Pan-Eurasian Experiment (PEEX): A Framework Program on the Land - Atmosphere - Ocean - Society Interactions of the Changing Arctic – Boreal Environments

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The Arctic is warming two times faster than the other regions of the Earth system. Spatially, the processes called "Arctic greening" and the Arctic tundra "browning" are bringing the Arctic change closer to the dynamics taking place in the boreal regions. To be able to understand the changing Arctic environments and societies as well as feedbacks between the Arctic and boreal regions and, on a larger scale, between the Arctic and the Earth system, we need a novel conceptual framework of research methods, infrastructures and procedures. The Pan-Eurasian Experiment Program (PEEX), established in 2012, is aiming to be a next-generation natural sciences and socio-economic research initiative using excellent multi-disciplinary science with clear impacts on future environmental, socio-economic and demographic development of the Arctic and boreal regions and China. PEEX is also a science community facilitating novel research infrastructures (in situ observation networks) in the Northern Pan-Eurasian region and China. PEEX delivers conceptual plans of coherent, coordinated, comprehensive in situ measurement and data systems of the Earth surface-atmosphere interactions. PEEX is making an assessment of the existing observation capacities including satellites, versus the future PEEX in situ observation network, which would cover the Northern Eurasian region from Scandinavia to East Asia. The principles of the PEEX in situ observation network is based on the SMEAR (Stations Measuring the Earth Surface – Atmosphere Relations) concept. PEEX is interested in expanding the land-based observation network to cover also the most relevant processes related to the Arctic Ocean and to make a conceptual design of the marine in situ component. In addition, PEEX is taking the first steps for implementing the seamless all-scales-modelling platform and continues to develop the PEEX View Modelling Tool.

Introduction

The Pan-Eurasian Experiment Program (PEEX) (https://www.atm.helsinki.fi/peex/) is a multi-scale and multi-disciplinary program aimed at finding science based solutions for the global environmental challenges, such as climate change, at the Northern high latitudes and in China. The PEEX kick-off meeting was held in October 2012. The cornerstones of the program are (i)

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carrying out a science based approach from deep understanding to practical solutions, (ii) using methods based on multidisciplinary, multiscale tools, (iii) coordinating fragmented observation sites towards coherent, coordinated research infrastructures, (iv) delivering scientific information and services receiving the greatest possible impact and (v) facilitating knowledge transfer and multidisciplinary education. The promoter institutes of PEEX have been the University of Helsinki and the Finnish Meteorological Institute in Finland; the Institute of Geography of Moscow State University, AEROCOSMOS, and the Institute of Atmospheric Optics (Siberian branch) of the Russian Academy of Sciences (RAS) in Russia; the Institute of Remote Sensing and Digital Earth (RADI) of the Chinese Academy of Sciences (CAS) and the Institute for climate and global change research of Nanjing University in China. The program governance and the communications is coordinated by the PEEX Offices in Helsinki (PEEX Headquarters), Moscow, Nanjing and Beijing under the guidance of the Program Steering Committee.

The program is aimed to be a long-term continuous activity carrying out coordinated research and the development of *in situ* observation networks and education of the next generation of experts having multidisciplinary skills and background. Starting from 2013, PEEX has defined its scientific scope and the thematic research areas of interest. The main interest is in the understanding of large-scale feedbacks and interactions between the land-atmosphere-ocean continuum in the changing climate of the Northern high latitudes. The PEEX research community or network is currently covering ca. 4,000 researchers representing mainly the natural sciences. The backbone of the research approach is the currently ongoing Finnish Center of Excellence in Atmospheric Science - From Molecular and Biological processes to The Global Climate, with the annual volume of published peer reviewed papers of about 150. PEEX is also gathering research results on the Arctic-boreal environments via the PEEX Special Issue in the Journal of Atmospheric Chemistry and Physics (http://www.atmos-chem-phys.net/special_issue395.html).

In addition to carrying out and making an integrative synthesis out of Arctic-boreal research, PEEX is also interested in coordinating the *in situ* network on Earth surface−atmosphere observations across the Northern Eurasian region and marine based observations over the Arctic Ocean (Figure 1). The principles of the PEEX *in situ* observation network is built on the SMEAR (Stations Measuring the Earth Surface – Atmosphere Relations) concept (Hari et al., 2016; Kulmala et al., 2016; Alekseychik et al., 2016). SMEAR concept is based on simultaneous observations on atmospheric composition, meteorology and ecosystem biological activity (photosynthesis, respiration). The flagship station introducing the SMEAR concept in operation is the SMEAR-II station situated in Hyytiälä, Finland. The SMEAR-II station is contributing to several European and global level monitoring and observation systems (www.atm.helsinki.fi/SMEAR/index.php/smear-ii) (Figure 1).

