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PAN-EURASIAN EXPERIMENT PEEX SCIENCE PLAN

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The list of Contributing Authors is provided in Appendix-1. The content of the PEEX Science Plan has arisen from the scientific outcomes of the PEEX meetings held in 2012-2014 in Helsinki (2012), Moscow (2013), Hyytiälä (2013), Beijing (2013) and St. Petersburg (2014), and from specific comments and contributions received during the science plan writing process.

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EURASIAN PAN-EURASIAN EXPERIMENT (PEEX)

The Eurasian Pan-Eurasian Experiment (PEEX) is a multidisciplinary, multi-scale program focused on solving grand challenges in northern Eurasia and China focusing in Arctic and boreal regions. PEEX will also help to develop service, adaptation and mitigation plans for societies to cope with global change. It is a bottom-up initiative by several European, Russian and Chinese research organizations and institutes with co-operation of US and Canadian organizations and Institutes. The PEEX approach emphasizes that solving challenges related to climate change, air quality and cryospheric change requires large-scale coordinated co-operation of the international research communities. Strong involvement and international collaboration between European, Russian and Chinese partners is needed to answer the climate policy challenge: how will northern societies cope with environmental changes? The promoter institutes of this initiative are 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. PEEX is built on collaboration by EU, Russian and Chinese parties, involving scientists from various disciplines, experimentalists and modelers, and international research projects funded by European, Russian and Chinese funding programs. The first active PEEX period is 2013-2033, though PEEX will continue until 2100. The first PEEX meeting was held in Helsinki in October 2012. PEEX is open for other institutes to join.

VISION

PEEX is a multidisciplinary, multi-scale research initiative aiming at resolving the major uncertainties in Earth System and Global Sustainability Science concerning the Arctic and boreal Pan-Eurasian regions including the impact and influence of China. 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 list of grand challenges cover subjects such as climate change, air quality, biodiversity loss, chemicalization, food supply, energy production and fresh water supply.

The PEEX vision includes the establishment and maintenance of long-term, coherent and coordinated research and education activities and continuous, comprehensive research infrastructures 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 particularly climate change and air quality.

MISSION

PEEX aim 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 as well as of China. PEEX is also a science community building novel infrastructures in the Northern Pan-Eurasian region and in China.

PREFACE

The precursor idea of the Eurasian Pan-Eurasian Experiment (PEEX) was introduced in 2011 in a paper titled "On measurements of aerosol particles and greenhouse gases in Siberia and future research needs", published in the Boreal Environment Research by Kulmala *et al.* This paper gave an overview of the aerosol and greenhouse gas (GHG) observation activities in the Siberian region, and addressed the importance of land-atmosphere dynamics of Siberian boreal forests for the climate system. The idea of the pan-Siberian experiment (PSE) was to organize a measurement program for aerosols, GHGs and biogenic volatile organic compounds (BVOCs), and to establish a coherent, coordinated observation network from Scandinavia to China, together with a science program focused on understanding processes in the land-atmosphere interface. Soon, the idea of PSE was expanded to cover the whole Northern Pan-Eurasian geographical domain, and was renamed the Pan-Eurasian Experiment (PEEX). The initiators of the PEEX idea were academy professor Markku Kulmala from the University of Helsinki, Division of Atmospheric Sciences (ATM), and professor Sergej Zilitinkevich from the Finnish Meteorological Institute and the University of Nizhny Novgorod.

The first Pan-Eurasian Experiment (PEEX) meeting was organized on 2-4 October 2012 by the University of Helsinki (ATM) and the Finnish Meteorological Institute. The first PEEX meeting gathered nearly 100 participants from Europe, Russia and China. Based on the meeting presentations and working group discussions, the research needs and the most urgent research questions of the Pan-Eurasian region were listed, and the first outline of the PEEX science plan was drafted. The PEEX preparatory phase organization was also established. It was agreed that the preparatory phase committee members, which are also the promoter institutes of the PEEX initiative, are the University of Helsinki, the Finnish Meteorological Institute, the Institute of Geography, Moscow State University, AEROCOSMOS, and the Institute of Atmospheric Optics (Siberian branch) of the Russian Academy of Sciences. It was also agreed that the PEEX preliminary phase program office, which acts as the headquarters of PEEX, would be established in Helsinki.

So far, the 1st PEEX meeting in Helsinki has been followed by four other PEEX meetings taking place in Moscow (12.-14. February 2013), in Hyytiälä, Finland (26.-28. August 2013) and in St. Petersburg (4.-6. March 2014). The PEEX China kick-off was held in Beijing in November 2013 at the institute of Remote Sensing and Digital Earth (RADI) of the Chinese Academy of Sciences (CAS). RADI has joined the PEEX preparatory phase committee member institutes, and has established the PEEX China office at the premises of RADI. As part of the PEEX China activities, the PEEX regional office was established at the Institute for climate and global change research at Nanjing University, which has been a long-term collaborator of the University of Helsinki in developing an *in-situ* atmospheric observations framework in China.

