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Introduction: The Pan-Eurasian Experiment (PEEX) – multidisciplinary, multiscale and multicomponent research and capacity-building initiative

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Abstract. The Pan-Eurasian Experiment (PEEX) is a multidisciplinary, multiscale and multicomponent research, research infrastructure and capacity-building program. PEEX has originated from a bottom-up approach by the science communities and is aiming at resolving the major uncertainties in Earth system science and global sustainability issues concerning the Arctic and boreal pan-Eurasian regions, as well as China. The vision of PEEX is to solve interlinked, global grand challenges influencing human well-being and societies in northern Eurasia and China. Such challenges include climate change; air quality; biodiversity loss; urbanization; chemicalization; food and freshwater availability; energy production; and use of natural resources by mining, industry, energy production and transport sectors. Our approach is integrative and supra-disciplinary, recognizing the important role of the Arctic and boreal ecosystems in the Earth system. The PEEX vision includes establishing and maintaining long-term, coherent and coordinated research activities as well as continuous, comprehensive research and educational infrastructure and related capacity-building across the PEEX domain. In this paper we present the PEEX structure and summarize its motivation, objectives and future outlook.

1 Introduction and background

The Earth system is facing several global-scale environmental challenges, called “grand challenges”, such as climate change, air quality, migration of peoples and other changes in human population, ocean acidification, freshwater and food supplies. Grand challenges are the main factors affecting human well-being, security and stability of future societies. All the grand challenges are interlinked via complex feedbacks in the Earth system (Fig. 1). The dynamics of grand challenges are driven by "global forces", identified as demographics, increasing demand for natural resources, globalization and climate change (e.g., Smith, 2010). The global forces are strongly geographically oriented and variable phenomena, depending on migration trends of human populations, variations in the availability of natural resources, capital flows within the economy, and the diverse impacts of global and regional climate change.

Coping with climate change and transformations of civilizations and ecosystems on a global scale is one of the ultimate challenges of the 21st century. Since grand challenges are highly coupled and interlinked, they cannot be solved separately. Therefore, a framework is needed where a multidisciplinary scientific approach has the required critical mass and is strongly connected to fast-track policy making. The potential solutions are typically tightly coupled with each other.

The northern Pan Eurasian regions, specifically the Arctic–boreal regions including the Arctic Ocean, are located at latitudes higher than 45° N (Fig. 2). These areas are expected to undergo substantial changes during the next decades (IPCC, 2014). The Arctic region, for example, is warming faster than any other region of the world (Smith et al., 2015), and this warming may reach levels as high as 8.3 ± 1.9 °C by the end of this century (IPCC, 2013). The importance of northern regions on a global scale is foreseen to increase in terms of all the four global forces: not only climate change but also globalization, demographics and the use of natural resources (Smith, 2010). Furthermore, it is worth recognizing the important role of China in setting global trends and in affecting the development of northern environments and societies.

The specific characteristics of pan-Eurasian Arctic–boreal natural environments are linked to the global climate. Thawing of permafrost and northward migration of the taiga zone will have significant consequences for the climate system, as these phenomena influence the sources and sinks of greenhouse gases (GHGs) and biogenic volatile organic compounds (BVOCs). The forests and peatlands in Siberia and elsewhere at high northern latitudes sequester large amounts of GHG compared to the net global emissions (Bondur, 2011, 2014, 2015; Frolking et al., 2011; Pan et al., 2011; Graven et al., 2013). BVOCs emitted by boreal forests contribute to atmospheric aerosol and cloud condensation nuclei formation processes, and therefore to both aerosol–radiation and aerosol–cloud interactions (Spracklen et al., 2008; Kulmala et al., 2013; Paasonen et al., 2013; Scott et al., 2014). The magnitude of BVOC emissions is linked to the total area of boreal forests, and to structural changes in the forest ecosystems (Laothawornkitkul et al., 2009). Due to the critical role of Siberian forests in global GHG and aerosol budgets, there is a specific need for comprehensive and continuous atmosphere–ecosystem data from the northern Eurasian region (Kulmala et al., 2011b; Quinn et al., 2014).

In addition to changing GHG exchange and BVOC emissions, major structural ecosystem changes are also predicted to take place in the pan-Eurasian Arctic and boreal natural environments. These include the appearance of invasive species and the extinction of existing ones, changes in ecosystem productivity and structure, and modifications in the ecosystems' roles as sinks or sources of climatically relevant gases (Epstein et al., 2013; Pearson et al., 2013; Buermann et al., 2014; Reich et al., 2015). The latter concerns vast areas of boreal forests and peatlands. The ecosystem changes may have unpredictable consequences on, e.g., food webs, and on interactions between different ecosystems and human activities.