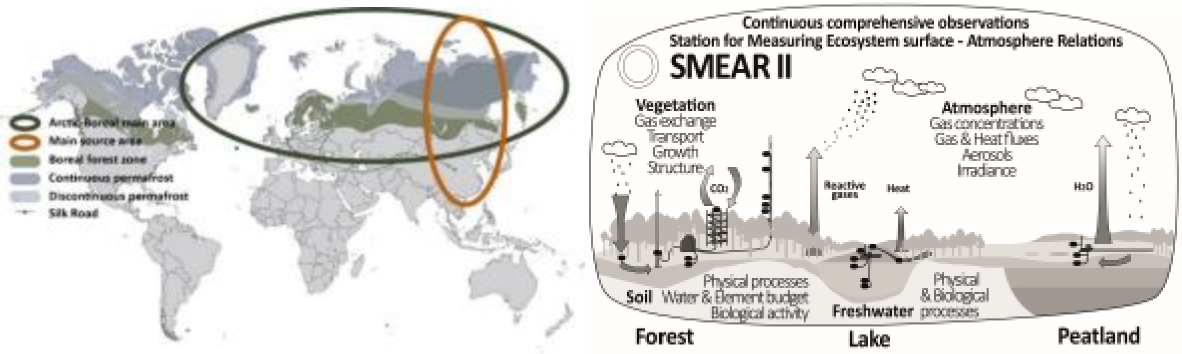

Figure 1. One of the main aims of PEEX is to improve the current *in situ* observation network and observation concept across the Northern Eurasian region. The PEEX geographical area of interest (left) and the schematics of the SMEAR-II station observations (right).

PEEX is interested in expanding the land-based observation network to cover also the most relevant processes related to the Arctic Ocean and make a conceptual design of the marine *in situ* component (Vihma et al. manuscript in preparation). New data are needed for comprehensive data analysis and modelling frameworks. PEEX will establish a seamless modelling framework from nano-scale modelling to Earth system models and introduce community-based services for data mining and for demonstrating air pollution events at regional scales (Baklanov et al., manuscript under preparation). Satellite observations provide daily observations of atmospheric composition and surface properties, complementary to *in situ* and modeling information. As a part of this approach, PEEX is delivering conceptual plans of the coherent, coordinated and comprehensive measurement and data systems of the land-atmosphere interactions.

The PEEX education is a cross-sectional activity, which covers young scientists training, including specific winter and summer schools, and the expert training targeted to more technical aspects of measurement techniques and running operations including data management aspects of field stations.

The PEEX Science Plan was delivered in 2015 (Lappalainen et al., 2015, http://www.atm.helsinki.fi/peex/images/PEEX_Science_Plan.pdf) and after that, the main focus has been on the conceptual design of PEEX tools. In this paper, we will introduce the latest progress made in different PEEX tools (observation network, marine observation concept, modelling platform, socio-economic data pools, education) during the last two years and give an overview of the next steps implementing the PEEX Science Plan.

Scientific Background

The Arctic is warming two times faster than the other regions of the Earth. Spatially, the processes called "Arctic greening" and the Arctic tundra "browning" are bringing the Arctic change closer to the dynamics taking place in the boreal regions (IPCC, 2013; Anderson et al. 2013; Myneni et al., 1997; Xu et al., 2013; Phoenix & Bjerke, 2016).

Research collaboration is required to solve those yet open scientific questions that are specifically important to Arctic-boreal land ecosystems in the coming years (Table 1). In particular, the scientific questions in the context of global climate change and its consequences for nature and northern societies are related to the net effects of various feedback mechanisms connecting the biosphere, atmosphere and human activities (e.g., Elmendorf et al., 2012; Macias-Fauria et al., 2012; Larsen & Fondahl, 2014; Callaghan et al., 2011; Schuur et al., 2015). Such feedbacks are triggered by increasing concentration of greenhouse gases (GHG), leading to higher temperatures and consequently to further permafrost thawing, land cover change, increased dissolved organic carbon content in freshwaters, acidification of the Arctic Ocean, sea ice decline, increased photosynthetic activity, changes in the carbon balance and energy budgets as well as greenhouse gas exchange between the atmosphere and terrestrial ecosystems, shrub encroachment, treeline advance, and increased biogenic volatile organic compound (BVOC) emissions into the atmosphere which leads to increased aerosol and cloud droplet number concentrations thereby affecting the Earth's radiation budget (Arneth et al., 2010, 2014; Ballantyne et al., 2012; Carslaw et al., 2010; Kulmala et al., 2014). These feedbacks may be expected to accelerate or decelerate the rate of climate change. The primary scientific focus of the PEEX is on the physical, chemical and biological processes affecting climate change. In addition to climate change and global warming, the PEEX community investigates biogeochemical cycles in different ecosystems, sustainable use and acclimation of forests to the changing climate, air quality, feedbacks between air pollution and changing climate, and related socio-economic aspects.