Since the 1st meeting in Helsinki, the PEEX science community from Europe, Russian and China has contributed to the content of the PEEX science plan in many ways. These include introducing research themes in the PEEX meetings, sending specific comments to the science plan, contributing to the editorial processing of the existing content, and writing sections related to specific areas of interest. The final version will be released in February 2015, in connection with the 1st PEEX science conference and the 5th PEEX meeting in Helsinki. After this point, the PEEX initiative will move towards detailed planning of the implementation of the PEEX infrastructure (coherent *in-situ* observation network, coordinated use of remote sensing observations, data systems and modeling platform). PEEX will continue to fill in the observational gap in atmospheric *in-situ* and ground base remote sensing data in the Siberian and Far East regions, and start the process toward standardized and harmonized data procedures. The future PEEX-RI conceptual design will find synergies with the major European land-atmosphere observation infrastructures such as the ICOS (a research infrastructure to decipher the greenhouse gas balance of Europe and adjacent regions), ACTRIS (aerosols, clouds, and trace gases research infrastructure network-project 2011-2015), GAW (Global Atmospheric Watch), and ANAEE (the experimentation in terrestrial ecosystem research) networks, and with the flagship measurement stations such as SMEAR (station for measuring ecosystem-atmosphere relations).

During the first years of action, PEEX has co-operate with International Eurasian Academy of Sciences (IEAS) and also been introduced at several conferences and scientific forums such as: ISAR-3 (Tokyo 2013), Future Earth (Paris 2013), Geo Secretariat meeting (Geneva 2013), the Climate Change Northern Territories Arctic Meeting (Reykjavik 2013), EMS Annual Conference (Reading 2013), Partnership Conference Geophysical Observatories, multifunctional GIS and data mining (Kaluga 2013), LCES-2013 at Euro-Asia Economic Forum (Xi'an 2013) Siberian aerosol Conference (Tomsk 2013), EGU (Vienna 2013, 2014), Arctic Observing Summit (2014), 4th iLEAPS Science Conference (Nanjing 2014), GEIA conference (Boulder 2014) and SPIE Remote Sensing Conference (Amsterdam 2014).

Contents

ABSTRACT

The Eurasian Pan-Eurasian Experiment (PEEX) is a multidisciplinary, multi-scale research program aimed 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 the 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, chemicalization, food supply, and the use of natural resources by mining, industry, energy production and transport. Our approach is integrative and interdisciplinary, 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 and continuous, comprehensive research and educational infrastructures across the PEEX domain.

The PEEX initiative is motivated by the fact that the role of northern regions will increase in terms of globalization, climate change, demography and use of natural resources. Land and ocean areas located at 45°N or higher latitudes will undergo substantial changes during the next 40 years. Even the most moderate climate scenarios predict that the northern high latitudes will warm by 1.5 °C - 2.5 °C by the middle of the century. The Pan-Eurasian Arctic-boreal natural environment will be a very important area for the global climate via the albedo change, carbon sinks and emissions, methane emissions and aerosol production via biogenic volatile organic compounds (BVOCs). In addition, the ecosystems will undergo potentially massive changes including the expansion of new species and the extinction of existing ones. These will have unpredictable consequences on food webs and the primary production of different plant ecosystems.

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. 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 to establish next-generation research and research infrastructures 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.

PEEX is built on the collaboration between European, Russian and Chinese partners, and is open to a broader collaboration in the future. The PEEX community will include scientists from various disciplines, funders, policy-makers and stakeholders from industry, transport, renewable natural resources management, agricultural production and trade, and it will aim at co-designing research in the region in the spirit of the Future Earth initiative.

PEEX aims to be operational starting from 2015. It will start building the long-term, continuous and comprehensive research infrastructures (RI) in Northern Pan-Eurasia. These RIs will include ground-based, aircraft, marine and satellite observations, as well as multi-scale modeling platforms. The PEEX domain covers the Eurasian boreal zone and 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. 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.

The scientific results of PEEX will be used to develop new climate scenarios on global and regional scales and 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 aims to help societies of this region in building a sustainable future.

