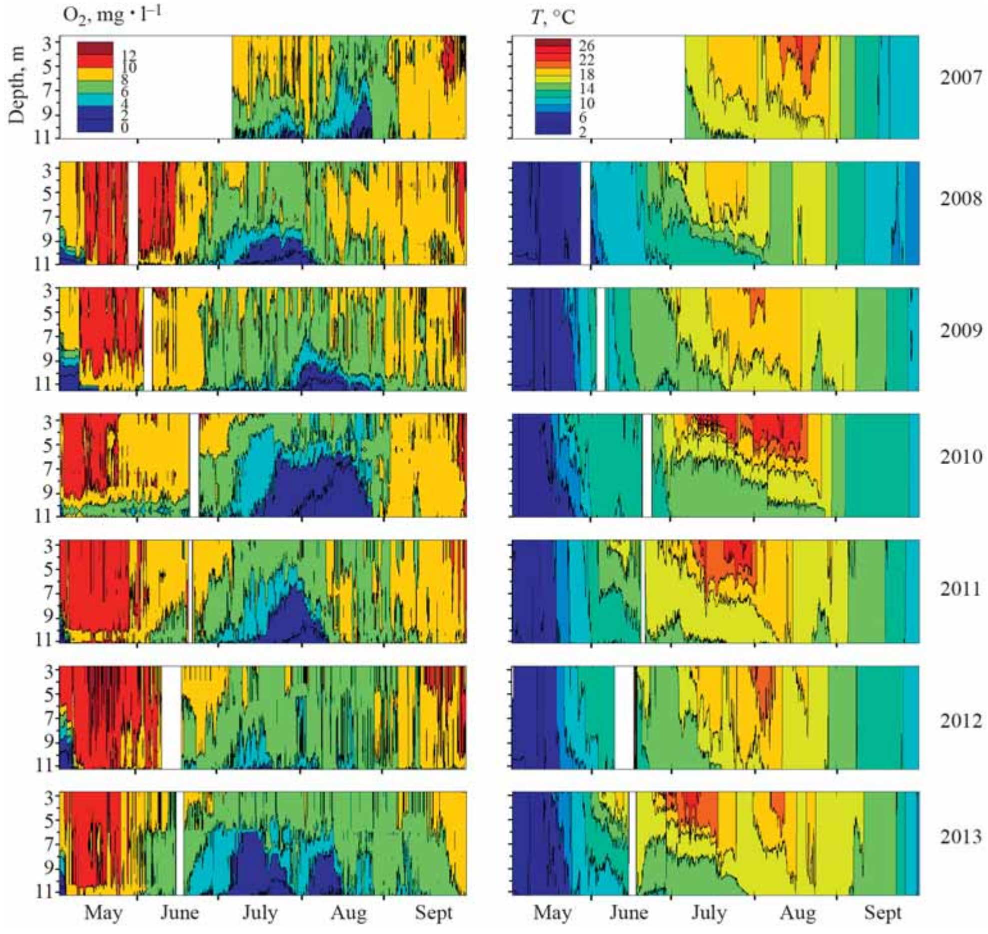

Fig. 3. Seasonal dynamics of DO concentration (left panels) and water temperature (right panels) in the deep-water central part of Lake Vendyurskoe in May-September of 2007–2013.

(Fig. 3). The thickness of the anaerobic zone did not exceed one meter, and its lifespan was not more than two-three weeks. A danger of the accumulation of greenhouse gases was minimal.

In contrast, a pronounced thermal stratification occurred during a period of hot windless weather in July and early August of 2010, 2011 and 2013 (Fig. 3).

The most dramatic situation was observed in the summer of 2010 as a result of the stationary anticyclone which blocked the western transfer of air masses [Trenberth & Fasullo, 2012]: the average monthly temperature in July 2010 at the meteorological station Petrozavodsk was 22.3 °C, which exceeded the average value (16.5 °C) for the period of 1953–2011 by 3.1 standard deviations, and was higher than the basic norm (1961–1990) by 6.2 °C [Efremova et al., 2015]. A sharp thermocline was developed in Lake Vendyurskoe: the temperature gradient reached 5 $°C·m^{-1}$at depth of 3–5 m in the middle of July 2010; by mid-August, it was 3–4 $°C \cdot m^{-1}$ and dropped to the depths of 5–7 m. The thermocline prevented aeration of the bottom layers of the water column, so the oxygen conditions were much worse. The concentration of DO did not exceed 4 $mg \cdot l^{-1}$ at depth of 6 m and sharply decreased to values close to zero at depth greater than 7–8 m from the end of July to mid-August. The thickness of the anaerobic zone reached 3–4 m from August 1 to August 20, 2010. The data for 2011 and 2013 have also shown that anaerobic conditions quickly develop in bottom layers of the lake on the background of hot windless weather, creating a base for the accumulation of greenhouse gases.

Numerous measurements on boreal lakes show that during the summer stratification, oxygen deficiency develops and accumulation of greenhouse gases occurs in the bottom layers [Huotari et al., 2009; Kankaala et al., 2013]. Wind and cooling moderate the gas transfer to the air-water interface [Heiskanen et al., 2014].

Autumn cooling. The surface temperature (20–25 °C) and heat content of the water column reached its annual maximum during the last ten days of July and the first part of August, 2007–2013. Autumn cooling starts when the heat loss prevails. Wind convection leads to deepening and destruction of the seasonal thermocline. At this point, the benthic anaerobic zone is destroyed, and a large greenhouse gas emission is possible. As shown by Lohila et al [2015], a significant CO_2 peak was observed at the stage of the autumn cooling after complete mixing of Lake Pallasjärvi. Mixing promotes the uniform temperature and oxygen distribution in the water column. At the stage of the autumn cooling the lake is nearly homothermal; the water temperature gradually decreases, and the oxygen content increases with the growth of its solubility. At this stage, the oxygen saturation occurs at the bottom layers, and there is no risk of the accumulation of greenhouse gases.

CONCLUSIONS

Throughout the year, the ice season and long periods of warm windless weather during summer are potentially dangerous in terms of the accumulation of greenhouse gases. The greatest risk of greenhouse gas emissions exists for several days after the ice breakup and at the time of the erosion of the seasonal thermocline at the end of the summer. The observational data suggest that oxygen consumption is much faster in summer than in winter. This is evidenced by a more rapid increase in the thickness of the anaerobic zone in the bottom layers: just one month of summer thermal stratification leads to anaerobic zone thickness greater than three meters, while the five months of winter stagnation translate into the one-meter anaerobic zone. Consequently, the risk of accumulation of the large amounts of greenhouse gases in summer is also pronounced, even when the periods of hot windless weather are short. At the same time, cold summers are favorable for the oxygen saturation of the water column and do not present a risk in terms of the accumulation of greenhouse gases in the lake.

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NUMERICAL SIMULATION OF METHANE EMISSION FROM SUBARCTIC LAKE IN KOMI REPUBLIC (RUSSIA)

ABSTRACT. During last decades, a special attention has been paid to methane emission from lakes [Bastviken et al., 2004; Wik et al., 2016 and etc.] as one of the significant sources of this important greenhouse gas to the atmosphere. However, attempts to simulate methane production and efflux at the air-water interface are scarce [Stepanenko et al., 2011; Tan et al., 2015a; Tan et al., 2015b] and models proposed so far need further validation using observation datasets. In this study, we use the 1D + numerical model LAKE [Stepanenko et al., 2011; Stepanenko et al., 2016]. The LAKE model was applied to a small subarctic lake in the Seida study site (Komi Republic, Russia) for identification of the key factors influencing the surface CH_4flux and its concentration in the lake. We carried out a calibration of biogeochemical constants involving qualitative considerations of the character of biogeochemical and physical processes occurring in the lake and aiming at a satisfactory agreement with observations, performed by the University of Eastern Finland (UEF) [Lind et al., 2009; Marushchak et al., 2016]. Comparing our model calibration results to earlier studies suggest that the crucial parameter of the model – methane production rate constant ($P_{\mathrm{new},\,0}$) – has similar values for lakes of different types in high latitudes.

KEY WORDS: methane, methane production rate, methane oxidation, lakes, numerical simulation.

INTRODUCTION

Since the second half of the 20th century, atmospheric methane concentration has increased by about 1.5 times [IPCC, 2013]. According to the International Panel on Climate Change (IPCC), methane is the second greenhouse gas in its contribution to modern global warming. Though lakes occupy only 1.8–4 % of a terrestrial surface [Downing et al., 2006; Doganovsky, 2012; Choulga et al., 2014], methane emissions from lakes (by different estimates) contribute to about 6–16 % of the total flux of natural biogenic sources[Tranvik et al., 2009; Bastviken et al., 2011; Ortiz-Llorente & Alvarez-Cobelas, 2012]. Therefore, it is important to consider the contribution of lakes to the regional estimates of methane fluxes, as well as to develop models of methane emissions from lakes, in particular, for their subsequent incorporation into climate models.

Currently, about four known mathematical models of methane emission from lakes have been developed: one comparatively simple model describing a majority of the chemical processes of methane and carbon dioxide emission from lakes, but with schematic representation of physical processes [Makhov & Bazhin, 1999; Bazhin, 2001] and more complex, sophisticated models [Stepanenko et al., 2011; Stepanenko et al., 2016], [Kessler et al., 2012], [Tan et al., 2015a; Tan et al., 2015b]. Model of [Kessler et al., 2012] is a 3-D numerical model of permafrost dynamics below lakes with a simulation of methane release, taking into consideration topography of the landscape. The model by [Tan et al., 2015a; Tan et al., 2015b] is 1-D and contains a mathematical description of dynamics of the following gases: CO_2, CH_4, O_2, and N_2. Meanwhile, the sources and sinks of carbon dioxide and oxygen do not include such important processes as photosynthesis and respiration in the water column. All of them were calibrated on lakes commonly located in Siberia and Alaska. Additionally, observation datasets collected on Lake Kuivajärvi, Finland, have also been used with the model simulations [Stepanenko et al., 2016].

In our study we use the lake model LAKE [Stepanenko et al., 2011; Stepanenko et al., 2016]. The LAKE model includes key physical and biogeochemical processes occurring in a lake that control methane fluxes to the atmosphere. In previous studies [Stepanenko et al., 2011; Stepanenko et al., 2016] the model was verified using observation data collected on two lakes: Shuchi Lake (North Eastern Siberia, Russia)and Lake Kuivajärvi(Finland). In both cases, LAKE demonstrated good agreement with the observations in thermal state and vertical transfer of greenhouse gases.

Here, we applied this model to a small subarctic lake in the Seida study site, located in the North European Russia. The objective was to obtain a detailed understanding of the processes regulating the CH_4 budget of this lake, such as an aerobic methane oxidation and a sedimentary oxygen demand, etc. We made a calibration of constants keeping in mind physical considerations and basing on existent empirical data on these constants from literature. The aim was to achieve satisfactory agreement with observations. Calibration of constants is inevitable in biogeochemical modules as the mathematical formulation there so far cannot be derived from first principles.

MATERIALS AND METHODS

Area of study

This study was conducted for a lake in a tundra area in North East European Russia (67°03′N, 62°56′E, 103 m a.s.l.) in Seida study site, Komi Republic. The climate of this region is subarctic with both Arctic and Atlantic influence. In general, it can be characterized as severe, with a short and cool summer and a long frosty winter. The climate is formed under the conditions of limited solar radiation (the net radiation is about 700 $MJm^{-2}yr^{-1}$), under the influence of the Atlantic seas and the intensive westerlies. An advection of a marine warm air, occurring with the Atlantic cyclones, passing through the area of study, and the frequent outbreaks of the cold Arctic air from the Arctic Ocean leads to instability in weather conditions throughout the year. The area of study belongs to the discontinuous permafrost zone. Here, the effects of climate warming are assumed to be significant since it is close to the transition zone between taiga and tundra and also because the long-term mean temperature of permafrost is close to zero [Lind, 2009].