The Arctic Ocean plays an important role in the climate system. The essential processes related to the interaction between the ocean and other components of the Earth system include the air-sea exchange of momentum, heat and matter (e.g., moisture, CO_2, and CH_4, sea spray aerosol), as well as the dynamics and thermodynamics of sea ice. The remaining open scientific questions are related to the role of the ocean in the Arctic amplification of climate change, to the reasons for the Arctic sea ice decline, to the GHG exchange between the ocean and atmosphere, and to the various effects that the sea ice decline has on the ocean, surrounding continents and aerosol budgets (Lappalainen et al., 2015). Furthermore, the ice cover of the Arctic Ocean is undergoing fast changes, including a decline of summer ice extent and ice thickness, and is affecting the dynamics of the ocean biology. Sea ice changes will result in a significant increase in the ice-free sea surface during the vegetation season, and an increased duration of this season. This will initiate a pronounced growth of the annual gross primary production (GPP) and phytoplankton biomass. Higher GPP may in turn cause an increase in CO_2 fluxes from the atmosphere to the ocean and an increase in the overall biological production, including the production of higher trophic level organisms and fish populations. An increase in surface water temperature might "open the Arctic doors" for new species and change the Arctic pelagic food webs, energy flows and biodiversity. Climatic and anthropogenic forces at the drainage areas of Arctic rivers may lead to changes in flood timing and increase in the amount of fresh water and allochthonous materials annually delivered to the Arctic shelves, and further to the Arctic Basin. All these processes could impact the Arctic marine ecosystems and their productivity, as well as the key biogeochemical cycles in the region. One of the most important potential changes in the marine Arctic ecosystems is related to the progressive increase in the anthropogenic impacts of oil and natural gas drilling and transportation over the shelf areas, via the long-term backwash effect (Lappalainen et al., 2015).

Introduction to PEEX Tools

In order to understand the changing Arctic environments and societies and the feedbacks between the Arctic and boreal regions and, at a larger scale, between the Arctic and the Earth's system, we need a novel conceptual framework of research methods, infrastructures and procedures. The so-called PEEX tools, Earth surface-atmosphere and marine observation networks, satellite observations, modelling platforms, socio-economic data pool, and educational tools serve this need.

Table 1. The main large scale research questions are introduced in the PEEX Science Plan; see also Kulmala et al., 2015.

LARGE-SCALE RESEARCH QUESTIONS
LAND SYSTEM
Q-1 How could the land regions and processes that are especially sensitive to climate change be identified, and what are the best methods to analyze their responses?
Key topic: shifting of vegetation zones, Arctic greening
Q-2 How fast will permafrost thaw proceed, and how will it affect ecosystem processes and ecosystem-atmosphere feedbacks, including hydrology and greenhouse gas fluxes?
Key topic: risk areas of permafrost thawing
Q-3 What are the structural ecosystem changes and tipping points in the future evolution of the Pan-Eurasian ecosystem?
Key topic: Ecosystem structural changes
ATMOSPHERIC SYSTEM
Q-4 What are the critical atmospheric physical and chemical processes with large-scale climate implications in a northern context?
Key topic: atmospheric composition and chemistry
Q-5 What are the key feedbacks between air quality and climate at northern high latitudes and in China?
Key topic: urban air quality, megacities and changing PBL
Q-6 How will atmospheric dynamics (synoptic scale weather, boundary layer) change in the Arctic-boreal regions?
Key topic: weather and atmospheric circulation
AQUATIC SYSTEMS – THE ARCTIC OCEAN
Q-7 How will the extent and thickness of the Arctic sea ice and terrestrial snow cover change?
Key topic: The Arctic Ocean in the climate system
Q-8 What is the joint effect of Arctic warming, ocean freshening, pollution load and acidification on the Arctic marine ecosystem, primary production and carbon cycle?
Key topic: The Arctic maritime environment
Q-9 What is the future role of Arctic-boreal lakes, wetlands and large river systems, including thermokarst lakes and running waters of all size, in biogeochemical cycles, and how will these changes affect societies (livelihoods, agriculture, forestry, industry)?
Key topic: lakes, wetlands and large river systems in the Siberian region
ANTHROPOGENIC ACTIVITIES
Q-10 How will human actions such as land-use changes, energy production, the use of natural resources, changes in energy efficiency and the use of renewable energy sources influence further environmental changes in the region?
Key topic: Anthropogenic impact
Q-11 How do the changes in the physical, chemical and biological state of the different ecosystems, and the inland, water and coastal areas affect the economies and societies in the region, and vice versa?
Key topic: Environmental impact
Q-12 In which ways are populated areas vulnerable to climate change? How can their vulnerability be reduced and their adaptive capacities improved? What responses can be identified to mitigate and adapt to climate change?
Key topic: Natural hazards
FEEDBACKS – INTERACTIONS
Q-13 How will the changing cryospheric conditions and the consequent changes in ecosystems feed back to the Arctic climate system and weather, including the risk of natural hazards?
Q-14 What are the net effects of various feedback mechanisms on (i) land cover changes, (ii) photosynthetic activity, (iii) GHG exchange and BVOC emissions (iv) aerosol and cloud formation and radiative forcing ? How do these vary with climate change on regional and global scales?
Q-15 How are intensive urbanization processes changing the local and regional climate and environment?
Key topics: Atmospheric composition, biogeochemical cycles: water, C, N, P, S