The other geographical area dominating the acceleration of climate change is the Arctic Ocean and its maritime environments. One major consequence of the warming of northern latitudes is related to changes in the cryosphere, including the thawing of permafrost and the Arctic Ocean becoming ice free part of the year (Tarnocai et al., 2009; Hayes et al., 2014; Schaefer et al., 2014; Döscher et al., 2014). This will boost global trade activities in the Arctic if the northern sea route is opened for shipping between the Atlantic and Asia's far east. The Arctic Ocean is currently covered by ice for most of the year (from October to June), preventing ship traffic. However, the amount of sea ice is declining rapidly. The predicted shortening of the ice cover period draws attention to exploitable natural resources (oil, natural gas and minerals) in the region. It has been predicted that the role of natural resources originated from the Arctic Ocean in the global energy market will become significant, as the region may hold 25 % or more of the world's undiscovered oil and gas resources (Yenikeyeff and Krysiek, 2007). Future thawing of permafrost threatens the durability of infrastructure (power networks, buildings, ice roads, oil drilling) and may have large influences on the living conditions and culture of indigenous people living in the north.

A strong involvement and international collaboration between European, Russian and Chinese partners are needed to answer the grand challenges in the northern context: how will northern societies cope with environmental changes? A new large-scale initiative called the Pan-Eurasian Experiment (PEEX), started in 2012, is contributing to solving the grand challenges in the northern pan-Eurasian and Chinese context (Lappalainen et al., 2014). PEEX is a bottom-up initiative by European, Russian and Chinese partners, and it is open to a broader collaboration in the future. Presently over 110 institutes from over 20 different countries are contributing to PEEX. The promoter institutes of this program have been the University of Helsinki and the Finnish Meteorological Institute in Finland; Moscow State University, the AEROCOSMOS Research Institute for Aerospace Monitoring

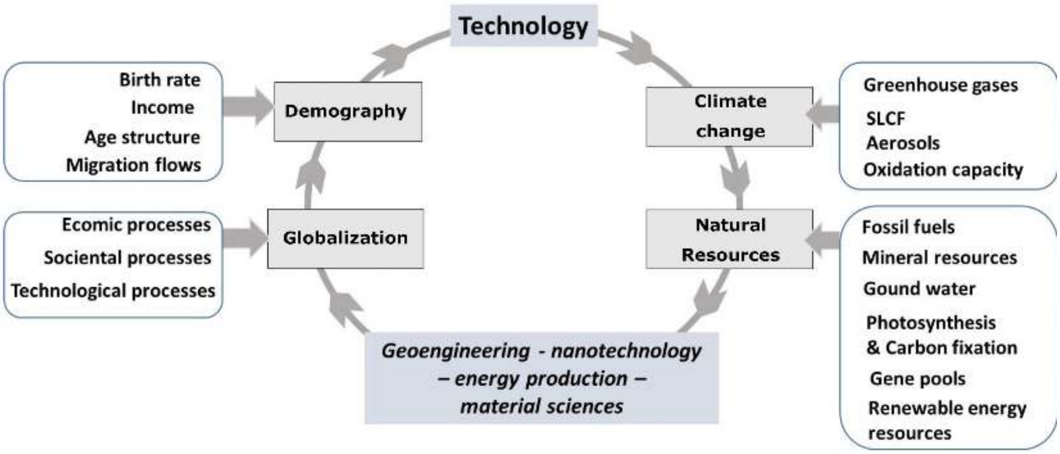

Figure 1. The interlinked global forces (climate change, natural resources, globalization, demography) (Smith, 2010) modifying the northern regions' future within the next 40 years. The technological development provides the framework for the future development trends.