According to the long-term weather data from the nearest meteorological station, Vorkuta (67°48′N, 64°01′E, 172 m a.s.l.; 70 km from the study site), the mean annual air temperature in the region is –5.6 °C and the total precipitation is 501 mm (long-term averages for 1977–2006; Komi Republican Center for Hydrometeorological and Environmental Monitoring). The duration of the growing season is approximately 80 days. In long-term, the warmest month of the growing season is July (+ 13.0 °C).The landscape consists of shrub tundra, peat plateau complex with thermokarst lakes and wet fens located along to the border of peat plateau.

According to [Lind, 2009] the fen and thermokarst lakes are important sources for atmospheric CH_4.It is found in the study that lakes produce high CH_4emissions (48–112 mg $CH_4 m^{-2} d^{-1}$).

The object of our study is one of the three thermokarst lakes studied by [Lind et al., 2009] – a small, shallow lake with an area of approximately 0.9 ha (Fig. 1). The depth in the lake varies from 1.1 to 2.6 m. It has intermediate surface area and depth compared to the two other lakes located nearby and studied by UEF as well. Our choice of the lake was determined by that the measurement data from this lake were most apt to be compared to our lake model results: gas collectors were in the middle of the lake and there was small vegetation coverage. The lake model being used is 1D and does not explicitly take into account gas transfer by vegetation. The subsurface gas collectors in one of these two lakes were deployed near the shore with high peat walls and other lake had too small open water area because of the vegetation [Lind, 2009].

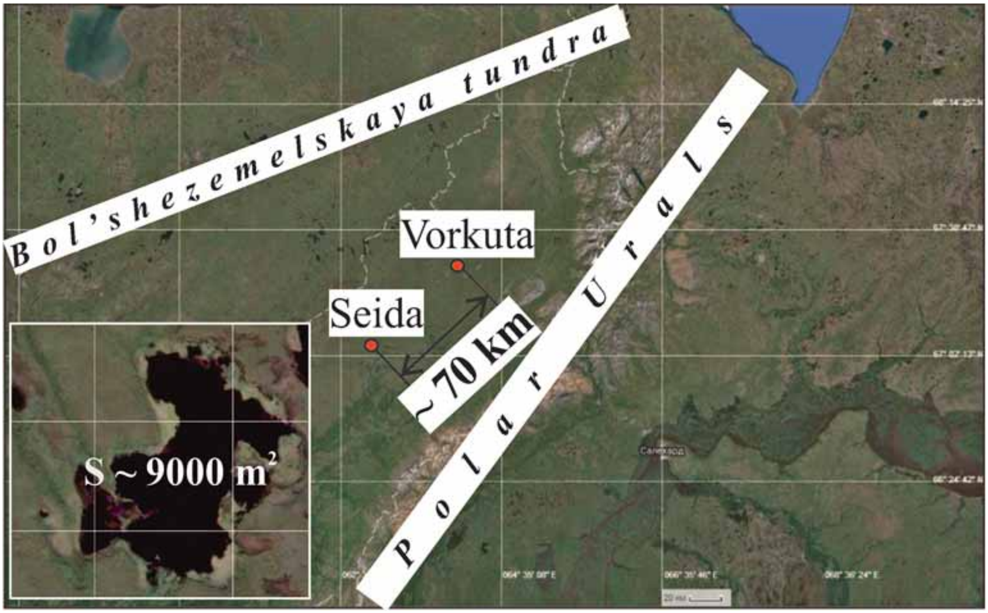

Fig. 1. Location of a lake under study.

Observation Data and Measurement Site

All observation data used in this research were provided by University of Eastern Finland, Kuopio [Lind et al., 2009; Marushchak et al., 2016]. These data consist of two types of measurements: lake surface water samplings and atmospheric measurements. The lake surface water measurements were conducted between mid-July and the end of August 2007. Among the main observed characteristics were: water temperature at the depth of 10 cm (T_{10cm}), surface-water methane and carbon dioxide concentration $\left(X_{CH_4}, S_{CO_2}\right)$, diffusion flux ($F_d$) and ebullition flux ($F_e$) of methane to the atmosphere (Table 1). The last two variables represent two methane emission pathways to the atmosphere: *diffusion* from the surface water to the atmosphere following Fick's law and *ebullition* occurring due to methane concentration reaching a critical value in the lake sediments. The water samples were taken in the middle of the lake at the same times as the floating chamber measurements were done.

The site weather data form the driving variables for a top boundary condition of the model. Meteorological variables were recorded in the Seida study site using a Hobo Micro Station H21 data logger (Onset, USA), including: wind speed (S-WSA-M003, Onset, USA), air temperature, relative humidity (S-THAM0006, Onset, USA), air pressure (S-BPA-CM10, Onset, USA), precipitation (7852 Rain Collector, Davis, USA), photosynthetically active radiation (PAR; S-LIA-M003, Onset, USA), cloudiness [Lind et al., 2009; Marushchak et al., 2016].

Overview of the LAKE model

The numerical model LAKE [Stepanenko et al., 2011; Stepanenko et al., 2016] is a model of a closed water body with biogeochemical module for simulation of processes causing the development of lake's methane, oxygen and carbon dioxide vertical concentration profiles. It is a one-dimensional, hydrothermodynamic model. One of the important improvements recently introduced in the model are the multiple soil columns (Fig. 2) that allow to

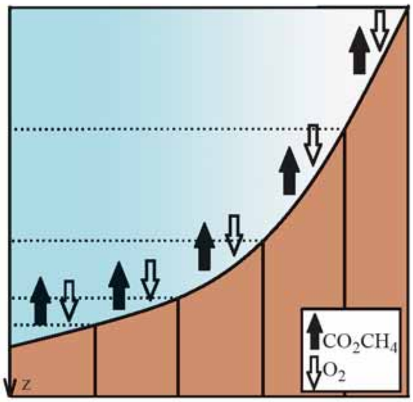

Fig. 2. A scheme of the soil columns in LAKE model.

Table 1. Observation data on Seida lakes [Lind et al., 2009; Marushchak et al., 2016]

Observed value	Dates of measurements	Total number of measurements (1 time per day)	Measurement techniques
T_{10cm}	22.07.2007, 28.07.2007, 04.08.2007, 11.08.2007, 18.08.2007, 27.08.2007	6 times	Tenma 72-2060 with temperature probe (Fluke 80PK-22)
C_{CH_4}, C_{CO_2} (mol $\cdot$ m^{-3})	22.07.2007, 28.07.2007, 04.08.2007, 11.08.2007, 18.08.2007, 27.08.2007	6 times	head-space method [Huttunen et al., 2002]
F_d (mg $CH_4 \cdot m^{-2} \cdot d^{-1}$)	04.08.2007, 11.08.2007, 18.08.2007, 27.08.2007	4 times (between 9:00–20:00)	floating chamber [Lambert & Fréchette, 2005]
mean F_e (mg $CH_4 \cdot m^{-2} \cdot d^{-1}$)	15.7.2007, 22.7.2007, 24.7.2007, 28.7.2007, 4.8.2007, 11.8.2007, 18.8.2007, 27.8.2007	8 times	subsurface bubble gas collectors [Huttunen et al., 2001]

account for bottom temperature and gas fluxes horizontal distribution, according to the morphometry of a lake (justifying to add "+" into the dimensionality abbreviation of the model, i.e. "1D + model").

A structure of the LAKE model in essence consists of three numerical modules jointly solving a coupled system of one-dimensional equations for different environments (snow, ice, water, soil):

1. hydrothermodynamic module – describes thermal and hydrodynamic processes in a water body;

2. thermodynamic module – includes thermodynamics of snow, ice at the top of lake and soil at the bottom;

3. biogeochemical module – includes biogeochemical processes, acting on concentrations of methane, carbon dioxide and oxygen in the lake, all linked to each other.

Hydrothermodynamics of the model. The basic equation for the first numerical component of the LAKE model is a 1D heat transfer equation including vertical turbulent heat transport, solar radiation absorption and heat exchange to sediments being the main terms:

$$c_w \rho_w \frac{\partial \overline{T}}{\partial t} = -\frac{1}{A} \int_{\Gamma_{A(\xi)}} T\left(u_h \cdot n\right) dl + \frac{1}{Ah^2}\frac{\partial}{\partial \xi}\left(Ak_T \frac{\partial \overline{T}}{\partial \xi}\right) - \frac{1}{Ah}\frac{\partial A\overline{S}}{\partial \xi} + \frac{1}{Ah}\frac{\partial A}{\partial \xi}\left[S_b(\xi) + F_{tz,b}(\xi)\right] + M(\xi, t)\frac{\partial \overline{T}}{\partial \xi}, \tag{1}$$

where $\overline{T}$ – horizontally averaged water temperature, t – time; h – the maximum depth of a water body; $\xi = z/h$; z is a vertical coordinate, directed along the gravity force (downward) and measured from the surface of a water body; k_T – the thermal diffusivity coefficient equal to the sum of molecular and turbulent diffusivities; $S_b(\xi)$ – shortwave radiation flux; $F_{iz,\,b}(\xi)$ – soil heat flux at the level z; c_w is the heat capacity of water; ρ_w – the mean density of fresh water; $M(\xi, t) = \left(\frac{\xi}{h}\frac{dh}{dt} = \frac{B_s}{h}\right)$ being a metric term arising from usage of the normalized vertical coordinate; B_s – the water budget at the water–air interface (precipitation minus evaporation, r–E).

Gas transfer in the water column. Biogeochemistry module of LAKE considers the dynamics of three gases in the water column: *methane, carbon dioxide and oxygen*. Their concentrations in the water column follow, respectively $\left(C_{CH_4}, C_{CO_2}, C_{O_2}\right)$, the following governing equations:

$$\frac{\partial C_{CH_4}}{\partial t} = (\xi, t)\frac{\partial C_{CH_4}}{\partial \xi} + \frac{1}{Ah^2}\frac{\partial}{\partial \xi} \times \left(Ak_s \frac{\partial C_{CH_4}}{d\xi}\right) + B_{CH_4} - O_{CH_4}; \tag{2}$$

$$\frac{\partial C_{CO_2}}{\partial t} = M(\xi, t)\frac{\partial C_{CO_2}}{\partial \xi} + \frac{1}{Ah^2}\frac{\partial}{\partial \xi} \times \left(Ak_s \frac{\partial C_{CO_2}}{d\xi}\right) + B_{CO_2} - P_{CO_2} + R_{CO_2} + D_{CO_2} + S_{CO_2} + O_{CO_2}; \tag{3}$$

$$\frac{\partial C_{O_2}}{\partial t} = M(\xi, t)\frac{\partial C_{O_2}}{\partial \xi} + \frac{1}{Ah^2}\frac{\partial}{\partial \xi} \times \left(Ak_s \frac{\partial C_{O_2}}{d\xi}\right) + B_{O_2} - P_{O_2} + R_{O_2} + D_{O_2} + S_{O_2} + O_{O_2}, \tag{4}$$

where the right-hand sides of these equations represent diffusion (assuming k_s to be the same eddy diffusivity for all species), sources and sinks due to the following processes: dissolution/exsolution of gases at the bubble-water interface $\left(B_{CH_2}, B_{CO_2}, B_{O_2}\right)$, photosynthesis $\left(P_{CO_2}, P_{O_2}\right)$, respiration $\left(R_{CO_2}, R_{O_2}\right)$, biogeochemical oxygen demand in the water column $\left(D_{CO_2}, D_{O_2}\right)$, sedimentary oxygen demand – *SOD* $\left(S_{CO_2}, S_{O_2}\right)$, methane aerobic oxidation in the water column $\left(O_{CH_2}, O_{CO_2}, O_{O_2}\right)$.

Methane aerobic oxidation. The stoichiometry of methane oxidation (MO) in water and soil follows equation (Eq. 5) below and its rate is described by Michaelis-Menten kinetics (Eq. 6).

$$CH_4 + 2O = CO_2 + 2H_2O; \qquad (5)$$

$$O_{CH_4} = V_{\max} \frac{C_{CH_4}}{K_{hs,CH_4}} \frac{C_{O_2}}{K_{hs,O_2} + C_{O_2}}. \qquad (6)$$

In the last expression there are three parameters: a potential MO rate $V_{\max}$ and half-saturation constants K_{hs,O_2} and K_{hs,CH_4}, that influence the rate of oxidation.