Earth surface-atmosphere observation network

Continental observations

To ensure a successful research approach, PEEX will establish its own long-term, coherent and coordinated research infrastructure activities, such as an *in situ* observation network of ecosystem–atmosphere interactions (Lappalainen et al., 2014; Alekseychik et al., 2016; Kulmala et al., 2016). The concept of the hierarchical PEEX *in situ* station network is based on the know-how of the 20-year development of the SMEAR-II flagship station measurement theory and techniques (Hari et al., 2016). The backbone of the station network is built on the existing land surface (biosphere/ecological or urban) and atmospheric observation networks in collaboration with European, Russian, Chinese and global partners (Figure 2).

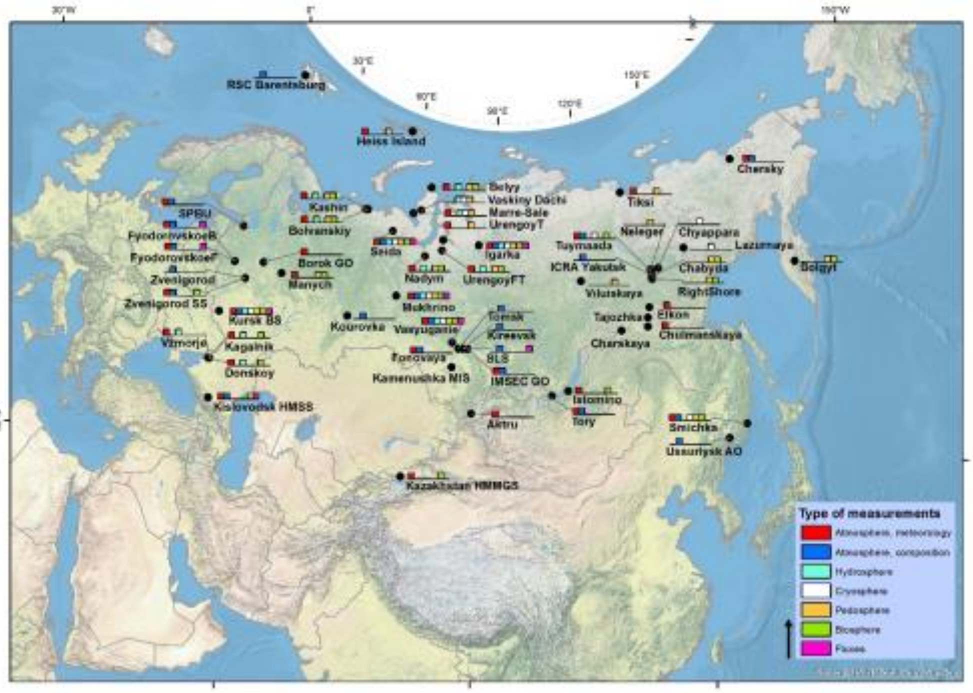

Figure 2. Starting from 2016, the PEEX program has gathered metadata information from the Russian stations conducting ecosystem, atmospheric composition and/or meteorological measurements. The metadata poll is based on the SMEAR concept. By June 2017, we have metadata information (information on the measured variables, descriptions of the field station and the measurement site) from 54 stations (figure by Nuria Altimir and Alla Borisova, University of Helsinki 2017). We plan to release a station metadata e-catalogue in 2018.

Establishment of new SMEAR stations are envisioned. The first ideas of the Global SMEAR network were introduced in the Paris COP side-meeting. PEEX will also contribute to the WMO Global Atmosphere Watch (GAW) observation program and the Integrated Global Greenhouse Gas Information System (IG3IS). WMO GAW provides the standards for atmospheric measurements, while IG3IS will establish, propagate and, over time, improve the methodological standards for how the atmospheric transport inverse model analyses of atmospheric GHG concentration measurements ("top-down") can be combined with spatially and temporally explicit socioeconomic emission inventory data ("bottom-up") to better inform and manage emission reduction policies and measures.