EXTENDED SUMMARY

Background and motivation

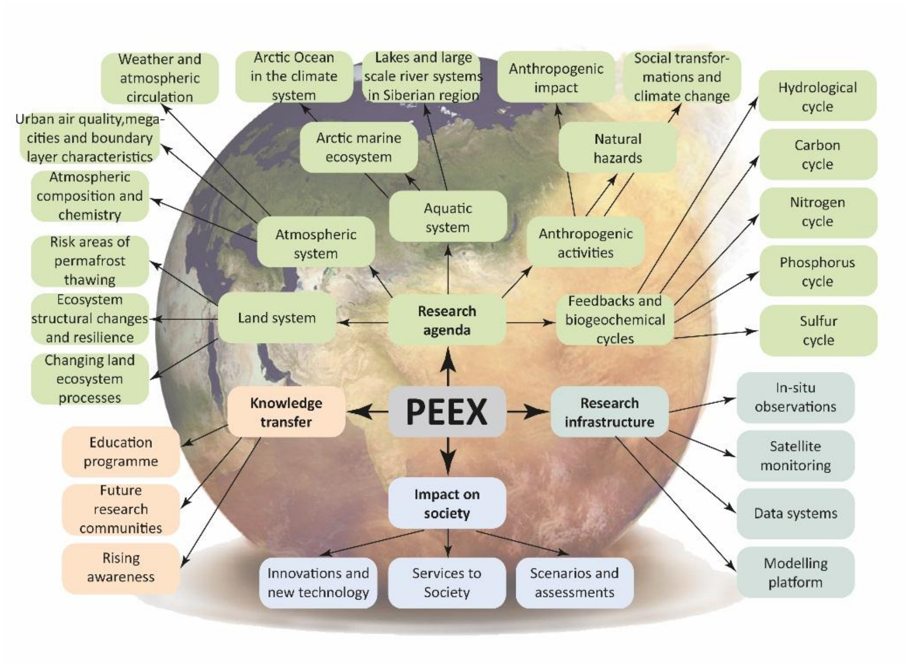


Figure 1 Schematic figure of the PEEX Structure.

Solving of any of the grand challenges – such as climate change, air quality, ocean acidification, clean water or food supply – requires a multi-scale, multidisciplinary research program linked with fast-track policy making. The Pan-Eurasian Experiment (PEEX) is a multidisciplinary, multi-scale global change and societal change initiative and research infrastructure development program focused on the northern Eurasian area, in particular on the Arctic and boreal regions including impact and influence of China. The overall goal of PEEX is to solve interlinked global challenges, such as climate change, air quality, biodiversity loss, chemicalization, food supply, energy production and fresh water supply, in an integrative way, while recognizing the increasing role of the Arctic and northern biomes in the context of global change.

The PEEX initiative is motivated by the fact that the role of northern regions will increase in terms of globalization, climate change, demography and use of natural resources (Smith 2011). Land and ocean areas located at 45°N or higher latitudes will undergo substantial changes during the next 40 years. Even the most moderate climate scenarios predict that the northern high latitudes will warm by 1.5 °C - 2.5 °C by the middle of the century, and by 3.5 °C by the end of the century. This is more than double compared to the global average warming (IPCC, 2013).

The Pan-Eurasian Arctic and boreal natural environments will be a very important area for the global climate via the albedo change, carbon sinks and emissions, methane emissions and aerosol production via biogenic volatile organic compounds (BVOCs). In addition, the ecosystems will undergo oppressive changes including the expansion of new species and the extinction of existing ones. These will have unpredictable consequences on food webs and the primary production of different plant ecosystems.

Climate change is shaking the dynamics of the whole global climate system, and is also triggering interlinked loops between global forces: demographic trends, the use and demand of natural resources, and globalization. Warming will affect demographic trends by increasing urbanization and migration to northern regions, and by accelerating changes in societal issues and air quality. 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. This will accelerate global trade activities in the Arctic region if the northern sea route is opened for shipping between the Atlantic and Asia's Far East. Northern ecosystems and Arctic regions are a source of major natural resources such as oil, natural gas and minerals. The exploitation of natural resources depends on how badly the permafrost thaw will damage infrastructure.

The PEEX approach emphasizes the converging understanding of physical and socio-economic processes within the Earth system, especially in the changing pristine and urban (also in Chinese megacities) environments of the northern (45°N latitude or higher) regions.

The PEEX domain covers a major part of the relevant areas of the boreal forest zone and the permafrost regions of the northern hemisphere, including the maritime environments (

Figure 2). The program agenda is divided into four focus areas (1. Research agenda, 2. Infrastructures, 3. Impact on society and 4. Knowledge transfer) (Figure 1) and is built on research collaboration between Russian, Chinese and European parties. The research agenda 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. The research infrastructure introduces the current state of the art observation systems in the Pan-Eurasian regions and presents the future baselines for the coherent and coordinated research infrastructures in the PEEX domain. The impact on society addresses key aspects related to mitigation and adaptation 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 is focused on education programs at multiple levels, strengthening future research communities, and raising awareness of global changes and environmental issues. The science plan also introduces the basic components of the implementation of the research agenda, and of designing and building the research infrastructures. Detailed descriptions of the implementation plans are provided in the separate PEEX documents.