Sedimentary oxygen demand (*SOD*).The sedimentary oxygen demand appears as a sink in Eq. 4 $\left(S_{O_2}\right)$ representing a downward O_2 flux at the lake's margins, and at the same time it is one of the main sources of CO_2 in Eq. 3. In the LAKE model, this process follows the simplified stoichiometry (Eq. 7 below) [Stefan & Fang, 1994] and kinetics [Walker & Snodgrass, 1986] (Eq. 8 below). The Walker and Snodgrass formulation contains a Michaelis-Menten kinetics term (similar to Eq. 6) that is called a "biological" part, and the other term is the "chemical" part, quantified asa diffusion at the bottom of a lake.

$$C + O_2 = CO_2; \qquad (7)$$

$$S_{O_2} = \mu \frac{C_{O_2}}{J_{hs,\,O_2} + C_{O_2}} + k_{c_0} C_{O_2}, \qquad (8)$$

where k_{c_0} is the oxygen diffusion constant, that is in general case dependent on the turbulent mixing in near-bottom flows in a lake, temperature and soil porosity.

Methane production.The methane production, transport and sink in the bottom sediments beneath a lake are included in the following equation for methane concentration, $C_{CH_4,sed}$ [Walter & Heimann, 2000]:

$$\frac{\partial C_{CH_4,sed}}{\partial t} = \frac{\partial}{\partial z} k_{CH_4,m} \frac{\partial C_{CH_4,sed}}{\partial z} + \\ + P - E - F. \qquad (9)$$

This mathematical expression represents the three main methane transport mechanisms: diffusion of dissolved methane $\left(\frac{\partial}{\partial z} C_{CH_4,m} \frac{\partial C_{CH_4,sed}}{\partial z}\right)$, its ebullition (*E*), and the transport by plants (*F*). The main source of methane is the methane production (*P*) from anaerobic decomposition of organic matter.

In the current study we don't take into account methane transport by plants, as this flux has not been measured on the lake, and up-to-date approaches to simulate this pathway are not comprehensive and need specific validation. Also, plants grow only on the shoreline of the lake, which accounts for a relatively small area. The anaerobic decomposition of organics occurs due to the *Archaea* activity in the bottom sediments and is represented in the LAKE model by two types-production from old (P_{old}) [Stepanenko et al., 2011] and new (P_{new}) [Walter & Heimann, 2000] organic material:

$$P = P_{new} + P_{old}, \qquad (10)$$

In the current study we neglect the second term in (Eq. 10), as there is no exact information, whether permafrost exists below the lake, and P_{old} is significant in vicinity of the talik-permafrost boundary only. The methane production due to the new organics decomposition is calculated as follows:

$$P_{new} P_{new,0} e^{-\alpha_{new} z_s} q_0^{T/T_0} H(T), \qquad (11)$$

where $P_{new,0}$ is a calibration parameter, α_{new} is the parameter that determines the rate of decrease in methane generation with depth of sediments, 3 m^{-1}, z_s is the depth measured from the lake bottom, q_0 and T_0 are constants equal to 2 units [Stepanenko et al., 2011] and 10 °C [Walter & Heimann, 2000], respectively, *H*(*T*) is the Heaviside function, temperature, T, is given in degrees Celsius.

As a result, in general, the process of methane production depends on the temperature, the depth and the calibration constant – $P_{new,0}$.

Table 2. Main parameters of a baseline experiment

Parameter	Value	Parameter	Value
Lake's area, m^2	9000	Coefficient of solar radiation extinction in the water body, m^{-1}	5
Maximum depth, m	2.6	Constant of temperature dependence q_0 of methane production (Eq. 11)	2
Number of computational layers in water	10	Methane production rate constant $P_{new,0}$, $mol \cdot m^{-3} \cdot s^{-1}$ (Eq. 11)	$4.0 \cdot 10^{-8}$
Number of computational layers in soil	10	Half-saturation constant K_{hs,CH_4}, $mol{\cdot}m^{-3}$ (Eq. 6)	$6.88 \cdot 10^{-3}$
Number of soil columns	5	Half-saturation constant K_{hs,O_2}, $mol{\cdot}m^{-3}$ (Eq. 6)	$2.1 \cdot 10^{-2}$
Time step of integration, s	10	Methane oxidation potential V_{max}, $mol \cdot m^{-3} \cdot d^{-1}$ (Eq. 6)	$1 \cdot 10^{-1}$
The duration of integration, days	92	Oxygen diffusion constant k_{c_0}, $m \cdot s^{-1}$ (Eq. 8)	0.045
Start of simulation	01.07.2007		

Boundary conditions. The boundary conditions for methane at the sediments-water body interface are:

$$\frac{-k_s}{h}\frac{\partial C_{CH_4}}{\partial \xi}\bigg|_{\xi=1} = -k_{s,s}\frac{\partial C_{CH_4,sed}}{\partial z_s}\bigg|_{z_s=0}; \qquad (12)$$

$$C_{CH_4}\Big|_{\xi=1} = \left(\frac{C_{CH_4,sed}}{p}\right)\bigg|_{z_s=0}, \qquad (13)$$

where p – soil porosity.

Model experimental setup

The parameters of a baseline experiment with LAKE are demonstrated in Table 2. The values of biogeochemical constants were tuned in previous LAKE model applications to other water bodies.

The surface water temperature from baseline experiment reasonably well corresponds to the observed one, with root-mean-square deviation (RMSD) 1.38 °C [Stepanenko et al., 2014].

RESULTS AND DISCUSSION

Calibration of methane production rate constant in the baseline experiment

We calibrated the methane production rate constant ($P_{new,0}$) for the adequate simulation of the observed value of methane ebullition flux (F_e). Calculated and observed ebullition flux time series are shown on the Fig. 3 (red dashed line and green points, respectively).

The values of modelled and observed ebullition fluxes agreed well with $P_{new,0} = 4{\cdot}10^{-8}$ $mol \cdot m^{-3} \cdot s^{-1}$ (RMSD – 20 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$, mean observed F_e – 34 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$, mean modeled F_e – 32 mg${\cdot}CH_4 \cdot m^{-2} \cdot d^{-1}$). Fig. 3 suggests that temporal variation of ebullition flux is likely to be significantly higher than that measured by infrequent sampling. In the model, oscillations of F_e are partially a consequence of atmospheric pressure fluctuations caused by synoptic weather variability. Modeled time series of methane ebullition flux are smoother, if atmospheric pressure is set constant (see Fig. 3, blue dashed line) (RMSD – 26 mg${\cdot}CH_4 \cdot m^{-2} \cdot d^{-1}$, mean modeled F_e – 29 mg $\cdot CH_4 \cdot m^{-2} \cdot d^{-1}$).

It is important to note, that the $P_{new,0}$ value obtained here is close to those estimated in the previous studies both for lakes and wetlands at high latitudes (Table 3). This suggests, that this constant can be of the same order of magnitude for all subarctic lakes, however, this hypothesis requires further validation. We regard this experiment as a baseline for comparison with other

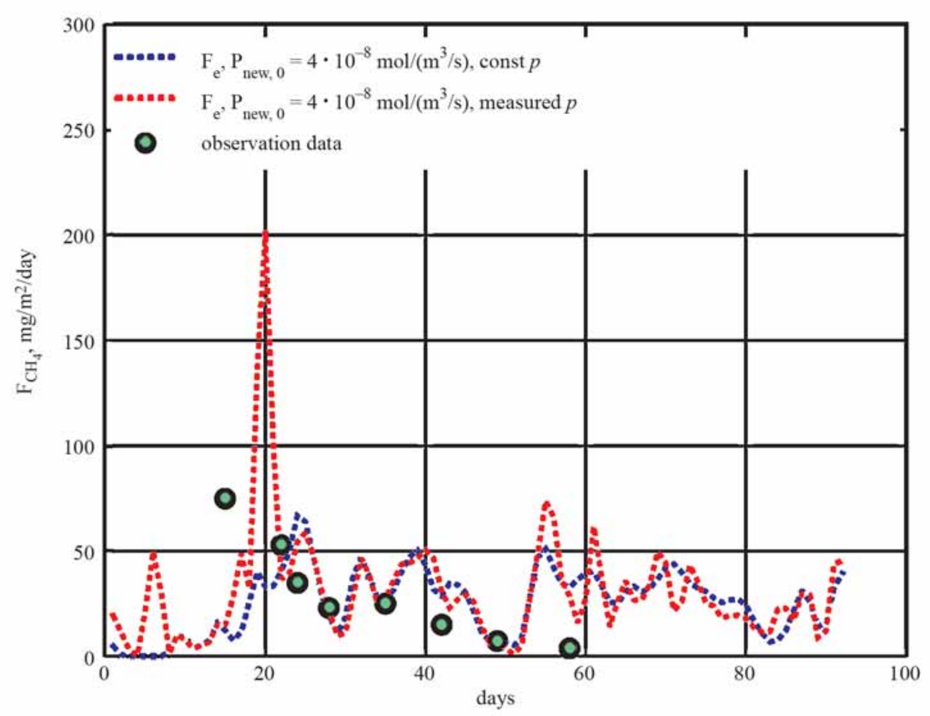

Fig. 3. Daily-averaged model ebullition flux of methane (F_e) at the lake surface (July–September 2007); "0" on horizontal axis corresponds to 01.07.2007 (blue dashed line represent model experiment with constant atmospheric pressure, *p*, red dashed line – with measured *p*).

Table 3. Methane production rate constant $P_{new,0}$ in other studies

$P_{new,0}$ (mol · m^{-3} · s^{-1})	Source
$3.0 \cdot 10^{-8}$	Lake Kuivajärvi, Finland [Stepanenko et al., 2016]
$2.55 \cdot 10^{-8}$	Shuchi Lake, North Eastern Siberia, Russia [Stepanenko et al., 2011]
$8.3 \cdot 10^{-8} – 1.6 \cdot 10^{-7}$	High latitude wetlands [Walter & Heimann, 2000]
$4.0 \cdot 10^{-8}$	Lake at the Seida site, current study

model runs, described in the following sections.

Calibration of other biogeochemical constants

Methane aerobic oxidation. Results of a baseline experiment demonstrate order of magnitude lower values of surface methane concentration and diffusion flux at the water-air interface in comparison with the observation data (green line in Fig. 4). Therefore, calibrating the methane production constant only is not sufficient to match observations in terms of these variables.

Once methane is produced in sediments and transported upwards by turbulence, the main process reducing the value of methane concentration and its diffusion flux at the lake surface is the methane aerobic oxidation (see Eq. 5, Eq. 6). It is likely that the model overestimated methane oxidation in the baseline run.

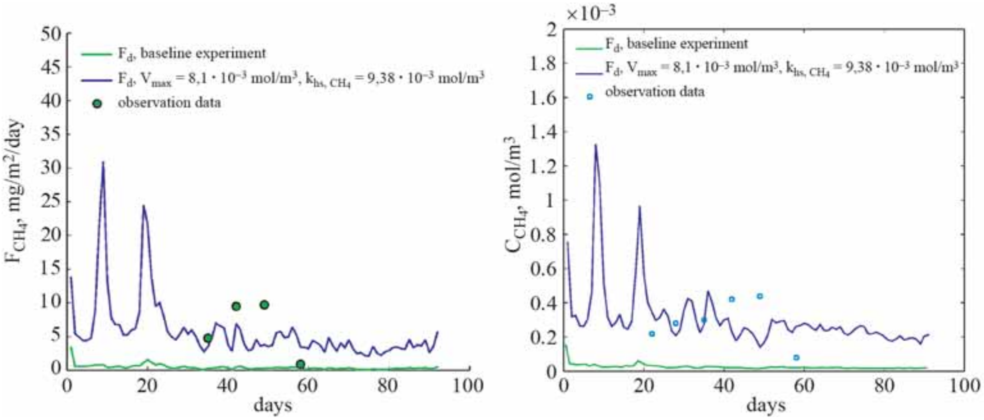

Fig. 4. (A) – daily-averaged diffusion flux of methane to the atmosphere; (B) – daily-averaged concentration of methane at the lake surface (July–September 2007); "0" on horizontal axis corresponds to 01.07.2007 (RMSD for F_d – 0.45 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$; RMSD for C_{CH4} – $7.9 \cdot 10^{-5}$ $mol \cdot m^{-3}$).