Marine observations

The marine component of PEEX will address the Arctic Ocean and adjacent seas. Its basis will be a hierarchical concept of an *in situ* station network analogous to that in the Eurasian continent, but affected by the practical challenges in making long-term observations in and over the sea (Hari et al., 2016). Observations from the ocean, sea ice and atmosphere are needed to obtain a better understanding on the state and change of the marine Arctic climate system (Döscher et al., 2014). The processes to be studied include the sea ice thermodynamics and dynamics, ocean heat and freshwater budgets, ocean circulation, waves and tides, ocean chemistry and ecosystems, atmospheric heat and moisture budgets, synoptic-scale cyclones and polar lows, troposphere-stratosphere coupling, atmospheric boundary-layer processes, as well as aerosols and clouds (Vihma et al., 2014). Some of the *in situ* observations will be made during research cruises, manned ice stations and research aircraft campaigns, while the majority of the data will be collected by applying long-lasting installations. These include drifting buoys on sea ice and ocean surface, gliders in the ocean, moored thermistor chains and current meters, ice-tethered platforms and coastal stations. The *in situ* observations will be supported by satellite and ship/ice-based remote sensing observations.

A particularly interesting aspect is the interaction of the marine, atmospheric and terrestrial components of PEEX. Among the major interactive processes are the effects of river discharge on the ocean and sea ice, coastal erosion, subsea permafrost in the Siberian continental shelf, transports of heat, freshwater, aerosols and air pollutants from lower latitudes to the central Arctic, as well as the effects of Arctic amplification of climate warming on Eurasian weather and climate.

The concept of the SMEAR stations, i.e., integrated measurements at a fixed position, can be established in the coastal island of the Arctic Ocean, whereas a central Arctic observatory could only be based on a ship or other floating platform anchored and drifting within the pack ice. In addition to the legendary Russian ice stations (Romanov et al, 1997), only three ship based campaigns, SHEBA (Perovich et al., 1999), Tara (Gascard et al., 2008) and N-ICE2015 (Granskog et al., 2016), have been successfully completed during the last 20 years.

The next major international Arctic Ocean research effort will be the MOSAiC study (Multidisciplinary drifting Observatory for the Study of Arctic Climate experiment, http://www.mosaicobservatory.org/), where the R/V Polarstern will be anchored on pack ice for one year beginning in Autumn of 2019. The expected drifting route follows the Transpolar Drift which will carry the ship from the Laptev Sea to Fram Strait via the North Pole region. The MOSAiC observatory will include ship-based measurement of the atmosphere, ice and ocean physical-chemical and biological properties as completely as possible in terms of absolute values of different variables and their vertical distribution. The ship-based observatory will be complemented with a network of automatic ice-tethered buoys and profilers, underwater drifters, unmanned aerial systems, aircrafts, additional ships and satellites.

Satellite observations

The PEEX Program research infrastructure pillar underlines that the satellite observations need to be connected with the ground-based observations of the PEEX network. Satellite observations (European Space Agency, NASA) provide daily observations over the whole Northern Eurasian region, complementary to ground-based observations and thus filling the gaps between *in situ* stations. At the northern high latitudes, polar orbiting satellites provide a good coverage with several overpasses over the same area each day, depending on the sensors' swath width, and a spatial resolution of typically 1-10 km. However, serious disadvantages are the long polar night and presence of clouds, which hamper observations at the wavelengths of the solar spectrum often used for measuring the atmospheric composition, land surface reflectance and temperature, and vegetation. Another problem may be the high reflectance of surfaces covered with snow and ice, which makes it difficult to separate the surface reflectance from that of the atmospheric components, including clouds (Kokhanovsky & de Leeuw, 2009; Istomina et al., 2010; Sogacheva et al., 2017). Yet, successful approaches to retrieving aerosols and clouds over snow and ice have been published. As an alternative, one can use instruments having wavelengths in the thermal infrared (TIR) like the Infrared Atmospheric Sounding Interferometer (IASI) that provides important information on trace gases and GHG, active instruments (lidars) like the Cloud-*Aerosol* Lidar with Orthogonal Polarization CALIOP that provides information on the vertical distribution of aerosols and clouds, or radars (Hilton et al., 2012; Winker et al., 2009).

The UV/VIS (*Visible* and *Ultraviolet* Spectroscopy) instruments are most useful at high latitudes over darker surfaces between early Spring and late Autumn when sufficient light is available. In these conditions, satellite information is available on aerosol properties, GHGs and trace gases such as O_3, NO_2, SO_2 and VOCs, as well as on cloud properties, surface reflectance, surface temperature and vegetation. Taken together, these measurements provide important information on Earth surface-atmosphere interactions, such as how aerosols and their precursor concentrations contribute to various feedbacks in a changing climate. Forest fires occur frequently during the Summer. Satellites can be used to investigate influences of forest fires on the biosphere, atmosphere and climate, as satellite observations provide information on aerosol and trace gas emissions, dark burnt area after a fire and subsequent recovery of vegetation. Furthermore, effects of megacities on surface reflectance, atmospheric composition and spatial extent of the pollutants emitted by large cities or even power plants can be detected, and the emissions strengths can be evaluated by combining satellite data with inverse modeling (e.g., van der A et al., 2017).