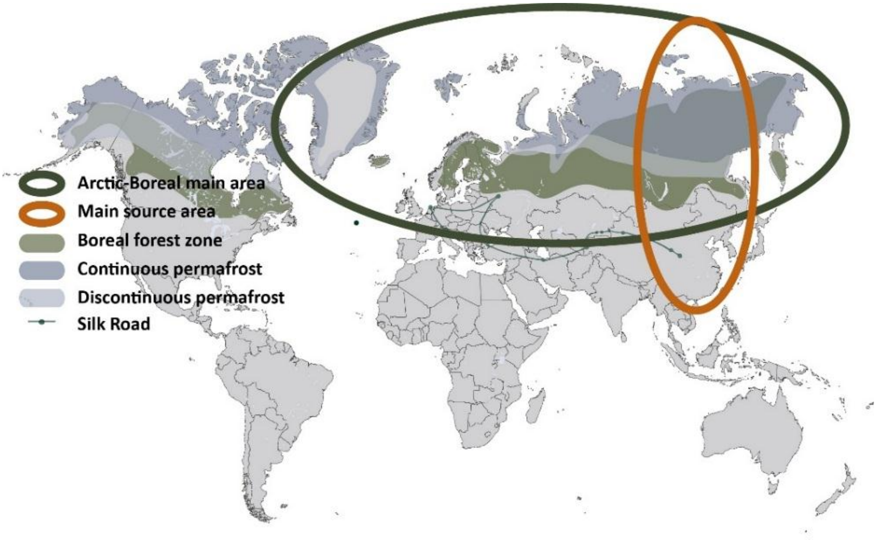


Figure 2 PEEX geographical region.

The PEEX Research Agenda (Focus-1)

The PEEX research agenda is designed as a research chain, 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, and extend to regional and global scales. Our focus is to understand the complex land-atmosphere-ocean-society system in an Arctic, northern Pan-Eurasian and Chinese context. PEEX will study the changes and processes driven by the following interlinked forces: (i) radiative forcing, (ii) Arctic warming, (iii) changes in the cryosphere, (iv) society, human activities, and (v) society-climate-biosphere interactions and feedbacks.

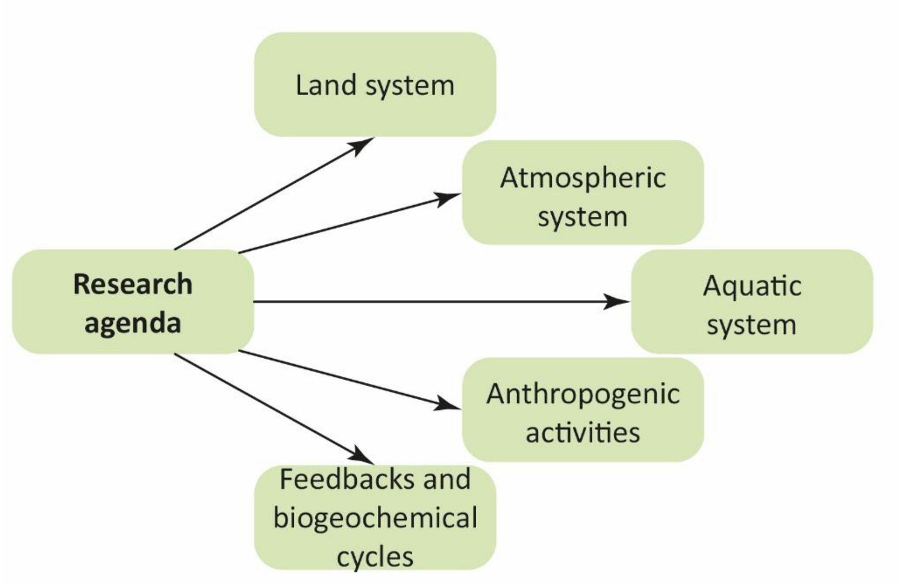


Figure 3 Substructure of PEEX Research Agenda (F1).

The research agenda covers different spatial and temporal scales, and encompasses diverse geographical regions including both natural and urban environments. The four major large-scale systems studied by PEEX are the land, atmosphere and aquatic systems, and anthropogenic activities (Figure 3). For each of the main systems we introduce three key topics and related large-scale research questions. In addition to the four major systems, the PEEX research agenda addresses the feedbacks and interactions between the systems and the major biogeochemical cycles (water, carbon, nitrogen, phosphorus, sulfur).

The scientific results of PEEX will fill the current gaps in our knowledge of the processes, feedbacks and links within and between the major components of the Earth system, and the biogeochemical cycles, in the Arctic-boreal context. The PEEX domain covers a wide range of interactions and feedback processes between humans and natural systems, with humans acting both as the source of climate and environmental change, and the recipient of the impacts. Reliable climate information and scenarios for the coming decades are crucial for supporting the adaptation of northern societies to the impacts of climate change and cryospheric changes. Human decision-making concerning, for example, land use and fossil fuel burning are represented by agent-based models (ABM), integrated assessment models (IAM), 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 scenarios, 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 socio-economic research covers (i) the superposition of natural and socio-economic factors, (ii) the dependence of the consequences of climate change on socio-economic condition and its dynamics, (iii) identification of opportunities and methods of mitigation and adaptation to climate change and socio-economic change, (iv) the spatial differentiation of the response of societies on national, regional, and local levels (regional and local, urban and rural cases) to environmental and socio-economic challenges.