Table 4. Constants of methane aerobic oxidation reaction rate

Parameter	Value in the baseline experiment	Mean value ± SD	New calibrated value
V_{max} $(mol \cdot m^{-3} \cdot d^{-1})$	0,1	$1.8 \cdot 10^{-2} \pm 0.01$ [Martinez-Cruz et al., 2015]	0.0081
$K_{hs,\,CH_4}$ $(mol \cdot m^{-3})$	$6.88 \cdot 10^{-3}$	$6.8 \cdot 10^{-2} \pm 0.003$ [Liikanen et. al., 2002; Lofton et. al., 2014] max: $4.4 \cdot 10^{-2}$ [Martinez-Cruz et al., 2015]	$9.38 \cdot 10^{-3}$

In a baseline model experiment we used the values of methane oxidation constants, MO potential rate V_{max} and half-saturation constant $K_{hs,\,CH_4}$ from [Liikanen et. al., 2002], who investigated an interval of values for single lake Kevätön. The recent research [Martinez-Cruz et al., 2015] presents a wider range of values for these constants, estimated for several lakes in non-yedoma permafrost region (Table 4). Seida Lake belongs to the same type.

We calibrated MO potential rate and a half-saturation constant for methane in the range known from [Martinez-Cruz et al., 2015] so as to reduce the methane oxidation rate in water, and thus to increase the methane concentration at 1.5–2 m depth (Fig. 5) and at the air-water interface. As a result, we obtained an agreement between calculated data and measurements in typical averaged levels of methane diffusion flux (F_d), and surface methane concentration $\left(C_{CH_4}\right)$ (Fig. 4). As for the half-saturation constant for oxygen, K_{hs,O_2}, its empirical range is much narrower [Martinez-Cruz et al., 2015], and we found its variation to cause insignificant effect on surface water methane content.

Sedimentary oxygen demand (SOD). Since the measurement data of carbon dioxide concentration in the mixed layer of the lake were available, it was reasonable to check how the model would represent it. The baseline experiment underestimated values of carbon dioxide concentration at the lake surface, about three times lower than in the observation data (Fig. 6). This was likely due to the erroneous calculation of sedimentary oxygen demand (or *SOD*, see Eq. 8), as this is the main source of CO_2 in many lakes.

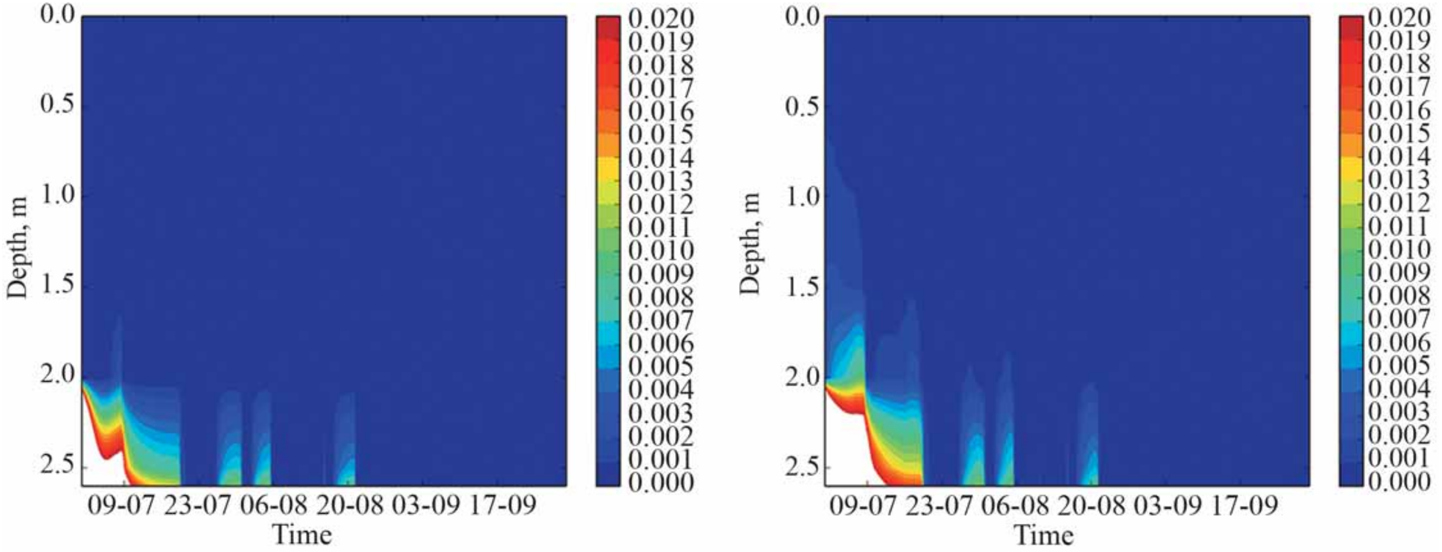

Fig. 5. The time-depth distribution of CH_4 concentration ($mol \cdot m^{-3}$) (July–September 2007): (A) – a baseline experiment; (B) – an experiment with calibrated V_{max} and $K_{hs,\,CH_4}$.

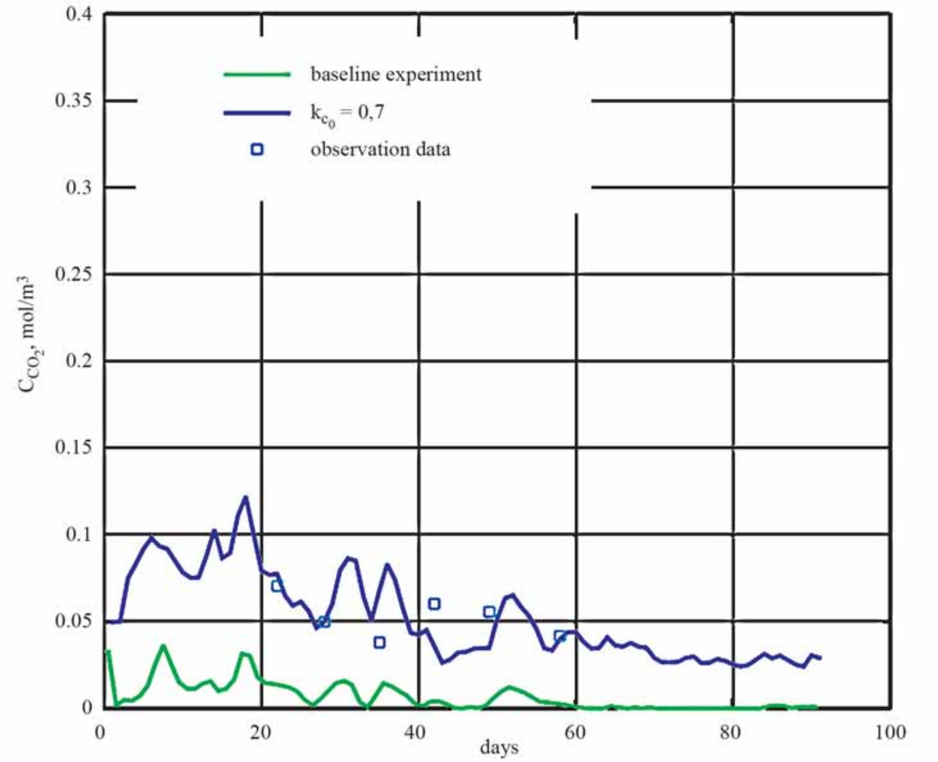

Fig. 6. Daily-averaged concentration of CO_2 at the lake surface (July – September 2007); "0" on horizontal axis corresponds to 01.07.2007 (RMSD for C_{CO_2} – $1.6 \cdot 10^{-2}$ mol·m^{-3}).

As mentioned above, the Seida region is characterized by strong winds, thus there should be the seiche-like bottom flows in lakes. These flows increase the turbulent mixing near the bottom thereby enhancing an oxygen diffusion into the sediments and corresponding CO_2 production. The coefficient k_{c_0} in Walker and Snodgrass model is responsible for oxygen diffusion, however, to the best of our knowledge, no dependence on near-bottom turbulence has been proposed for it in the literature.

In view of this, we increased k_{c_0} from the baseline value k_{c_0} = 0.045 m·s^{-1} to k_{c_0} = 0.7 m·s^{-1}, delivering much better agreement between simulated CO_2 surface concentration and that observed (Fig. 6).

This change of k_{c_0} led to higher production of carbon dioxide (according to Eq. 7) in sediments, and its penetration into upper layers of the lake. This effect is demonstrated in Fig. 7. Physical justification of this 15-fold increase of k_{c_0} would involve more sophisticated SOD models incorporating bottom boundary layer characteristics.

CONCLUSION

Basing on the experience gained from this simulation exercise, we conclude the following.

1. The value of methane production rate constant maybe of the same order of magnitude for all northern lakes.

2. LAKE model adequately simulates average surface water concentration of methane and carbon dioxide, diffusion and ebullition fluxes of methane into the atmosphere.

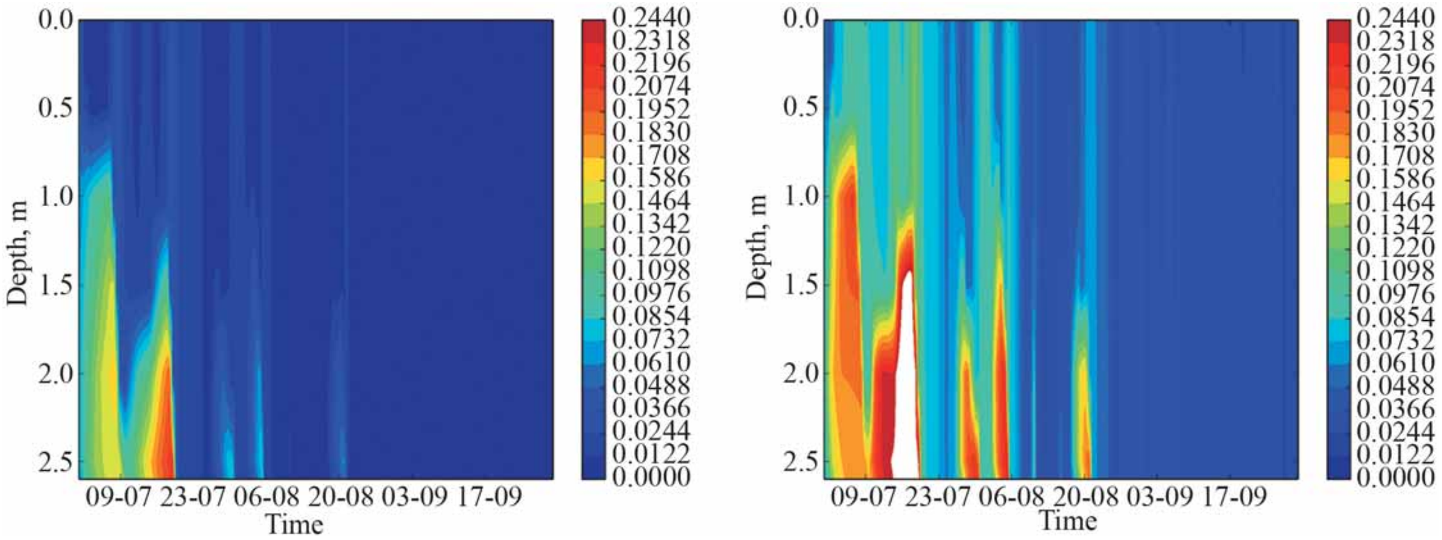

Fig. 7. The time-depth distribution of CO_2 concentration (mol·m^{-3}) (July–September 2007):

(A) – a baseline experiment; (B) – an experiment with calibration of k_{c_0} to 0.7.