Satellites are frequently used to provide information on land-water boundaries and water surface properties, such as the water temperature, wave properties, surface reflectance, effects of whitecaps, ocean colour, presence of algae, presence of sea ice and snow melt. This is particularly important considering the logistical problems associated with ground-based observations at high latitudes and in the harsh Arctic climate as described in the section on marine observations.

In general, different aerosol parameters are the key parameters relevant to global climate by effecting the radiation balance and cloud formation processes (Kulmala et al., 2014, Paasonen et al., 2013). To illustrate the use of satellite observations over the PEEX area, the full mission ATSR-retrieved seasonal aerosol optical depth (AOD) time series (17 years, 1995-2012) is shown in Figure 3 "AOD" for Eastern China, with high AOD increasing over the years, and for western Russia, with much lower AOD, close to or lower than the global average AOD over land which is shown as a reference. Each of these time series shows the common Summer maxima and Winter minima, further modified by year-to-year changes in meteorological conditions and emissions like the occurrence of forest fires in Russia in 2010.

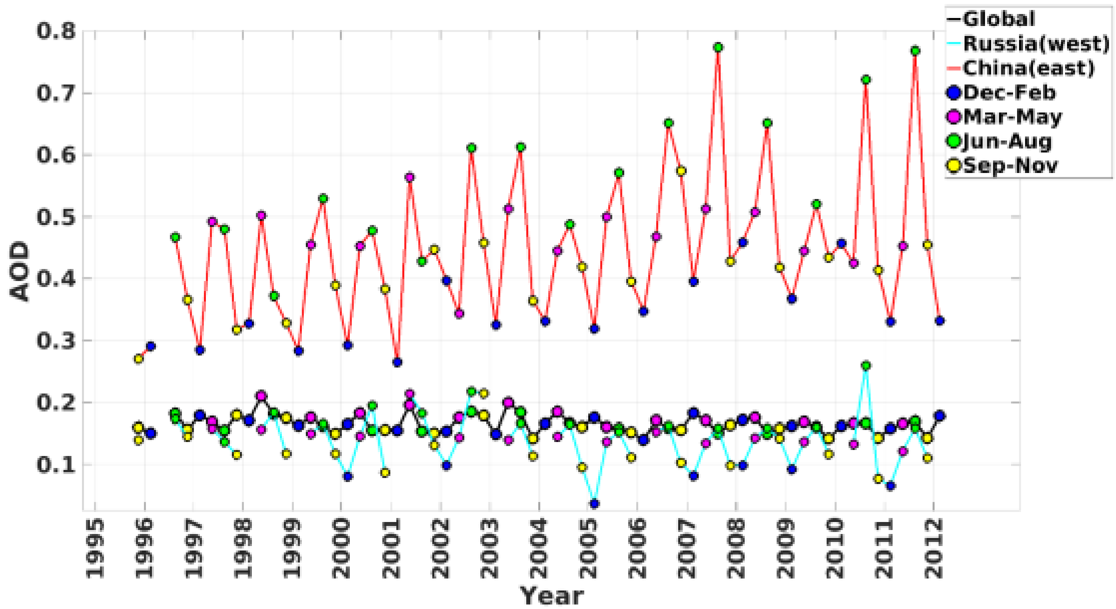

Figure 3. Aerosol optical depth (AOD) seasonal variation of the AOD over land for the years 1995-2012 over eastern China (red line), western Russia (blue line), and global (black line). Seasons are indicated with different colors in the legend (Figure by Larisa Sogacheva, Finnish Meteorological Institute 2017).

Modelling Platform

Different aspects of integrated model development, evaluation and understanding will be considered within the PEEX Modelling Platform (PEEX-MP). Several new integrated modelling developments are expected: i) improved numerical weather prediction (NWP) and chemical weather forecasting (CWF) with short-term feedbacks of aerosols and chemistry on meteorological variables, two-way interactions between atmospheric pollution or composition and climate variability or change, ii) better prediction of atmosphere and/or ocean state through a closer coupling between the component models to represent the two-way feedbacks and exchange of the atmospheric and ocean boundary layer properties, and iii) more complete, or detailed, simulation of the hydrological cycle through linking atmospheric, land surface, ecosystems, hydrological and ocean circulation models (Baklanov et al., 2017; Baklanov et al., manuscript under preparation).