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 for mitigation and adaptation strategies for the changing Arctic environments and societies, and will also carry out risk analysis of both human activities and natural hazards (floods, forest fires, droughts, air pollution). 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 enhanced 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 both past, present and future conditions.

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

Land system

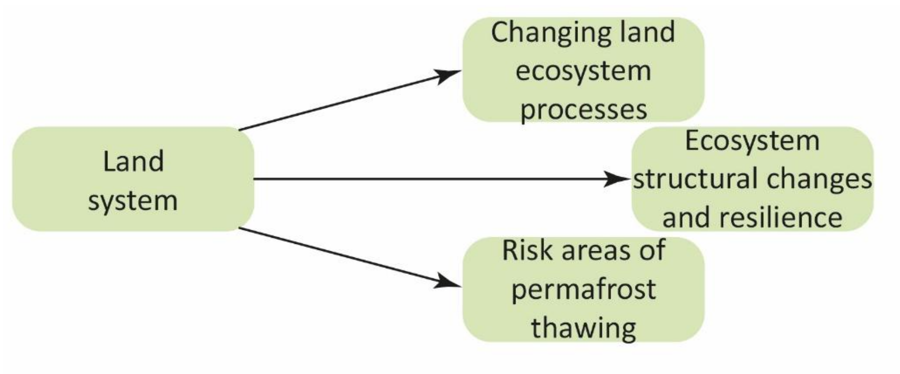


Figure 4 Substructure of land system research agenda.

Q-1 How can the land regions and processes that are especially sensitive to climate change be identified, and what are the best methods to analyze their responses?

Climatic conditions influence the structure and functions of all Arctic and boreal ecosystems. In the future, many processes are sensitively responding to climate change. This affects the productivity and functions of the ecosystems. These changes may lead to unpredictable consequences *e.g.* on the magnitude of the ecosystem carbon sinks, the production of aerosol precursor gases and the surface albedo.

Q-2 How fast will the permafrost thaw proceed and how will it affect ecosystem processes and ecosystem-atmosphere feedbacks, including the hydrology and greenhouse gas fluxes and VOC emissions?

The major part of the Northern Pan-Eurasian geographical region is covered by continuous permafrost. Even small proportional changes in the turnover of the soil carbon stocks due to permafrost melting will switch the terrestrial ecosystems from being carbon sinks to carbon sources. Accordingly very little is known on VOC emissions related to changing permafrost. The fate of permafrost soils in tundra is important for global climate with regard to all greenhouse gases and also on the potential VOC emissions and consequent aerosol production. These scenarios underline the urgent need for systematic permafrost monitoring, together with GHG and VOC measurements in various ecosystems. The treatment of permafrost conditions in climate models is still not fully developed.

Q-3 What are the structural ecosystem changes and the tipping points of the ecosystem changes in the north?

The PEEX biogeographical domain is characterized by very different types of ecosystems: agricultural regions, steppe, tundra, boreal forest and wetlands. Expected climate change and increasing anthropogenic pressure will cause substantial redistribution of bioclimatic zones, with consequent changes in the structure, productivity and vitality of terrestrial ecosystems. Many of the species found in boreal ecosystems are living at the edge of their distribution, and are susceptible to even moderate changes in their environment. The ecosystem structural changes are tightly connected to adaptation needs, and to the development of effective mitigation and adaptation strategies. Predictions concerning the shifting of vegetation zones are important for estimating the impacts of the region on future global GHG, BVOCs and aerosols budgets. Furthermore, natural and anthropogenic stresses such as land use changes and biotic and abiotic disturbances are shaping the ecosystems in the Arctic and boreal regions, and have many important feedbacks to climate. In a warmer climate, northern ecosystems may become susceptible to insect outbreaks, drought, devastating forest fires and other natural events. Also human impacts may cause sudden or gradual changes in ecosystem functioning. The ecosystem resilience is dependent on both the rate and the magnitude of these changes. In some cases, the changes may lead to system imbalance and cross a tipping point, after which the effects are irreversible

Atmospheric system

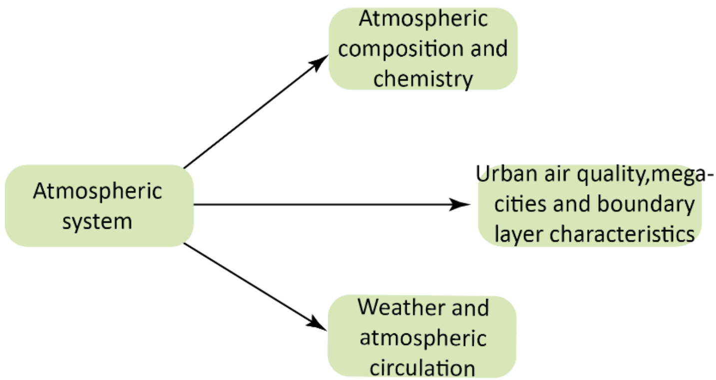


Figure 5 Substructure of atmospheric system research agenda.