3. LAKE model demonstrates significant sensitivity to variation of biogeochemical parameters controlling methane-related processes and those of oxidation of organic matter in sediments.

The model LAKE requires further calibration on the other types of lakes in the different geographical regions.

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GROUND-BASED STATION NETWORK IN ARCTIC AND SUBARCTIC EURASIA: AN OVERVIEW

ABSTRACT. The international Pan-Eurasian Experiment (PEEX) program addresses the full spectrum of problems related to climate change in Eurasian Northern latitudes. All PEEX activities rely on the bulk of high-quality observational data provided by the ground and marine stations, remote sensing and satellite tools. So far, no coordinated station network has ever existed in Eurasia, moreover, the current scope of relevant research remains largely unknown as no prior assessment has been done to date. This paper makes the first attempt to overview the existing ground station pool in the Arctic-Boreal region with the focus on

Russia. The geographical, climatic and ecosystem representativeness of the current stations is discussed, the gaps are identified and tentative station network developments are proposed.

KEY WORDS: PEEX region, observations, ground-based stations, station networks, research infrastructure, climate change research

INTRODUCTION

The Pan-Eurasian Experiment (PEEX) is a multifaceted, multidisciplinary program that aims to bring together climate change research, infrastructure management, societal initiatives and policy-making in order to understand and mitigate the effects of climate change over Eurasia [Kulmala et al. 2011b, Kulmala et al. 2015, Lappalainen et al. 2014, Lappalainen et al. 2016]. PEEX addresses the critical problems, such as ecosystem shifts, infrastructure degradation and societal processes that are expectedto occur in the region.

The PEEX-labelled studies aim to elucidate the climate change processes at a high spatio-temporal resolution. Such a target can only be achieved by combining ground observations, remote sensing products and advanced modeling approaches [Kulmala et al. 2015, Hari et al. 2015]. In this triad, the ground-based observations component is probably the most crucial element that largely determines the quality of the model forecasts. It is clear that in such a large and diverse region as Eurasia, only a very extensive ground-based observation network would yield satisfactory results. PEEX proposes the establishment of such a network as a part of its 2nd focus area, PEEX Infrastructure [Hari et al. 2015, Kulmala et al. 2015, Kulmala et al. 2016]. Siberia (and Russia as a whole) is currently lacking a coordinated, coherent ground based atmosphere-ecosystem measurement network.

The most important task of PEEX Research Infrastructure is to initiate motion towards high level Pan-Eurasian Observation Networks, which is based on a hierarchical SMEAR-type (Station for Measuring Ecosystem-Atmosphere Relations) integrated land-atmosphere observation system. As the first step, maximal utilization of the existing ground infrastructure is planned. This measure will be superseded by upgrading the currently functioning sites or building new sites where necessary.

The potential PEEX ground-based research infrastructure is centered around the Flagship stations (supersites), supported by flux/advanced and standard stations [Hari et al. 2015, Kulmala et al. 2015]. The structure of the potential Flagship stations echoes that of the supersite SMEAR-II in Hyytiälä, Southern Finland, which is equipped for research into a broad spectrum of atmospheric physics, biogeochemistry and geophysics topics. Designed to address more specific and local processes, the Standard and Flux stations are supposed to provide a higher-definition view of the processes in different climates, biomes and vegetation communities. At least one Flagship station per each representative ecosystem or every1000–2500 km should be founded in order to ensure sufficient coverage [Hari et al. 2015, Kulmala et al. 2015]. Worldwide, an optimal ground observation network would consist of about 20 supersites, 500 flux stations and 10000 standard stations [Hari et al. 2015], of which a large fraction would be situated within the PEEX domain, due to its great extent. However, in spite of the apparent scale of the problem, no attempt to summarize the existing ground-based observational site network for the PEEX region and identify the potential gaps has been attempted to date.

This study employs the ground-based observational infrastructure inventory conducted by the University of Helsinki together with the institutes of the Russian Academy of Sciences and Moscow State University. First, an overview of the existing facilities within Russia is presented, taking into account their geographical distribution, representation of ecosystems and climates. Then, the needs of development in the ground-based observational site network are discussed. Station infrastructure in China is discussed shortly as well.

MATERIALS AND METHODS

First, the information on measurement and research facilities was collected, processed and classified so that to allow systematic overview and demonstration. In particular, the information on the station location, ecosystem features, facilities and equipment was considered. See Table 1 for the list of specific items collected for each station.

The collected data was processed to derive further information on the stations. Special attention was paid to the presence of specific instrumentation such as aerosol measurement devices and eddy-covariance setups.

With the use of mapping tools, spatial distributions of the research facilities were investigated in relation to geographical areas, climates and vegetation zones. The Natural Earth (http://www.naturalearthdata.com/) satellite-derived spatial data were used to build the underlying land cover map.

Table 1. Land observation station metadata collected for the project

№	Metadata type
1	official name
2	coordinates
3	height a.s.l.
4	contact details
5	ecosystem type
6	research/measurement equipment
7	station facilities/infrastructure
8	participation in networks

For the climate analysis, the Köppen-Geiger classification scheme was employed. The Köppen-Geiger approach classifies the climates according to the seasonality and mean levels of precipitation and air temperature [Peel et al. 2007]. A raster Köppen-Geiger climate map by NASA Earth Data was used (http://webmap.ornl.gov/ogcdown/wcsdown.jsp?dg_id = 10012_1).

The elevations of the sites above sea level, where missing, were estimated from a world digital elevation map (https://asterweb.jpl.nasa.gov/gdem.asp).

RESULTS AND DISCUSSION

Geographical distribution of the stations

The PEEX program addresses continental-scale processes, which necessitates the use of a wide observational network. The focus area covering Northern Europe, Russia and China encompasses several geographical regions and is highly heterogeneous is terms of data coverage. Fig. 1 shows the locations of the land observational facilities in the PEEX domain in comparison with the stations belonging to European environmental research infrastructures ICOS (Integrated Carbon Observation System), Aerosols, Gases and Trace Gases Research Infrastructure network (ACTRIS) and International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT).It is easy to see the stark contrast between the well-covered regions (Western Europe, European Russia, West Siberia and East China) and the poorly covered regions (Northern Urals, Central and East Siberia, West China).

Fig. 2 presents the latitudinal distribution of the sites. One can see that, within the PEEX region, the Russian sites prevail in the Northern latitudes (50°–80°), while the Chinese sites contribute to the southern latitudes (15°–45°). There is a significant overlap with the Western European stations in the interval of 35°–80°. Of the stations/continuous measurement sites shown on the map, 206 are in Russia, of which 16 participate in the preliminary PEEX ground station network; 75 stations are located in China and 185 more elsewhere, mainly in Western Europe.

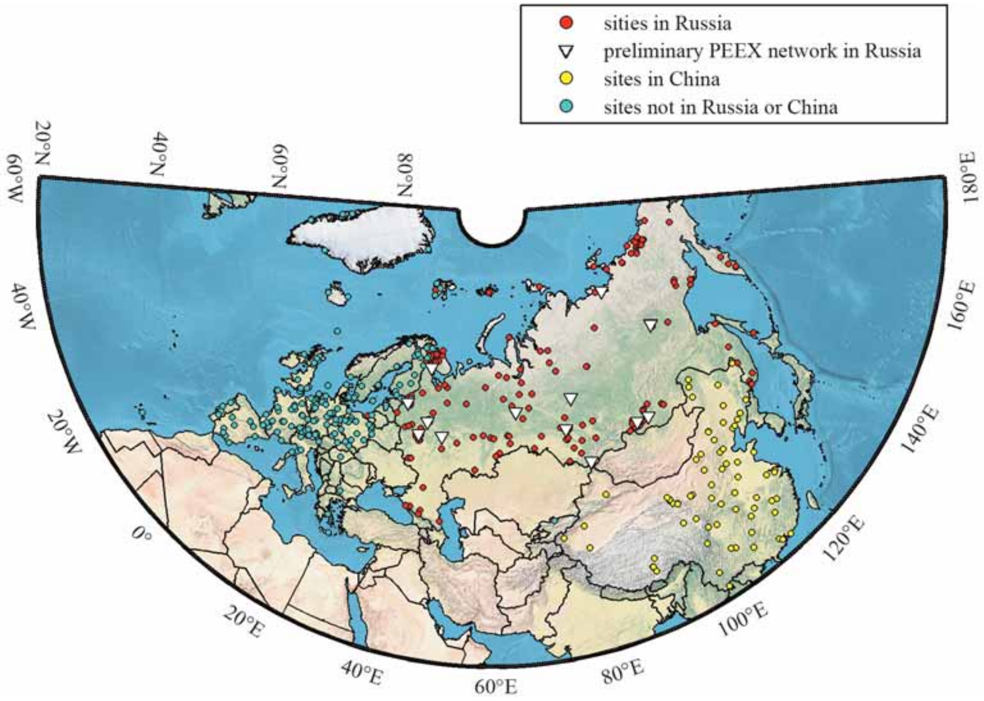


Fig.1. Locations of permanent ground-based observation stations in the PEEX domain on a satellite-derived land cover map [Lappalainen et al. 2016, manuscript in preparation].

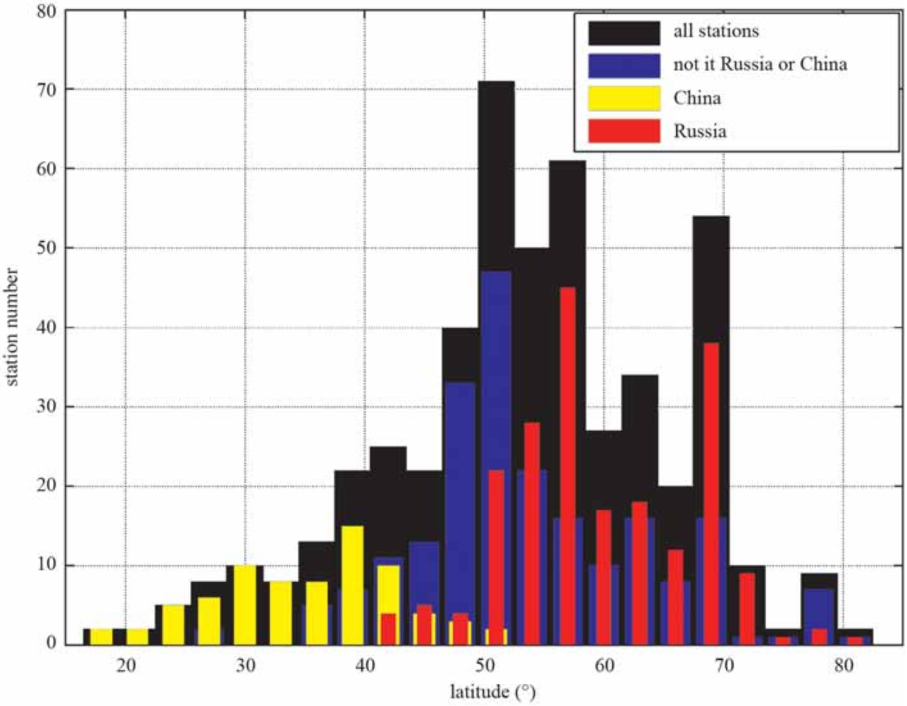


Fig.2. Latitudinal distribution of the stations.