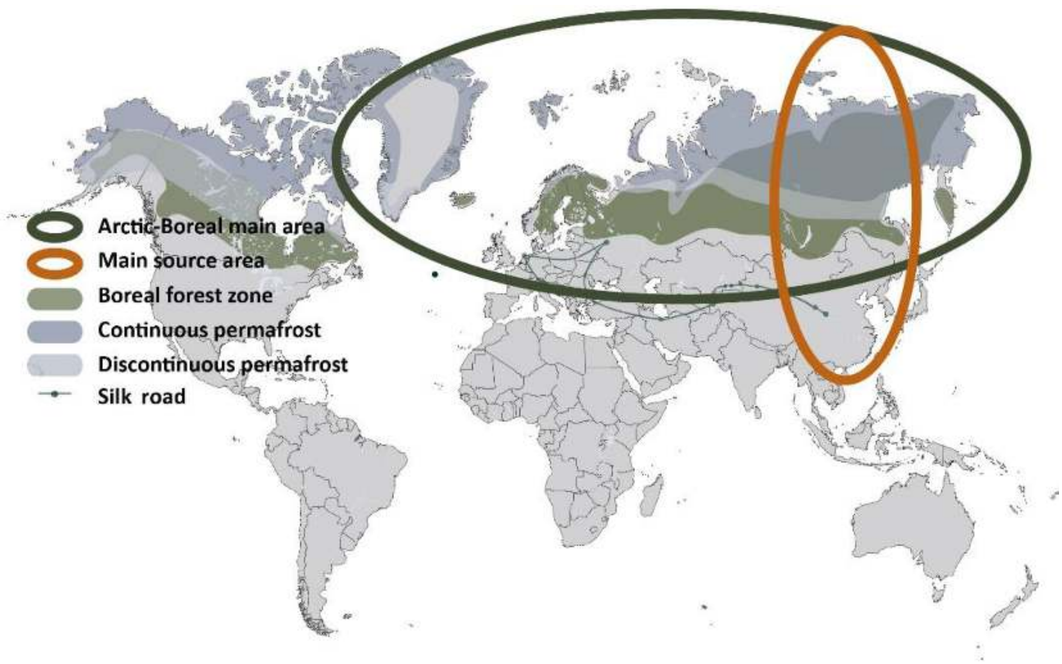

Figure 2. The northern pan-Eurasian geographical region encompasses both permafrost and boreal zones.

(Moscow), the Department of Geography of Moscow State University and the Institute of Atmospheric Optics of the Siberian branch of the Russian Academy of Sciences (RAS) in Russia; and 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, with the endorsement of the International Geosphere-Biosphere Program core project Integrated Land Ecosystem Atmosphere Process Study. Today, the PEEX community includes scientists from various disciplines as well as representatives of international organizations and programs (e.g., WMO GAW, IIASA, IGBP/Future Earth), and stakeholders from industry, transport, renewable natural resources management, agricultural production and trade. The PEEX community will aim at co-designing research in the region in the spirit of the Future Earth initiative as well as the Climate and Clean Air Coalition.

2 Vision, mission and objectives

The vision of PEEX is to solve interlinked, global grand challenges influencing human well-being and societies in northern Eurasia and China in an integrative way, recognizing the significant role of boreal and Arctic regions in the context of global change. The PEEX vision includes the establishment and maintenance of long-term, coherent and coordinated research and education activities and continuous, comprehensive research infrastructure in the PEEX domain. PEEX aims to contribute to the Earth system science agenda and climate policy in topics important to the pan-Eurasian environment, and to provide adaptation and mitigation strategies for the northern pan-Eurasian and Chinese societies related to grand challenges, in particular climate change and air quality.

The mission of PEEX is to be a next-generation natural-science and socioeconomic research initiative using excellent multidisciplinary science with clear impacts on future environmental, socioeconomic and demographic development of the Arctic and boreal regions as well as China. The PEEX initiative consists of four main focus areas (F-1–4) described in detail in Sect. 3. Each focus area has its own specific objectives listed below.

- F-1: PEEX research agenda:
  - to understand the Earth system and the influence of environmental, societal and economic changes, interactions and feedbacks in pristine and industrialized pan-Eurasian environments (systems understanding: land, atmosphere, aquatic, anthropogenic/society);
  - to determine processes in a multidimensional and multidisciplinary way relevant to climate change, demographic development and the use of energy and mineral resources in the Arctic–boreal regions (understanding of processes).
- F-2: PEEX infrastructure:
  - to establish and sustain long-term, continuous and comprehensive ground-based, airborne and seaborne observation infrastructure together with satellite data (observation component);
  - to develop the new data sets and archives with continuous, comprehensive data flows in a joint manner (data component);
  - to implement the validated and harmonized data products in models of appropriate spatial and temporal scales and topical focus (modeling component).
- F-3: PEEX impact on society:
  - to use new research knowledge together with the research infrastructure services for producing
    - as reliable scenarios and assessments as possible, to support practical solutions for addressing the grand challenges in the northern context and in China (climate change, natural resources, human health);
    - early-warning systems for the sustainable development of societies (demography development).
  - to promote technological innovations needed for coherent global environmental, technological, economical or social processes in an interconnected world (globalization).
- F-4: PEEX knowledge transfer and capacity building:
  - to educate the next generation of multidisciplinary experts and scientists capable of finding tools for solving grand challenges (young scientist multidisciplinary advancement);
  - to increase public awareness of climate change impacts in the pan-Eurasian region (public outreach);
  - to distribute the new knowledge and data products to scientific communities (enhance multidisciplinary research);
  - to deliver tools, scenarios and assessments for climate policy makers and authorities (policy support).