Q-4 What are the critical atmospheric physical and chemical processes with large scale climate implications?

The largest anthropogenic climate forcing agents are greenhouse gases (GHGs) and aerosol particles. Especially in the Arctic, there are also several possible amplifying feedbacks related to aerosols and GHGs, which are expected to result from the changing climate. Furthermore, the Arctic environment is highly sensitive to changes in aerosol concentrations and composition. Concentrations of aerosols in the Arctic winter and spring are affected by "Arctic haze" (Shaw, 1995); a phenomenon suggested to arise from the transport of pollutants from lower latitudes *e.g.* (Stohl, 2006), and further strengthened by the strong stratification of the Arctic wintertime atmosphere.

Q-5 What are the key feedbacks between air quality and climate at northern high latitudes and in China?

PEEX urban environments are mainly characterized by cities in Russia and China with heavy anthropogenic emissions from local industry, traffic and housing, and by the megacity regions of Moscow and Beijing with alarming air quality levels. Bad air quality has serious health effects, and also damages ecosystems. Furthermore, atmospheric pollutants and oxidants (SO_2, O_3, NO_x, BC, sulfate, secondary organic aerosols) play a central role in climate change dynamics via their direct and indirect effect on global albedo, radiative transfer and cloud - precipitation processes.

Q-6 How will atmospheric dynamics (synoptic scale weather, boundary layer) change in Arctic-boreal regions?

Changes in the atmospheric dynamics taking place in the Arctic and boreal regions have severe impacts on (i) short-term predictions of physical conditions in the domain, and also beyond the domain, due to non-linear multi-scale interactions in the atmosphere and closely coupled sub-systems, and on (ii) long-term predictions and projections concerning the bio-geochemical systems in the domain, and world-wide.

Aquatic system and the Arctic Ocean

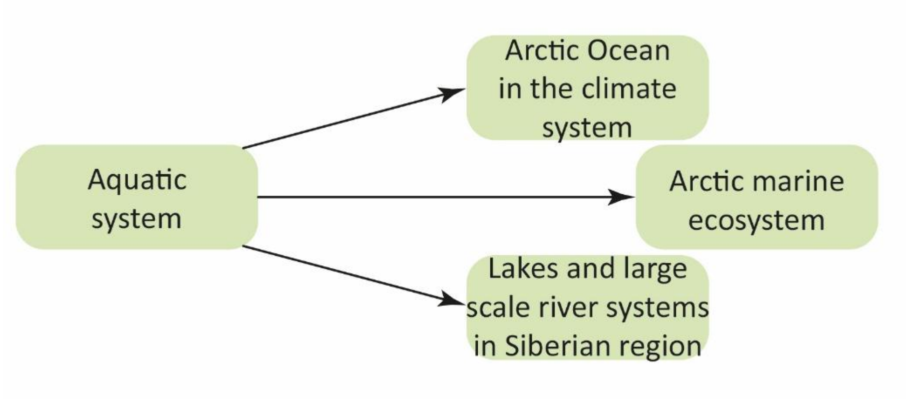


Figure 6 Substructure of aquatic system and the Arctic Ocean research agenda.

Q-7 How will the extent and thickness of the Arctic sea ice and the terrestrial snow cover change?

The Arctic Ocean plays an important role in the climate system. The essential processes related to the interaction between the ocean and the other components of the Earth system include the air-sea exchange of momentum, heat, and matter (*e.g.* moisture, CO_2, and CH_4), and the dynamics and thermodynamics of sea ice. The major issues to be studied are (i) the role of the ocean in the Arctic amplification of climate change, (ii) reasons for the Arctic sea ice decline, (iii) greenhouse gas exchange between ocean and atmosphere, and (iv) various effects that the sea ice decline have on the ocean, surrounding continents and aerosol budgets.