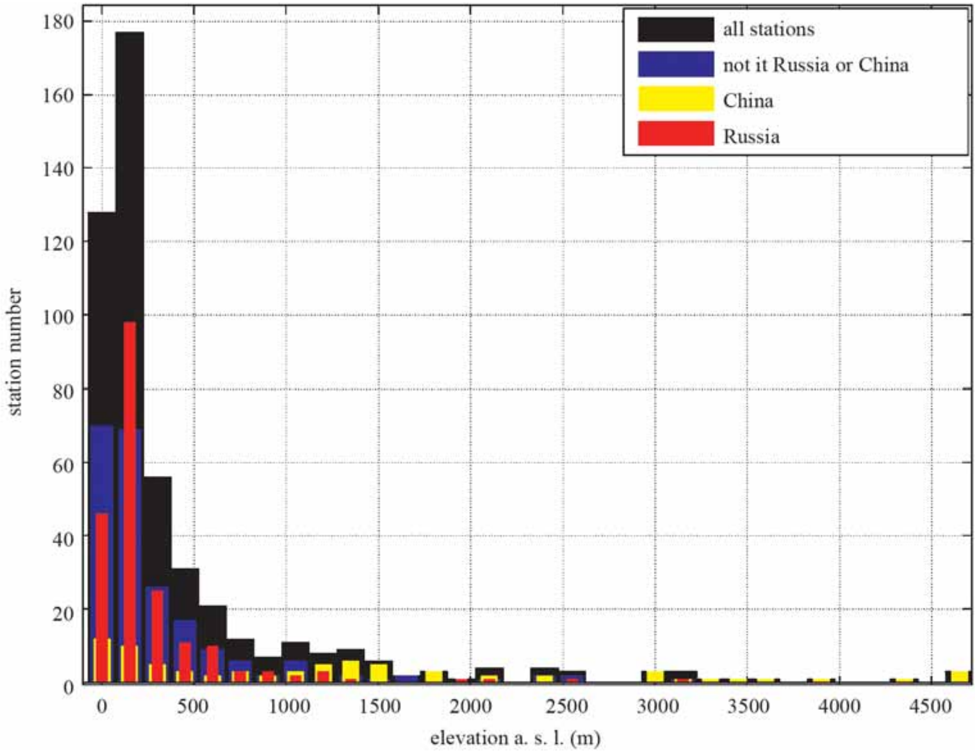


Fig.3. Altitudinal distribution of the stations.

The altitudinal distribution of the sites (Fig. 3) is comparatively similar between the Russian, Chinese and West European stations. However, since many sites in Western Europe are situated in coastal areas, this region has a greater share of low-lying sites (height a.s.l. <100 m). China has rather equal shares of low- and high-elevation sites, having the largest number of sites above 1500m.

WMO-GAW, eddy-covariance and aerosol measurement sites

PEEX aims to promote the use of state-of-the-art measurement techniques for aerosol and flux measurements. Aerosol measurement tools falling into this category include e.g. differential mobility particle sizers (DMPS), whereas the relevant flux measurement technique is eddy-covariance (EC). The sites in Russia equipped with aerosol or EC instrumentation are shown in Fig. 4. The emerging spatial distribution of the sites, while covering the main geographical units of Russia, still leaves extensive areas empty. The existing EC flux and aerosol measurements are concentrated in the Western part of European Russia, around the populated areas of West and central Siberia, around the Baikal Lake and along the Arctic Ocean coast. Some areas, including the North-East of European Russia, Urals, great parts of Siberia and the Russian Far East are not covered by measurements at all. A number of stations contribute to the Global Atmospheric Watch network (WMO-GAW), providing data on precipitation chemical composition, total ozone and greenhouse gas concentrations from different parts of Russia.

Recent developments in the ground-based measurement station network

Since the first overview by Kulmala et al. [2011], three new EC sites have been launched, to the knowledge of the authors: the temperate bog site in the Central Forest Nature Reserve (A.N.

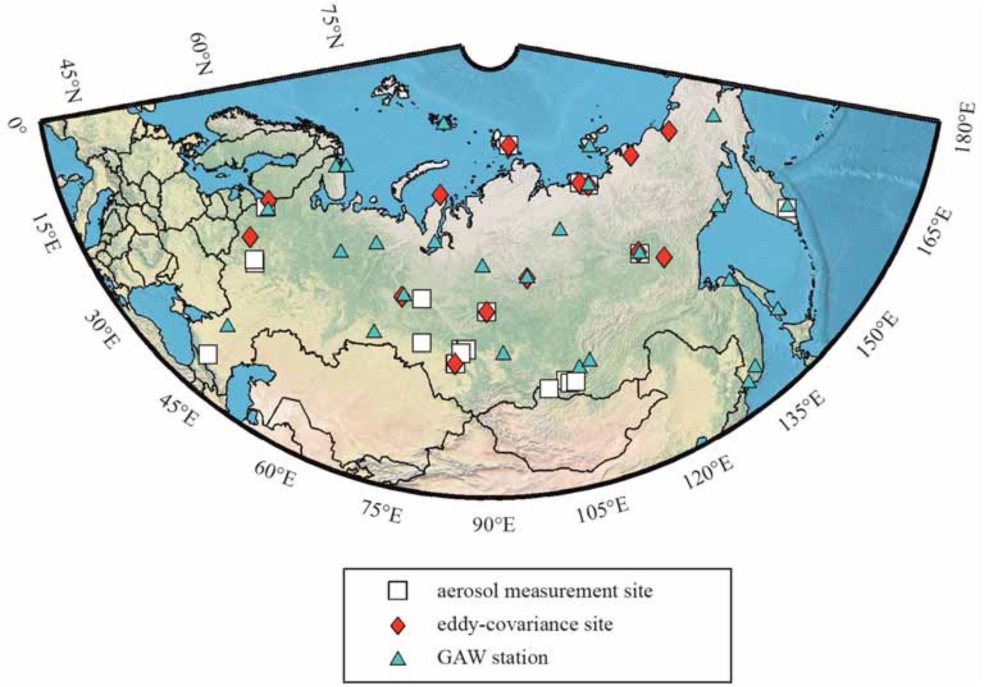
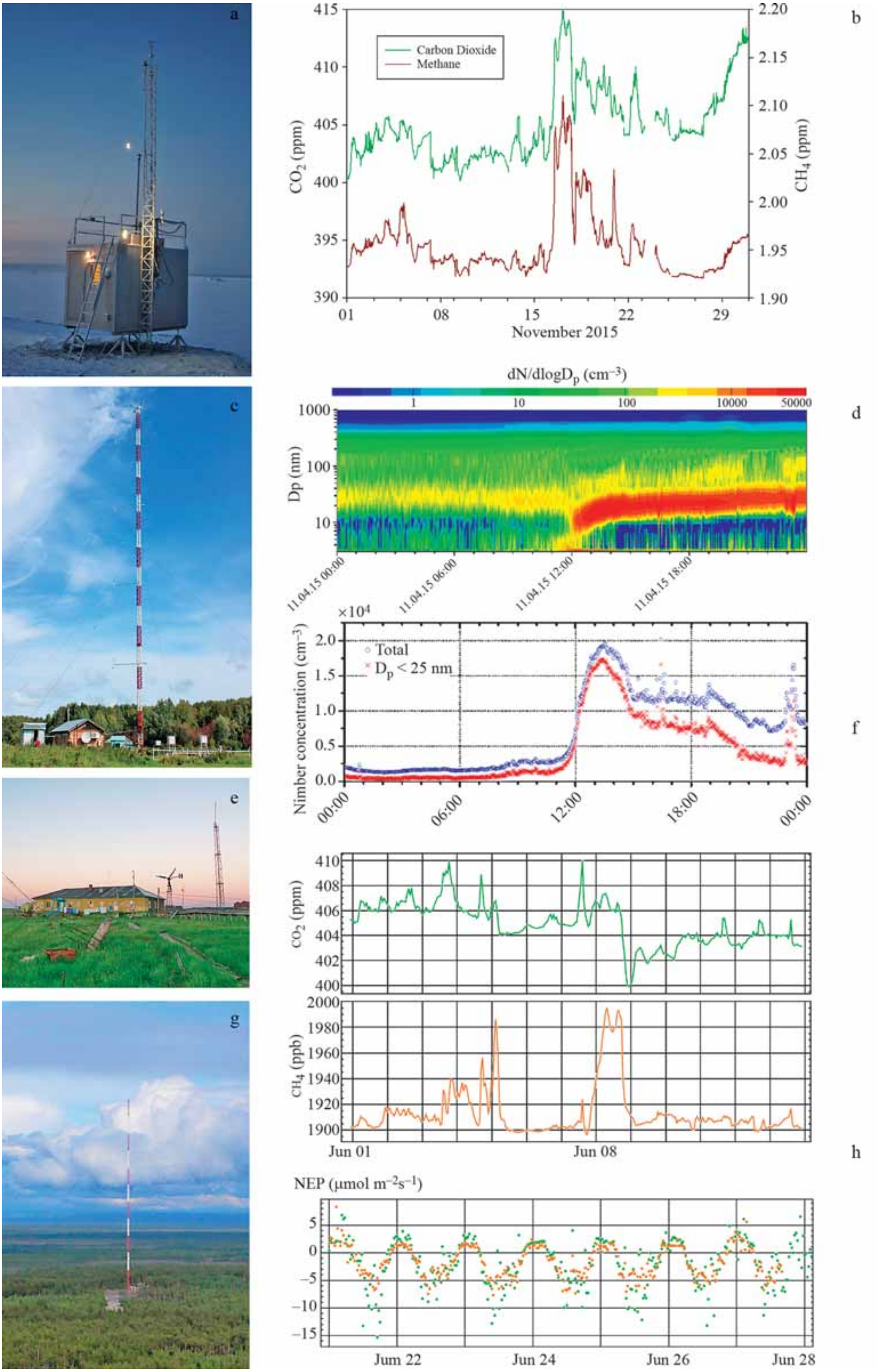


Fig.4. Eddy-covariance, aerosol measurement sites and GAW stations in Russia. A satellite-derived land-cover raster image is shown on the background.

Severtsov institute of ecology and evolution RAS), the boreal bog site at Mukhrino Field Station (Yugra State University) and the arctic site of Ice Base Cape Baranova (Finnish Meteorological Institute (FMI)/Arctic and Antarctic Research Institute (AARI)).Some of the newly established aerosol measurement sites are located at the Ice Base Cape Baranova station (FMI/AARI) and Akademgorodok, Novosibirsk (Institute of Chemical Kinetics and Burning of the Siberian Branch of the Russian Academy of Sciences).

A number of stations in Russia deliver novel measurement data from the regions that remained unexplored until recently. Several prominent examples of such data are given in Fig. 5. Two stations represent the Arctic islands and coast (Ice Base Cape Baranova and Ambarchik), while the two other represent the south and middle taiga zones (Fonovaya and ZOTTO). These stations set a high standard for the aerosol and greenhouse gas monitoring in remote parts of Northern Eurasia.

Fig.5. (next page) a–b) A photo and a graph showing several days of the CO_2 and CH_4concentration data from the newly established Cape Baranova station, Bolshevik island (Finnish Meteorological Institute/ Arctic and Antarctic Research Institute, Russia); c–d) a photo and an aerosol formation event registered on 11 April 2015 at the Fonovaya station, Tomsk (Institute of Atmospheric Optics SB RAS); e–f) a photo and CH_4concentration time series from the new greenhouse gas monitoring station at Ambarchik (Max Planck Institute for Biogeochemistry); g–h) a photo and eddy-covariance net ecosystem productivity time series from ZOTTO station (Max Planck Institute for Biogeochemistry / I. V. Sukachev Institute of Forest, SB RAS). The green data points in (h) correspond to the Scots Pine forest measurements and the orange dots to the ombrotrophic bog measurements.


a
b
Carbon Dioxide
Methane
CO2 (ppm)
CH4 (ppm)
415
410
405
400
395
390
2.20
2.15
2.10
2.05
2.00
1.95
1.90
01
08
15
22
29
November 2015
c
d
dN/dlogDp (cm−3)
1
10
100
10000
50000
Dp (nm)
1000
100
10
11.04.15 00:00
11.04.15 06:00
11.04.15 12:00
11.04.15 18:00
e
f
×10^4
Nimber concentration (cm−3)
Total
Dp < 25 nm
2.0
1.5
1.0
0.5
0.0
00:00
06:00
12:00
18:00
00:00
g
h
CO2 (ppm)
410
408
406
404
402
400
CH4 (ppb)
2000
1980
1960
1940
1920
1900
Jun 01
Jun 08
NEP (μmol m−2s−1)
5
0
−5
−10
−15
Jum 22
Jun 24
Jun 26
Jun 28

Representation of climates by the measurement network

The continent-wide extent of the PEEX domain means that it spans multiple climatic and vegetation zones. The PEEX target zone is mainly represented by the continental climates (the *D* group in Köppen-Geiger classification), but also the areas experiencing subtropical or steppe climate are found in the Black Sea region and along the Mongolian border. In terms of areal coverage, the dominating climates are continental *Dfb*, typical of Central and Eastern Europe and South-Western Siberia, and *Dfc*, a major Boreal climate variety (Table 2).The absolute majority of measurement sites are found in these two climates, with small numbers in the Arctic coast tundra and the drier South Boreal climate zone *Dwc*.