3 PEEX structure and interlinks

The research agenda (F-1) defines the large-scale key topics and research questions of the land–atmosphere–aquatic–anthropogenic systems in an Arctic–boreal context as well as megacity–climate interactions and air quality issues, including socioeconomic research aspects. The research infrastructure (F-2) introduces the current state-of-the-art observation systems in the pan-Eurasian regions and presents the future base for the coherent and coordinated research infrastructure in the PEEX domain. The impact on society (F-3) addresses key aspects related to mitigation and adaptation strategies supporting development of useful and effective policy strategies. It also involves planning for preparing northern societies to cope with environmental changes, developing reliable early-warning systems, and addressing the role of new technology in the implementation of these strategies and plans. Knowledge transfer and capacity building (F-4) are focused on improving education programs at multiple levels, strengthening future research communities, and raising awareness of global changes and environmental issues. The summary of PEEX structure is presented in Fig. 3.

3.1 Research agenda (F-1)

The PEEX research agenda is designed as a research chain (Kulmala et al., 2011a), which aims to advance our understanding of the interactions in the Earth system (encompassing not only the atmosphere and the land and ocean ecosystems, but also human activities and societies) through a series of connected activities. These research activities start at the molecular scale, to understand key atmospheric processes, and extend to regional and global scales, to understand the complex processes in, e.g., the climate system and its interaction with society. Our focus is to understand the complex land–atmosphere–ocean–society system in an Arctic, northern pan-Eurasian and Chinese context.

A very important aspect is that the research agenda cover a large area, with studies covering diverse spatial and temporal scales, and it encompass diverse geographical regions, including both natural and urban environments. The major large-scale systems studied by PEEX are the land, atmosphere and aquatic systems, along with anthropogenic activities (Fig. 3). The PEEX research agenda also addresses various feedbacks and interactions between these systems, as well as the major biogeochemical cycles (water, carbon, nitrogen, phosphorus, sulfur). The key topics and related large-scale research questions associated with these components are summarized in Table 1. These questions have been identified during the PEEX meetings with a preliminary list of questions presented earlier by Lappalainen et al. (2014). The present version introduced in Table 1 was accepted at the PEEX meeting in February 2015.

Human decision making concerning, for example, land use and fossil-fuel burning are represented by agent-based models, integrated assessment models and climate scenarios, which will be utilized and further developed for the northern pan-Eurasian region. In urban and industrialized regions, the process understanding of biogeochemical cycles includes anthropogenic sources, such as industry and fertilizers, as essential parts of the biogeochemical cycles. PEEX climate studies, especially estimates of the type and frequency of natural hazards in the future, will be used to improve climate prediction capacities in Europe, Russia and China. Furthermore, PEEX socioeconomic research covers the superposition of natural and socioeconomic factors, dependence of the consequences of climate change on socioeconomic condition and its dynamics, identification of opportunities and methods of mitigation and adaptation to climate and socioeconomic changes, as well as the spatial differentiation of responses of the societies to environmental, demographical and socioeconomic challenges on national, regional and local levels (regional and local, urban and rural cases).

Feedbacks are essential components of our climate system as they either increase or decrease the changes in climate-related parameters in the presence of external forcings (IPCC, 2013). The PEEX domain covers a wide range of interactions and feedback processes involving human activities, natural systems and biogeochemical cycles (Heimann and Reichstein, 2008; Arneth et al., 2010), with humans acting both as the source of climate or environmental changes and the recipients of the impacts. One of the first feedback mechanisms to be quantified is that connecting the atmospheric carbon dioxide concentration, ambient temperature, gross primary production, secondary biogenic aerosol formation, clouds and radiative transfer with each other (Kulmala et al., 2014). Covering the PEEX area with several comprehensive stations enables us to understand feedbacks and interlinks in quantitative ways (Ding et al., 2013a, b). Although these feedback mechanism and several processes have been investigated in several flagship stations like at SMEAR II in Hyytiälä, Finland, there is a need to establish a flagship station network and also improve other tools to be able to meet research challenges in the PEEX domain.