The PEEX-MP focuses on a new generation of multi-scale integrated models and is based on the seamless Earth System Modelling (ESM) approach (WWRP, 2015) to evolve from individual to seamless meteorology-composition-environment models to address limitations in weather, climate and atmospheric composition fields whose interests, applications and challenges are now overlapping.

In a general sense, the seamless approach considers several dimensions of the online coupling, including: i) time scales (from real-time and short-term till decades and climate time-scale), ii) spatial scales (from street level to global scale with downscaling and upscaling methods), iii) processes: physical, chemical, biological, and social; iv) Earth system elements, environments or components: atmosphere, hydrosphere, lithosphere or pedosphere, ecosystems or biosphere; v) different types of observations and modelling as research tools: data processing and data assimilation, validation and verification of modelling results; and vi) linking with studies on health and social consequences, impact, assessment, as well as services and end-users. In addition, the methodology and research needs for realization of the Seamless Prediction Systems are presented and discussed in "Seamless Prediction of the Earth System: From Minutes to Months" (WWRP, 2015).

At the current phase of the PEEX Science Plan implementation, the seamless modelling approach is considered in relation to, at least, two aspects (Baklanov et al., manuscript under preparation). Firstly, at the process-scale where it refers to the coupling within a model of meteorology and composition processes in order to represent, for example, the two-way interactions between composition and radiative processes or microphysics, or the consistent treatment of water vapor. Secondly, in terms of temporal-spatial scales, it refers to the absence of discontinuities in model behavior when used at multiple temporal or spatial resolutions to have, for example, a consistent treatment of black carbon for air quality and climate applications or consistent coupling interval between land, ocean and atmosphere.

The PEEX-MP is characterized by a complex integrated Earth System Model (ESM) approach, in combination with specific models of different processes and elements of the system, acting on different temporal and spatial scales. The ensemble approach is the best when integrating modeling results from different models, participants and countries. PEEX will utilize the full potential of a hierarchy of available models: scenario analysis, inverse modeling and modeling based on measurement needs and processes. The models will be constantly validated and constrained by available *in situ* ground-based and remote sensing data of various spatial and temporal scales by using data assimilation and top-down modeling. The analyses of the anticipated large volumes of observational data and modelling results will be supported by a dedicated Virtual Research Platforms (VRP) with environments developed for these purposes (Baklanov et al., manuscript under preparation).

PEEX dataflow from observational and modelling platforms will be made easily accessible through Virtual Research Platforms (VRP) which allows for the visualization and first-hand analysis of various PEEX data and time series. Such VRP platform is specifically designed for holistic multidisciplinary understanding of large volume interconnected datasets. The first version of PEEX VRP, PEEXView, should be able to combine multidisciplinary datasets of varying temporal and spatial scales (Hari et al., 2009; Hari & Kulmala, 2005). This tool should not be limited only to natural science data, so even socio-economic indicators, such as industrial production index (IPI), can be used in analyzing changes in e.g. atmospheric properties. Currently, PEEXView holds 2D datasets (satellite products, regional and global simulations), time series (e.g. stations' observations), point-data (e.g., wildfire occurrence) and air mass trajectories. All datasets will be complemented with relevant metadata. The PEEXView has been designed to establish fluent comparison and evaluation of simulation and observational data.

Socio-economic data pools and socio-economic modeling

It is important to explore interactions between environmental change and societal transformations of natural resource utilization in northern Eurasia in order to assess the complexity of their socio-ecological consequences at global, regional and local levels (Figure 4). Socio-economic data needed for serving the research aims of the PEEX land – atmosphere – ocean – society nexus are related primarily to the following social sectors or realms: natural resources, industrial complexes, social security, public health and the political system, especially natural resource and environmental governance. The challenge in deriving relevant, reliable and valid data from these sectors in northern and eastern Eurasia, in Russia and China, is as acute as in any authoritarian political context. There are a lot of primary data on the two first mentioned realms of society in the form of official statistics that depict nation-wide phenomena (e.g., overall GHG emissions) and demographic indicators (e.g., morbidity). However, concerning, for example, emission volumes from extractive industries or epidemiological information on environment-related health issues, the relevance and reliability of such data are unfortunately low. For example, the state that runs the major energy companies in Russia has not been able to provide comprehensive and reliable data on specific emissions, such as oil spills or flaring of associated petroleum gas (e.g., Shvarts et al., 2016; Vasileva et al., 2015), which are both key indicators affecting northern ecosystems and public health.