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 ice cover of the Arctic Ocean is undergoing fast changes, including a decline of summer ice extent and ice thickness. This results in a significant increase of the ice-free sea surface in the vegetation season, and an increase in the duration of the season itself. This could result in a pronounced growth of the annual gross primary production (GPP) and phytoplankton biomass. Higher GPP may in turn cause (i) an increase in CO_2 fluxes from the atmosphere to the ocean and (ii) an increase in the overall biological production, including the production of higher trophic level organisms and fish populations. An increase in surface water temperature may "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 to an increase in the amount of fresh water and allochthonous materials annually delivered to the artic shelves, and further to the Arctic Basin. All these processes may impact the Arctic marine ecosystems and their productivity, as well as key biogeochemical cycles in the region. One of the most important potential changes in the marine Arctic ecosystems is related to the progressive increase of the anthropogenic impacts of oil and natural gas drilling and transportation over the shelf areas, via the long-term backwash effect.

Q-9 What is the future role of the 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)?

The gradient in water chemistry from the tundra to the steppe zones in Siberia can provide insight into the potential effects of climate change on water chemistry. In the last century, long-range trans-boundary air pollution has led to changes in the geochemical cycles of S, N, metals and other compounds. Furthermore, Northern Pan-Eurasian methane originates from random bubbling in disperse locations. Permafrost melting may accelerate emissions of methane from lakes. Furthermore, there is a risk of increasing toxic blooms. In China, pollution and the shortage of water resources has become worse during the last decades. The conservation of water resources has become crucial for society.

Anthropogenic activities and society

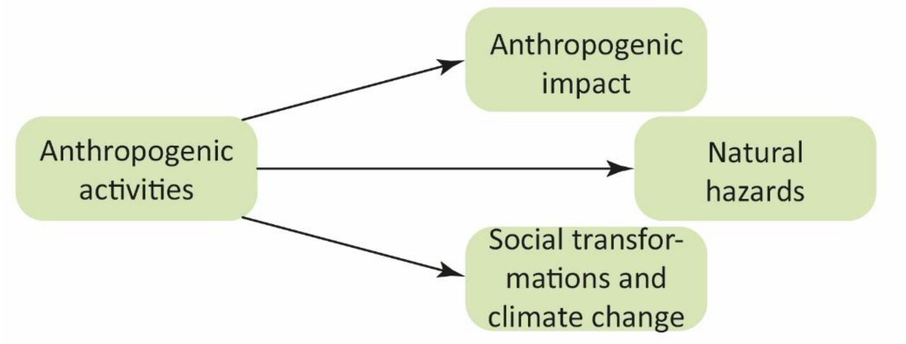


Figure 7 Substructure of anthropogenic activities research agenda

Q-10 How will human actions such as land-use changes, energy production, the use of natural resources, energy efficiency and the use of renewable energy sources) influence further environmental changes in the region?

Siberia is a treasure chest of natural resources for Russia, containing 85 % of its prospected gas reserves, 75 % of its coal reserves and 65 % of its oil reserves. Siberia has more than 75 % of Russia's lignite, 95 % of its lead, approximately 90 % of its molybdenum, platinum, and platinoides, 80 % of its diamonds, 75 % of its gold and 70 % of its nickel and copper. (Korynty, 2009). The industrial development of Siberia should be considered one of most important drivers of future land use and land cover changes in Russian territory.

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?

The frequency and intensity of weather extremes have increased substantially during the last decades in Europe, Russia and China. Further acceleration is expected in the future. The evolving impacts, risks and costs of weather extremes on population, environment, transport and industry have so far not been properly assessed in the northern latitudes of Eurasia. Important research topics include: analysis and improvements in forecasting of extreme weather conditions /

events; examination of the effect of wildfires on radiative forcing and atmospheric composition in the region; examination of the impacts of weather extremes on major biogeochemical cycles; studying the impacts of disturbances in forests on the emissions of BVOC and VONs (volatile organic nitrogen).

In northern Eurasia, from the eastern part of the Barents Sea to the Bering Sea, the permafrost is located directly on the sea coast. In many of these coastal permafrost areas, sea level rise and continuing permafrost degradation leads to significant coastal erosion, and to the possibility of collapse of coastal constructions such as lighthouses, ports, houses, *etc*. In this region, sea level rise is coupled to the permafrost degradation in a complex way, and should be focused on in future studies

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 changes?

Climate and weather strongly affect the living conditions of Pan-Eurasian societies, influencing people's health, the incidence of diseases, and the adaptive capacity. The vulnerability of societies, including their adaptive capacity, varies greatly, depending on both their physical environment, and on their demographic structure and economic activities. PEEX assesses the different ways in which societies are vulnerable to the impacts of climate change. PEEX will also help develop mitigation strategies that do not simultaneously increase the vulnerability of societies to climate change. More generally, PEEX analyzes the scientific background and robustness of the adaptation and mitigation strategies (AMS) of the region's societies, with special emphasis on the forest sector and agriculture.