A more detailed view is presented in Table 2, where the ecosystem dimension is added. Similar ecosystem types are found in different climates – for example, forests cover almost entire Russia except for the steppe and Arctic regions. The same can be said about the freshwater bodies and wetlands that are ample throughout the country. Although the population is sparse in large parts of Siberia and the Russian Far East, sizeable urban areas do occur everywhere, and they, too, frequently lack continuous observations.

This analysis reveals the apparent lack of any measurements or monitoring in many ecosystem/climate pairs. While the major temperate, Boreal and arctic climates (*Dwc*, *Dfb*, *Dfc*, tundra) can be described as well represented in terms of ecosystem coverage, the rest are poorly covered by measurements. Mountainous areas in many climatic zones are represented as scantly. Many climates represented by small fractions of land do not host any measurement stations at all. It is particularly striking that the number of permanent wetland sites is incomparably smaller then the number of forest sites, in all climates. The steppe climate *Bsk* and one of the boreal types *Dfd* are also represented by a disproportionately small number of stations.

Identifying the development needs of the PEEX ground-based observational network

The vastness of the PEEX target region, Northern and Eastern Eurasia, is both an advantage and a challenge. On the one hand, the wide geographical extent of the PEEX program, both the East-West and North-South gradients can be well described on a continental scale. The multitude of climates and ecosystems encountered across these gradients gives the potential to construct a realistic, high-definition vision of the climate change-related processes. On the other hand, however, the challenge lies in the fact that most of the PEEX target region is represented by pristine areas, which are often difficult to reach.

Since Russia covers most of the PEEX domain, the development of instrumentation over its vast area is of primary importance. The current permanent measurement site distribution in Russia is explained, firstly, by the proximity to the major population centers and developed infrastructure, and, secondly, by high interest in certain major biomes, such as boreal forest and tundra. Unsurprisingly, as a result, some areas are represented better than the other. Nevertheless, even when a certain region does host an isolated measurement station, this cannot be regarded as sufficient coverage. For instance, there is only one peatland research station with an EC setup in the whole of West Siberia (Mukhrino Field Station), the region that, in principle, is characterized with a great variety of peatland landscapes.

PEEX promotes the use of state-of-the-art equipment for advanced aerosol measurements, atmospheric composition and physics, surface-atmosphere exchange of matter and energy, ecophysiological and phenological monitoring. At the moment, such measurement data are deemed scarce in the PEEX region [Kulmala et al. 2011b,

Table 2. Russian land-based station numbers for the climate/ecosystem pairs.

Köppen-Geiger climate type	Cover fraction (%)	K-G index	Ecosystem types							
			freshwater	wetland	forest	steppe	high-elev.	tundra	marine	urban
milddesert	1.5	Bwk	0	–	–	–	–	–	–	0
mildsteppe	5.9	Bsk	0	–	–	1	1	–	0	0
humidsubtropical	≪1	Cfa	1	0	0	–	2	–	1	0
humid continental	≪1	Dsb	0	0	0	–	0	–	0	0
boreal, cold/dry summer/cold summer	0.5	Dsc	0	0	0	–	0	–	0	0
boreal, cold/dry summer/very cold winter	0.1	Dsd	0	0	0	–	0	–	–	0
humid continental, cold/dry winter/hot summer	0.7	Dwa	0	0	0	–	0	–	0	0
humid contin., cold/dry winter/warm summer	0.2	Dwb	1	0	2	–	2	–	0	2
boreal, cold/dry winter/cold summer	7.5	Dwc	2	0	**14**	1	1	1	0	2
boreal, cold/dry winter/very cold winter	1.6	Dwd	0	0	0	–	0	–	0	0
humid contin., cold/no dry season/hot summer	2.4	Dfa	0	0	0	–	1	–	–	1
humid contin., cold/no dry season/warm summer	19.5	Dfb	**16**	3	**27**	4	0	–	1	**15**
boreal, cold/no dry season/cold summer	44.3	Dfc	6	3	**42**	–	2	**13**	0	**12**
boreal, cold/no dry season/very cold winter	6.9	Dfd	0	2	4	–	0	0	–	1
polar/tundra	8.6	ET	0	0	–	–	0	**25**	1	0
polar/frost/ice	0.3	EF	0	–	–	–	0	–	1	–

Notes: "Cover fraction" is the fraction of the land area a given climate makes up of the total land area within 45°–90° N, 15°–180° E. Green shading indicates the presence of at least one station in a given combination of climate and ecosystem, while brown shading highlights the absence of stations. "Freshwater" unifies rivers, lakes and reservoirs. "Wetland" unifies peatlands of all types. The station counts of ten or more appear in bold

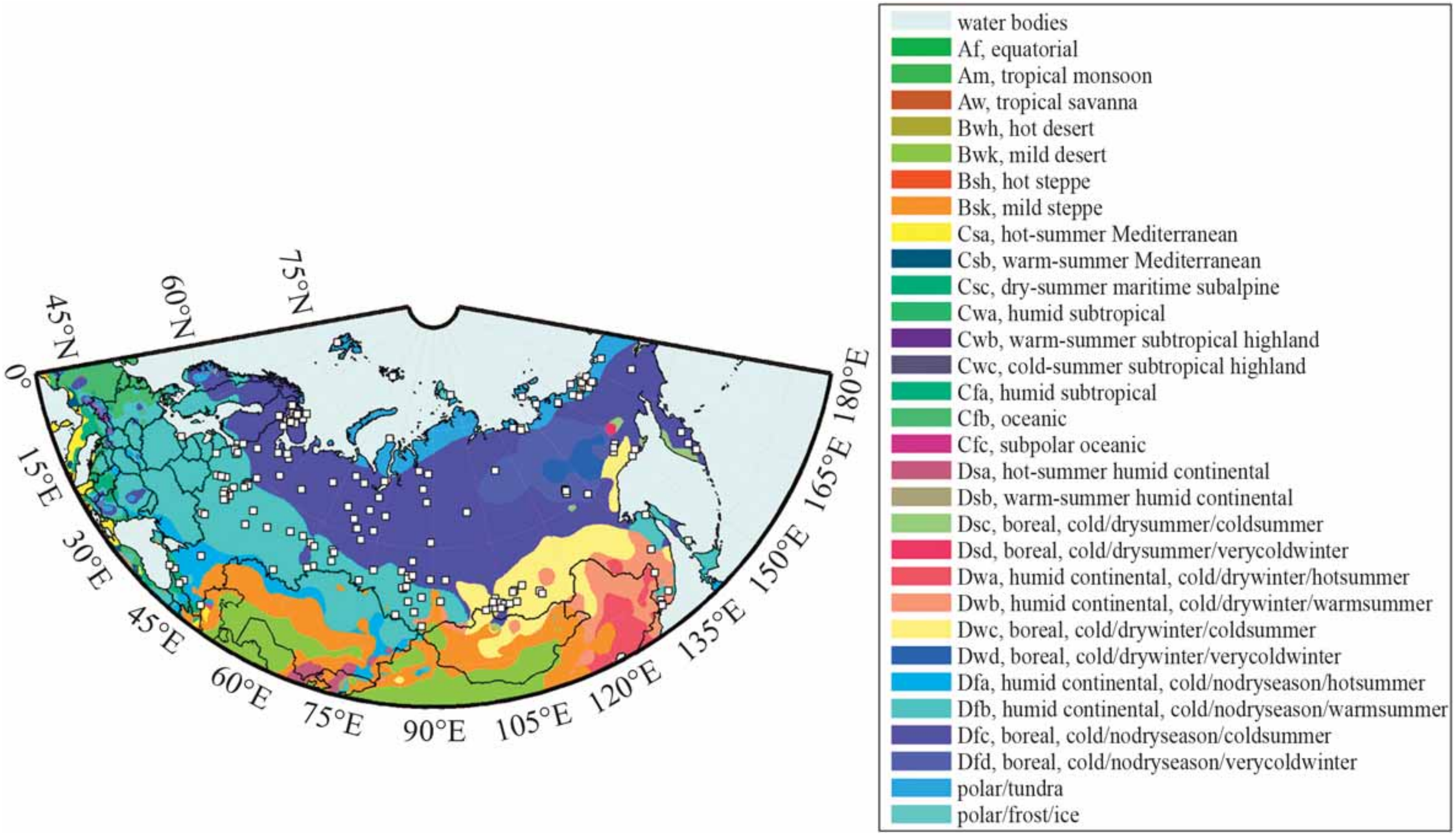


Fig.6. Measurement sites in Russia shown against the Köppen-Geiger climate map. The measurement station locations are marked with white squares.

Kulmala et al. 2015, Hari et al. 2015)]. An example of such deficiency in EC and aerosol measurements was given in Fig. 4. Adopting the estimate by Hari et al. (2015) that about 500 flux stations should exist worldwide, the present number of Russian EC sites is far behind the optimum; the same pertains to the aerosol measurements. As of June 2015, no Russian sites were part of the GAW In-Situ Aerosol Network.

Specific station network development needs have to be identified. One can approach this problem by identifying the climate/ecosystem groups that are currently missing continuous monitoring. This analysis reveals that many gaps remain (see Table 2). Ideally, each climate/ecosystem pair should be monitored by at least one Flux-level station, and preferably more than one as significant local variations are common. The existing Russian EC/aerosol sites may become the first Flux-level sites. In terms of Flagship stations, one per each climate in Table 2 is required, except maybe for the climates *Dsc*, *Dsd* and *Dwd* that are constrained to relatively small regions. At the same time, it would be reasonable to propose that in the dominant climates, the continental *Dfb* and the boreal *Dfc*, more than one Flagship station be established, owing to their latitudinal extent and internal variability. Finally, the standard stations can possibly be founded on the basis of the meteorological station network.

The nucleus of the future comprehensive infrastructure, the PEEX Preliminary Station Network, unifies a number of stations representing many parts of Russia. The participating Russian stations currently include: Yakutsk, Nizhni Novgorod/Moscow/Borok cluster, Petergof, Fonovaya station (Tomsk), White Sea Biological Station, Tiksi, Novosibirsk, ZOTTO (Krasnoyarsk Krai), Tyumen, Baikal/Irkutsk/Ulan Ude cluster, Mukhrino Field Station (Khanty-Mansijsk Autonomous Region), Aktru station (Altai Republic), Central Forest Nature Reserve (Tver region). WMO-GAW stations are potential members of the PEEX network as well. These stations will form the core of the future PEEX station network. Outside Russia, the PEEX Preliminary Phase Observational network includes the SMEAR-type stations in Finland (SMEAR-I-II-II-IV), Estonia (SMEAR-Järviselja) and China (SMEAR-Nanjing), and the ecosystem station network in China.

CONCLUSIONS

The success of the PEEX mission to provide the next generation solutions to the climate change problems directly depends on the quality and coverage of the ground station data. The ground measurement network in its current shape needs being upgraded and extended to the previously underrepresented ecosystems and climatic zones. To address these needs, we motivate the foundation of a network of Flagship, Flux and Standard stations that would cover the PEEX domain. The region in question features some of the most remote areas of the world, with harsh climate, low infrastructure development and sparse population. While the existing infrastructure provides a valuable basis, building a network complying with the criteria proposed by Hari et al. [2015] will require extensive efforts.