There are, however, solutions to overcome the observational data and modelling challenges posed by individual countries' and governments' restrictions and regulations, especially in the authoritarian contexts of Russia and China. In Russia, the economy and thus the whole political system has grown dependent on fossil fuels, and environmental governance restricting the (short term) economic possibilities of the natural resource sector are not easy to promote. In China, the environmental externalities of rapid economic growth and increased industrial production are visible signs of a system level failure to address these problems. Thus, the other side of the coin, the environmental consequences of core economic activities of Russia and China are easily 'green washed' and kept secret by the regimes in power in order to tampen popular moods critical of this environmental change (e.g., Tynkkynen & Tynkkynen, forthcoming 2018). However environmental studies, combining the latest knowledge on natural and social sciences, can provide solutions also for authoritarian governments on how to increase resilience in these societies on a longer perspective by addressing the socio-ecological problems, and not to hide them. This is the goal of the PEEX initiative, as well.

On the level of methods (and methodologies) there are wide possibilities to provide the information needed for sound socio-ecological policies and governance. In the era of the Internet, and the possibility to utilize spatial (geographical) information accessible via a large spectrum of satellite-derived data, the success of trying to hide the environmental consequences of economic activities is doomed to failure. Therefore, what the PEEX aims at is to explore the possibilities of above mentioned data sets, and concerning air emissions and human health data, for example, the possibilities offered by so-called 'big data' should be explored thoroughly. Information can be extracted e.g. via meta-analyses on available satellite data aiming at triangulating reliable levels of industrial and other emissions, or via web-based data that can tell more about environmental health issues on the regional and local levels than traditional statistics provided by the states and regional governments. Finally, the research available on political systems and different regimes in the Eurasian domain can already provide reliable background knowledge on possible pathways, stemming from regimes' previous reactions to global political, social and environmental issues, against which different environmental, emissions and population data can be compared to.

Figure 4. Krasnojarsk hydroelectric power plant (55°56'05"N 92°17'37"E) affects the local climate and the river never freezes for 200-300 kilometers downstream of the dam, see also https://web.archive.org/web/20110723191324/, http://www.ilec.or.jp/database/asi/asi-56.html (Photo by Veli-Pekka Tynkkynen, 2000).

Education of the next generation of experts

The PEEX educational program is based on life-long learning at multiple levels. There are two key objectives for researcher training and research career promotion within PEEX. First, PEEX educates the next generation of scientists by providing training in technical skills and scientific issues together with an understanding of societal dimensions related to the 'Grand Challenges' such as climate change, air pollution, deforestation, and ocean acidification. Second, PEEX contributes to the needs of society by educating scientists at masters and doctoral levels with a deep core understanding and multidisciplinary orientation, having also transferable skills to be readily applicable to the working environments outside of academia. Furthermore, PEEX is interested in establishing relationships with key European players in the fields of research, research infrastructures, service providers and research policy, and to provide transversal training addressing all aspects of environmental observations. This training ranges from data provision to data application in numerical models. For example, training related to measurements will range from instrument development to observation network building. Similarly, training related to modeling will cover everything from the application of simple one-dimensional numerical models to the development of holistic ESM (Earth System Models). Furthermore, training in social sciences will range from understanding modeling based approaches to decision-making to policy analysis. PEEX training will also apply the idea of horizontal learning (Lauri et al., 2016). In such a learning approach, teachers take the role of facilitators rather than lecturers. This strategy is carried out throughout the courses, and it is based on twenty years of international collaboration and analysis of learning outcomes. This allows for the social construction, sharing of information and cognition, and finally improves the metacognitive skills of the students which, in turn, enhance self-directed learning skills (PEEX Science Plan).

Discussion and Summary

Since 2012, the PEEX science community has delivered a comprehensive science plan, determined the program's science questions and made a conceptual design of the tools needed for implementing the research agenda. During the upcoming years, the mission focus will be on setting up the observational system together with the seamless modelling platform. The implementation of the research agenda will take place by separately funded projects. The core projects here are the Finnish Center of Excellence in Atmospheric Science – From Molecular and Biological processes to The Global Climate (FCoE-ATM) (ongoing); the European Research Council's Advanced Grant project on "Atmospheric Gas-to-Particle Conversion" (2017-2021); and the M. Kulmala's Academy professorship project "Air quality – climate interactions and feedbacks" (2017-2021). The main interest is on understanding the land – atmosphere feedback loops, but also on a deeper understanding of the role of the Arctic Ocean in this context. The PEEX research community consists currently of several disciplines of natural sciences. However, the PEEX mission is to be the next-generation program built on both natural sciences and socio-economics having a strong cross-disciplinary dimension. PEEX continues deepening the collaboration with the European, Russian, Chinese and global partners to maximize the impact of the PEEX research highlights, scientific assessment and research infrastructure development relevant to the climate policy processes. The key stakeholders in this are the Future Earth, Arctic Council (SAON); World Meteorological Organization (WMO); the intergovernmental Group on Earth Observations – Global Earth Observation System of Systems (GEO-GEOSS); Digital Belt and Road Initiative (DBAR); and International Institute for Applied Systems Analysis – The Arctic Futures Initiative (IIASA AFI).

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