Measurements of the changes in the hydrological and biogeochemical cycles on different temporal scales are needed to construct and improve the next generation of Earth system models. Such measurements should include, for example, the following quantities: concentrations and fluxes of aerosol particles, greenhouse gases and reactive trace gases, cloud microphysical and rain-forming properties, ecosystem functioning, and land use change. Earth system models are the best tools available for analyzing the effect of different environmental changes on future climate, and for studying the role of different processes in the Earth system as a whole. These types of analyses and predictions of future change are especially important in the high latitudes, where climate change is proceeding the fastest and where near-surface warming has been about twice the global average during recent decades.

3.2 Research infrastructure (F-2)

3.2.1 Coherent and coordinated observation program and data systems

Solutions to the interconnected global environmental problems can be provided only by a harmonized and holistic comprehensive observational approach utilizing all available modeling tools representing different spatial and temporal scales. However, all the tools, including models and observational/experimental devices, need to be developed further in order to answer the research questions and solve challenges. The PEEX approach uses methods ranging from nanometer and sub-second observations and process studies to global- and decadal-scale measurement activities, data sets and model simulations. The vision of the PEEX infrastructure is to provide comprehensive, continuous and reliable harmonized data products for forecasting services, and for the science community.

The PEEX research infrastructure aims to establish a long-term comprehensive field station network in the region covering Europe – particularly Scandinavia, Greenland and the Baltic countries – Russia and China. The conceptual philosophy of the network design relies on physical conservation laws of mass, energy and momentum, as well as on concentration gradients that act as driving forces for the atmosphere–biosphere exchange. The network will be composed of standard, flux/advanced and flagship stations, each having specific and identified tasks (Hari et al., 2015). Each ecosystem type has its own characteristic features that have

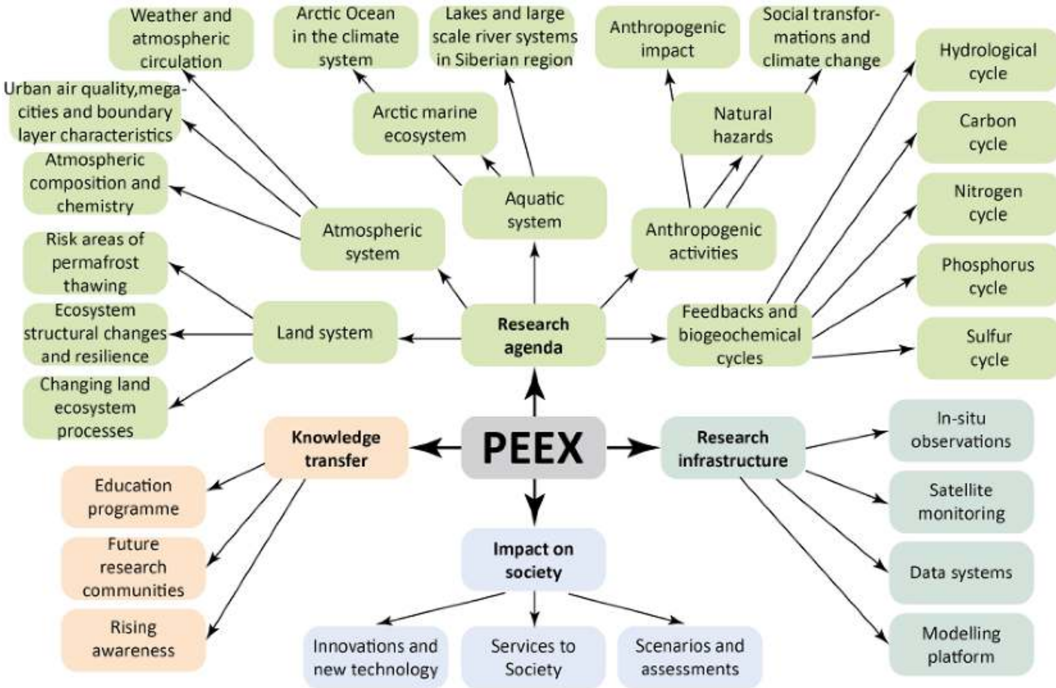

Figure 3. Schematic figure of the PEEX structure.