The initiation of the PEEX Observation Network – Preliminary Phase Program is the main approach to the infrastructure development at the moment. We envision that it should include the following practical actions:

- to identify the ongoing measurement routines of the PEEX Preliminary phase ground stations;
- to analyse the end-user requirements of the global and regional scale climate and air quality modelling communities in the PEEX domain;
- to provide an outline for the PEEX labelled network, including the

measurement and data product – archiving – delivery requirements for each station category;

- to identify the key gaps in the initial phase observational network including long-term observational activities within PEEX domain, in Europe, in China and globally;
- to initialize harmonization of the observations in the PEEX network following e.g. the accepted practices from World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme or European observation networks;
- to improve satellite observations over the PEEX domain of interest;
- to develop methods and methodology for inter-platform comparisons between the ground based and satellite observations;
- to establish a PEEX education program for instruction in measurement techniques and data analysis for both young scientists and technical experts.

These tasks require strong ties and international cooperation between the leading institutions, involving practical efforts to coordinate, harmonize and jointly manage the research infrastructure. The development of a coherent, extensive, continuous and comprehensive ground-based measurement site network thus poses a challenge for the scientific community and the governments.

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Pavel Alekseychik, M.Sc., is the PEEX Infrastructure officer and Ph.D. researcher at the University of Helsinki, Finland. He started his studies in hydrometeorology at the Russian State Hydrometeorological University in St. Petersburg in 2006 and in 2009 moved to Finland to complete the Bachelor's degree at the University of Helsinki, Department of Physics, Division of Atmospheric Sciences. It was the place where he obtained Master's degree in biosphere-atmosphere interactions in 2011 and continued with the research for his Ph.D. Pavel Alekseychik has been engaged in research into a number of topics, including forest micrometeorology, peatland biogeochemistry and boreal ecosystem ecology. He has also been actively involved in field campaigns and continuous measurements at several sites in Finland and Russia. His current work in the PEEX program is focused on the analysis and harmonization of the ground-based measurement station network.

PAN-EURASIAN EXPERIMENT (PEEX) – A RESEARCH INITIATIVE MEETING “THE GRAND CHALLENGES OF THE CHANGING ENVIRONMENT OF THE NORTHERN PAN-EURASIAN ARCTIC-BOREAL AREAS” (International Geographical Union Conference 2015, Moscow, Russia)[1]

The Pan-Eurasian Experiment (PEEX) is a multidisciplinary climate change, air quality, and environmental global change research program aimed at understanding biosphere-ocean-cryosphere-land-atmosphere interactions and feedbacks in the Northern Eurasian, particularly arctic and boreal, regions (https://www.atm.helsinki.fi/peex/). One of the sections of the International Geographical Union (IGU) Regional Conference held in Moscow in August 2015 was devoted to the PEEX program. The section hosted 34 oral and 16 poster presentations from the Russian Federation, Finland, Belarus, Norway, Greece, and China.

The keynote address “Pan-Eurasian Experiment (PEEX) Program – Grand Challenges in the Arctic-boreal context” was delivered by Markku Kulmala, in which he emphasized that the Earth system is facing several global-scale environmental challenges, called “Grand Challenges.” Grand challenges such as climate change, air quality, ocean acidification, fresh water, and food supplies are the main factors controlling the human well-being and security and stability of future societies. All the grand challenges are interlinked via complex feedbacks in the Earth system. He underlined that in the future, the Northern Eurasian natural environment will play a crucial role for the Earth system feedback processes due to albedo change, carbon sinks and emissions, methane emissions and aerosol production via biogenic volatile organic compounds. This presentation was closely connected with the reports by Hanna Lappalainen (“Pan-Eurasian Experiment [PEEX] research agenda – system understanding of the Arctic-boreal regions for scenarios and assessments of the Northern Pan-Eurasian environments”) and by Pavel Alekseychik (“Towards the harmonized PEEX project observational infrastructure: building the metadatabase”). In the latter presentation, the author summarized information about the observational facilities included in the PEEX metadatabase and provided the details about their organization, measurement equipment, and a number of other features.

One of the main traditional research areas in the PEEX program is the research of the atmospheric composition, its future scenarios and their role in biogeochemistry. Alexei Eliseev presented the results of the assessment of climatic and ecological impacts of tropospheric sulphate aerosols on the terrestrial carbon cycle using the parameterisation of tropospheric sulphate aerosols on the terrestrial gross in the coupled model. The model response to sulphate

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[1] The review is based on the IGU 2015 Book of Abstracts, International Geographical Union: Moscow, 2015.

aerosol loading is subdivided into the climatic and ecological impacts. It appears that the former basically dominates over the latter on the global scale and modifies the responses of the global vegetation and soil carbon stocks to external forcings by 10 %. Other model simulations were performed to evaluate the assessment of global CO_2 emissions to the atmosphere from crown, ground, and peat fires (Eliseev et al.). The results showed that ground and peat fires contribute significantly to the total emissions of CO_2 from natural fires (20–25 % at the global scale depending on scenario and calendar year). Meigen Zhang talked about the assessment of the biospheric contribution to surface atmospheric CO_2 concentrations over East Asia, in which a regional chemical transport model, RAMS-CMAQ, was employed to assess the impacts of biosphere–atmosphere CO_2 exchange on seasonal variations in atmospheric CO2 concentrations over East Asia. The presentation "Cold CO_2 emission from sub-boreal soils: current trends and effect of repeating freezing-thawing events" made by Irina Kurganova was based on the long-term measurements in the Moscow region. The results of several experiments with soil temperature and precipitation manipulation and their influence on CO_2 fluxes were presented by Valentin Lopes de Gerenyu and Irina Kurganova. Egor Dyukarev discussed the analysis of observations and modelling of carbon fluxes from peatlands in southern taiga of Western Siberia. Leonid Golubyatnikov talked about methane emissions from northern lakes in Karelia and Western Siberia. The study on wildfire forest and peat aerosol emissions in the PEEX regions including particulate matter and black carbon aerosols were presented by Olga Popovicheva. Another presentation on the aerosol optical depth retrieval over the arctic region using satellite data was made by Yong Xue.

The potential for space-borne monitoring of atmosphere pollution in Northern Eurasia under the PEEX framework was discussed by E. Mityushina. C.A. Arutyunyan presented "Studying emissions of trace gases and aerosols resulting from wildfires into the atmosphere of Northern Eurasia with satellites"; Vadim Rakitin talked about "Satellite and ground based measurements: comparison of CO and CH_4 total contents for background and polluted conditions" and "Background CO and CH_4 total contents: long-term IAP spectroscopic datasets, typical and abnormal variations and temporal tendencies.". Oleg Postylyakov discussed the investigation of atmospheric composition using ground-based methods in cloudy conditions within the Russian-Belorussian DOAS Network. Black carbon studies in the atmosphere over the White, Barents, Greenland, and Kara seas during summer 2014 were described by Vladimir Shevchenko. Anna Vinogradova also focused on the black carbon topic in her presentation "Black carbon atmospheric emissions from Russian oil/gas industry open fires". Aircraft-borne measurements over Southern Finland during the PEGASOS 2013 campaign were the subject of Riikka Väänänen's talk. Jiahua Zhang presented the results of the assessment of the biospheric contribution to surface atmospheric CO_2 concentrations over East Asia with a regional chemical transport model. Long-term variability of aerosols in Moscow according to AERONET, their radiation effects, and comparison with the results of radiative calculations in COSMO-Ru mesoscale model were discussed by Alexei Polyukhov. Yury Shtabkin presented the results of the seasonal variations of near-surface carbon monoxide (CO) concentration in central Siberia in 2007–2012, according to ZOTTO observations and model simulation. Natalia Pankratova analyzed ozone and nitric oxides in the surface air over Russia under background conditions and in extreme situations.

Tuukka Petaja with colleagues talked about "Biogenic Aerosols – Effects on Clouds and Climate (BAECC) project as a showcase for benefits of comprehensive atmospheric observations," where they described the comprehensive aerosol measurement facilities that allow linking precursor emissions and aerosols and aerosols at the surface and in the mixing layer and free troposphere, and investigating the aerosol indirect effects on clouds and precipitation. Xuemeng Chen discussed verification of aerosol diffusion spectrometer on the measurement of atmospheric aerosol particles.

The results of simultaneous measurements of the temporal variations in wind velocity, atmospheric pressure, and gas constituents (NO_2, NO) near Moscow and Beijing were presented by Igor Chunchuzov. The characteristics of the coherent structures (dominant periods, spatial scales, and translation speeds) in the troposphere were obtained, and their influence on temporal variability of gas components in the atmosphere has been evaluated. In addition, regular observations of the integral content of formaldehyde and nitrogen dioxide in the lower troposphere in the Moscow region were discussed by Alexander Borovski.

Valery Bondur talked about "Methods of satellite monitoring for the purpose of the Pan-Eurasian Experiment (PEEX)" and discussed different methods and the potential of remote sensing.

The new PEEX-labeled projects: "Influence of natural and anthropogenic emissions of greenhouse and polluting gases on climate and ecosystem changes in Eurasia" and "Project SLICFONIA: complicated study of short-lived climate forcers in the Arctic" were presented by Andrei Skorokhod.

The report "Cognitive chaos: turbulence in the Earth system" was made by Sergej Zilitinkevich. Igor Esau also analyzed interaction of temperature and planetary boundary layer (PBL) in "Paradox of the surface air cooling in response to the global warming: a role of the stably stratified PBL and free atmosphere temperature inversions." The evaluation of convective boundary layer parameterizations based on large-eddy simulation (LES) data was presented by Andrey Debolskiy and Victor Stepanenko.

Another important topic on sustainability of carbon fluxes between forest and bog ecosystems in southern taiga of European Russia was discussed by Juliya Kurbatova. The results of measurements of carbon dioxide fluxes have shown that southern taiga ecosystems can function during the vegetative period both as a source and a sink of carbon for the atmosphere.

Evgeny Gordov discussed web-GIS based virtual research environment for the Northern Eurasia climatic studies, which could be an important tool for regional climatic and ecological monitoring and modelling as well as for continuous education and training support.

In the presentation by Natalia Chubarova "Temporal and spatial variability of biologically active UV radiation and UV resources over northern Eurasia" a new approach was proposed, which allows a user to estimate different impacts of biologically active UV radiation (vitamin D production, eye damage, erythema) over the territory of Northern Eurasia and to characterize its benefit or hazard for people with different skin types. Using the same approach, an interactive tool has been developed, which was described by Ekaterina Zhdanova. Long-term UV variations in Moscow since 1968 and the reasons of UV change were discussed by Elena Nezval'.

Vladimir Platonov and Stanislav Myslenkov analyzed the meteorological conditions over Northern seas in the presentation "Implementation of SWAN model with COSMO-CLM wind forcing for the Barents Sea storm events." They showed that the technique of high-resolution coupling between regional atmospheric and wave models could well reproduce extreme events, such as polar lows, and its main features like strong winds, pressure, and temperature as well as ocean wave distribution. The SWAN wave model was also used for studying the influence of swell waves from the North Atlantic on the wave field in the Barents and White seas (Myslenkov et al.). Alexander Demidov talked about the mass structure and circulation in the south-eastern part of the Baltic Sea based on the data of the joint expeditions of Moscow State University and Baltic Federal University in 2009–2014. Alexander Chernokulski demonstrated a general increase of convective activity in Northern Eurasia over the last four decades, which also can be expected under the XXI century climate.

Several studies were devoted to the chemical composition and gas exchange in boreal lakes. Galina Gavrilenko discussed the oxygen regime of shallow lakes. Sofya Guseva and Victor Stepanenko presented the results on the numerical study of water-atmosphere gas exchange parameterization for a boreal lake.

Sergei A. Dobrolyubov
Natalia E. Chubarova

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