to be taken into consideration when planning the station network. The hierarchical network as a whole is able to tackle problems related to large spatial scales, heterogeneity of ecosystems and their complexity. The most comprehensive observations are to be conducted at the flagship stations. The process-level understanding can then be expanded to continental and global scales through the hierarchical station network, advanced data analysis, Earth system modeling and satellite remote sensing. The denser networks of flux and standard stations allow application and up-scaling of the results obtained from flagship stations to the global level. In the first phase, the land-based station network will be based on existing infrastructure consisting of standard stations such as weather stations, flux (FLUXNET) stations, flagship stations and satellite-receiving stations. The strategic focus is to ensure the long-term continuation of advanced (using, e.g., mass spectrometers, cloud radars and other state-of-the-art and next-generation methods, observing over 1000 different variables) measurements of aerosols, clouds, GHGs, trace gases and land surfaces and their interactions in the northern Eurasian area.

The cryosphere in the Arctic is changing rapidly (Döscher et al., 2014; Hayes et al., 2014; Vihma et al., 2014). Measurements of the current and past conditions of the cryosphere are made at deep boreholes, permafrost sites, and buoy/floating stations in the Arctic Ocean; on board ships; and through geophysical observations on board aircraft. The preliminary concept of a hierarchical network for aquatic observations in the surrounding seas would consist of simple buoys deployed on sea ice in the open sea, sophisticated buoys, research vessels, floating flagship stations, manned drifting ice stations, and permanent coastal and archipelago stations.

The PEEX flagship stations simultaneously measure meteorological and atmospheric parameters, together with ecosystem-relevant processes (including carbon, nutrient and water cycles; vegetation dynamics; and biotic and abiotic stresses). Ideally, the ground flagship station network will contain one flagship station in all major ecosystems, in practice a station for every 1000 to 2500 km (for details see Hari et al., 2015). The future PEEX research infrastructure will include aircraft and satellite observations, which provide complementary (to the local in situ observations) information on the spatial variability of atmospheric composition (aerosols, trace gases, greenhouse gases, clouds), and on land and ocean surface properties including vegetation and snow/ice. Vice versa, the PEEX infrastructure has an important role in the validation, integration and full exploitation of satellite data on the Earth system.

The PEEX program will produce an extensive amount of observational measurement data, publications, method descriptions and modeling results. The PEEX data product plan is built on the establishment of permanent PEEX-integrated platforms, documenting the variability of the various components of the ecosystem (atmosphere, terrestrial, marine), and utilizing state-of-the-art data management procedures including automatic data submission directly from the measurement sites, data processing, quality control, and conversion to formats used by the international user and storage

Table 1. List of PEEX – large-scale research questions.

Main component	Large-scale research questions	Key topic for research
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?	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?	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?	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?	Atmospheric composition and chemistry
	Q-5 What are the key feedbacks between air quality and climate at northern high latitudes and in China?	Urban air quality, megacities and changing PBL
	Q-6 How will atmospheric dynamics (synoptic scale weather, boundary layer) change in the Arctic–boreal regions?	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?	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?	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)?	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?	Anthropogenic impact
	Q-11 How do the changes in the physical, chemical and biological state of the different ecosystems as well as the inland, water and coastal areas affect the economies and societies in the region, and vice versa?	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?	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?	Atmospheric composition, biogeochemical cycles: water, C, N, P, S
	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?	

communities. The PEEX data will be harmonized with international measurement systems and data formats, in collaboration with existing global observation systems, such as the Global Atmosphere Watch program by the World Meteorological Organization (WMO-GAW, 2009), and with Arctic and boreal infrastructure projects, such as IASOA (International Arctic Systems for Observing the Atmosphere); INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic); the Russian System of Atmospheric Monitoring (RSAM), the Integrated Land Information System (ILIS); the US AERONET (AErosol RObotic NETwork), NDACC (Network for the Detection of Atmospheric Composition Change) and TCCON (Total Column Carbon Observing Network); and European research infrastructure such as ICOS (Integrated Carbon Observation System), ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network), SIOS (Svalbard Integrated Earth Observing System) and ANAEE (Infrastructure for Analysis and Experimentation on Ecosystems).

3.2.2 Modeling platform

The PEEX modeling platform is characterized by a multiscale approach starting from the molecular and cell levels and extending all the way to complex integrated Earth system modeling, in combination with specific models of different processes and elements of the system, acting on different temporal and spatial scales. We have preliminarily tested this kind of a multiscale approach in a framework of an integrated European research project (Kulmala et al., 2011a). PEEX takes an ensemble approach to the integration of modeling results from different models, participants and countries. PEEX utilizes the full potential of a hierarchy of models: inverse modeling, emission modeling based on economical and energy models, scenario analysis, process modeling based on measurement, regional and global chemical transport models and climate models, and Earth system models. The models will be validated and constrained by PEEX in situ and remote-sensing data of various spatial and temporal scales using data assimilation and top-down modeling. The analysis of the anticipated large volumes of data produced by PEEX models and sensors will be supported by a dedicated virtual research environment developed for this purpose.

There has been criticism that the processes, and hence parameterizations, in Earth system models are based on insufficient knowledge of the physical, chemical and biological mechanisms involved in the climate system, and that the spatial or temporal resolution of known processes is insufficient (e.g., Nobre et al., 2010; Baklanov et al., 2014). PEEX will tackle this issue by forwarding the necessary process understanding effectively to Earth system modeling frameworks. The PEEX modeling platform will also include integrated assessment models, agent-based models, economical and energy system models, and sociological and policy analysis.

3.3 Impact on society (F-3)

The PEEX research agenda supports the planning of the sustainable use of natural resources, climate change adaptation and mitigation strategies. PEEX provides scientific knowledge on natural and climatic processes, which are needed for assessing the extent of climate risks in the future. PEEX will accumulate scientific knowledge on how societies in Europe, Russia and China are able to adapt to and mitigate climate change, developing useful and realistic mitigation and adaption strategies. This will include economical and political analysis based on integrated modeling analysis using multidisciplinary PEEX data with open access.

The scientific results of PEEX intend to fill the current gaps in our knowledge of the processes, feedbacks and links within and between the major components of the Earth system in the Arctic–boreal context, including biogeochemical cycles and human activities. Reliable climate information and scenarios for the coming decades are crucial for supporting the adaptation of northern societies to the impacts of climate and cryospheric changes.

The PEEX research results are used for producing different types of scenarios on the impacts of climate change and air quality changes on human population, society, energy resources and capital flows. PEEX will provide information on mitigation and adaptation strategies for the changing Arctic environments and societies, in addition to which it will carry out risk analyses of both human activities and natural hazards (floods, forest fires, droughts, air pollution, high-impact weather events). These plans take into account different key aspects, such as sustainable land use, public health and energy production. The improved knowledge and scenarios on climate phenomena and impacts are needed to provide relevant climate predictions, and also to support adaptation measures. In particular, estimates of the type and frequency of extreme events, and possible nonlinear climate responses, are needed for past, present and future conditions.

Another main outcome of the PEEX preliminary phase (2012–2017) is the PEEX observation network, which will fill the current observational gap in the northern pan-Eurasian region and eventually provide data services for different types of users. The aim is to bring the observational setup into an international context with standardized or comparable procedures. The development of the European research infrastructure provides a model for the harmonized PEEX data products, and for the calibration of network measurements with international standards. PEEX will adopt the common European data formats and procedures for the PEEX research infrastructure development, including an open data policy. Furthermore, PEEX will actively collaborate within a framework of the circumpolar projects.

PEEX will provide new early-warning systems for the Arctic–boreal regions. The increasing utilization of natural resources in the Arctic region, together with increasing traffic, will increase the risk of accidents such as oil spills – as well as increasing anthropogenic emissions to the land, atmosphere and water systems – and cause negative land use changes in both forests and agricultural areas (Shvidenko et al., 2013). The thawing permafrost and extreme weather events accelerate both the risk of natural disasters – such as forest fires, floods and landslides – and the destruction of infrastructure, such as buildings, roads and energy distribution systems (UNEP Year Book, 2013; Bondur, 2011, 2015). The coherent and coordinated PEEX observation network, together with the PEEX modeling approach, form the backbone of the next-generation early-warning systems across the PEEX geographical domain.

The advanced knowledge on environmental changes and their feedbacks to economy and society enables us to address future scenarios and narratives for future food production, forestry and other ecosystem services; development of transport, energy production, and use of minerals; and changes in local and regional culture and networks. These interlinks are in most cases very nonlinear, and therefore we need deep multidisciplinary understanding for finding practical solutions to the grand challenges discussed earlier.

Society and research are tightly connected with each other. Society provides resources for the basic research, which generates new knowledge to be used in applied research. Applied research generates new innovations, which produce welfare and provide new resources back to society. PEEX is an active player in each part of this cycle. Technological development can answer some of the questions arising in F-1. However, all of society, including economic and cultural aspects, must be considered in the search for sustainable answers to grand challenges.

3.4 Knowledge transfer and capacity building (F-4)

One of the first activities of PEEX will be the establishment of a PEEX education and capacity-building program. The main emphasis is on facilitating the dissemination of existing educational material and on promoting the collaboration of national and regional programs. PEEX intends to participate in the training of researchers throughout their career, from undergraduate and graduate studies to the level of experts, professors and research institute leaders. Building bridges between the different natural sciences, as well as between natural and social sciences, is one of the most important goals of the international and interdisciplinary education collaboration.

PEEX will contribute to the building of a new, integrated Earth system research community in the pan-Eurasian region. In practice this means open access to the research and modeling infrastructure, as well as invitation of international partners and organizations to share their development and use. PEEX will be a major factor in integrating the socioeconomic and natural-science communities to work together toward solving the major challenges influencing the well-being of humans, societies and ecosystems in the Arctic–boreal region.

PEEX will distribute information to the general public in order to raise awareness on climate change, and on the human impacts at different scales of the climate problem. This will also increase the visibility of PEEX activities in Europe, Russia and China.

4 Summary and outlook of PEEX in the future society

As a multicomponent, multidimensional and multidisciplinary program, PEEX will provide future societies the tools for finding sustainable ways to meet existing and also future grand challenges. The basis for this is comprehensive research stations with proper satellite data and modeling framework, which enable us to improve our understanding, to answer our current research questions, and also to renew these questions in a proper way.

The scientific results of PEEX will be used to develop new scenarios in order to help decision makers and other stakeholders to meet and manage grand challenges also in the future. Since the global population will increase, the use of freshwater, the food supply, and the use and production of energy need to be organized in a sustainable manner. The health problems related to air pollution and epidemic diseases need to be solved. PEEX will contribute significantly to climate scenarios on global and regional scales, and provide novel services such as early-warning systems for the Arctic–boreal regions. PEEX aims to contribute to the Earth system science agenda, to climate policy concerning topics important to the pan-Eurasian environment, and also to help societies of this region in building up a sustainable future.

Because of the already-observable effects of climate change on society, and the specific role of the Arctic and boreal regions in this context, PEEX emphasizes the need for establishing next-generation research and research infrastructure in this area. PEEX will provide fast-track assessments of global environmental-change issues for climate policy making, and for mitigation and adaptation strategies for the northern pan-Eurasian region.

In practice, PEEX will develop and utilize an integrated observational and modeling framework to identify different climate forcing and feedback mechanisms in the northern parts of the Earth system, and therefore enable more reliable predictions of future regional and global climate. Besides climate-change–air-quality issues, PEEX aims to provide a continuum from deep scientific understanding to socioeconomic solutions. The timescale of the first phase of PEEX extends from 2013 to 2033, with a vision to continue several decades. The long timescale is required for solving the current and emerging interlinked grand challenges.

PEEX aims to be operational in the beginning of 2018. It will start designing and building long-term, continuous and comprehensive research infrastructure in northern pan-Eurasia. At first, the PEEX infrastructure will be based on the re-organization of the existing facilities, and it includes ground-based, aircraft, marine and satellite observations, as well as multiscale modeling platforms. The PEEX domain covers the Eurasian boreal zone and the Arctic regions of the hemisphere, including marine areas such as the Baltic, the North Sea and the Arctic Ocean. The PEEX area includes also China due to its crucial impact and influence on the Boreal and Arctic regions. The PEEX research agenda focuses on the multidisciplinary process understanding of the Earth system on all relevant spatial and temporal scales, ranging from the nano-scale to the global scale. The strategic focus is to ensure the long-term continuation of comprehensive measurements in the land–atmosphere–ocean continuum in the northern Eurasian area, as well as the interactions and feedbacks related to urbanization and megacities, and to educate the next generation of multidisciplinary scientists and technical experts capable of solving the large-scale research questions with societal impact of the PEEX geographical domain.

For successful operation PEEX needs to have

- excellent science: quality, critical mass, and inter- and multidisciplinary research;
- world-class research infrastructure, an integrated network of research networks, and open data;
- education and training: knowledge exchange and capacity building;
- innovations and contributions to an innovative environment;
- science to society: continuous dialog and stakeholder involvement.

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