Biogeochemical cycles and feedbacks

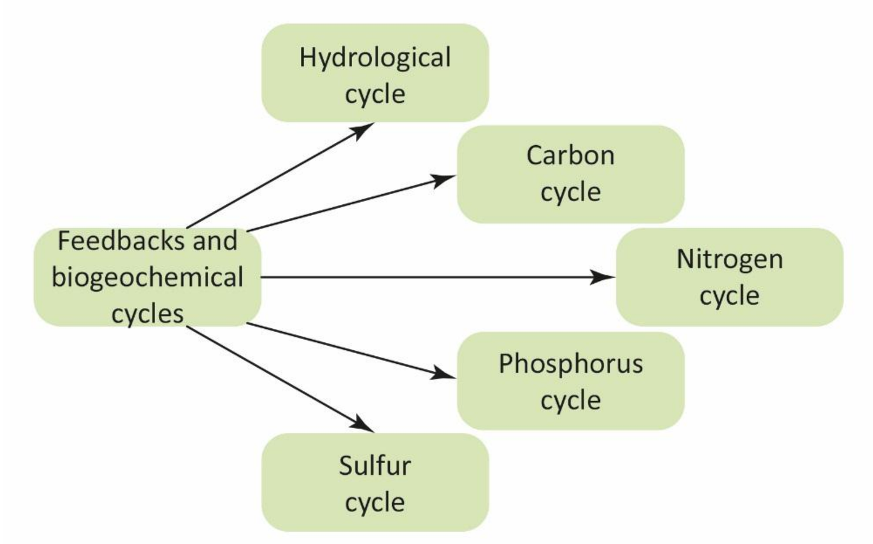


Figure 8 Substructure of feedbacks and biogeochemical cycles research agenda.

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 in (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?

Feedbacks are essential components of our climate system. They either increase or decrease the changes in climate-related parameters in the presence of external forcings (IPCC, 2013). One of the first feedback loops to be quantified is that connecting the atmospheric carbon dioxide concentration, ambient temperature, gross primary production, secondary biogenic aerosol formation, clouds and radiative transfer (Kulmala *et al.*, 2014). The Northern Pan-Eurasian Arctic-boreal geographical region covers a wide range of interactions and feedback processes between humans and natural systems. Humans are acting both as the source of climate and environmental changes, and as recipient of their impacts. The effects of climate change on biogeochemical cycles are still inadequately understood, and there are many feedback mechanisms that are difficult to quantify. 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. Measurements of the changes in the hydrological and biogeochemical cycles are needed to construct and parameterize the next generation of Earth System Models (EMSs).

EMSs are the best tools available for analyzing the effect of different environmental changes on future climate, or for studying the role of different processes in the Earth system as a whole. These types of analyzes 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 the recent decades.

The effects of climate change on biogeochemical cycles are still inadequately understood, and there are many feedback mechanisms, which are difficult to quantify (Arneth *et al.*, 2010; Kulmala *et al.*, 2014). They are related to, for example, the coupling of carbon and nitrogen cycles, permafrost processes and ozone phytotoxicity (Arneth *et al.*, 2010), or to the emissions and atmospheric chemistry of biogenic volatile organic compounds (Grote and Niinemets, 2008; Mauldin *et al.*, 2012), the subsequent aerosol formation processes, (Tunved *et al.*, 2006; Kulmala *et al.*, 2011a) and aerosol-cloud interactions (McComiskey and Feingold 2012; Penner *et al.*, 2012). For a proper understanding of the dynamics of these processes, it is essential to quantify the range of emissions and fluxes from different types of ecosystems and environments, and their links to ecosystem productivity, and also to take into considerations that there may exist previously unknown sources and processes (Su *et al.* 2011, Kulmala and Petäjä 2011, Bäck *et al.* 2010).

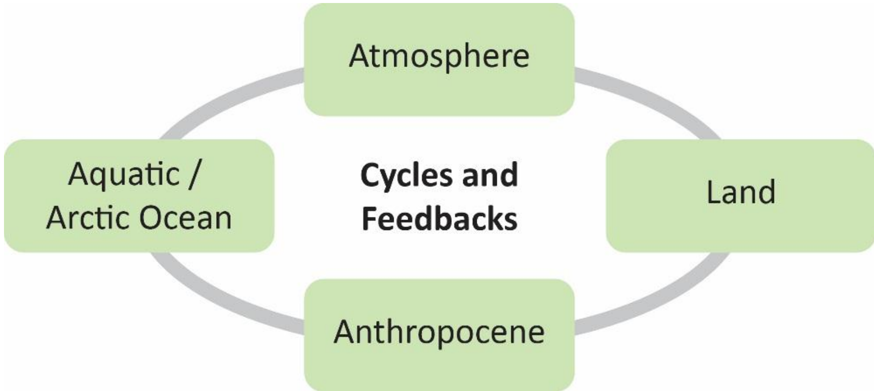


Figure 9 One of the main objects of PEEX research agenda is to create holistic understanding of the main processes in the land-atmosphere-aquatic systems-anthropogenic continuum.

Research infrastructures (Focus-2)

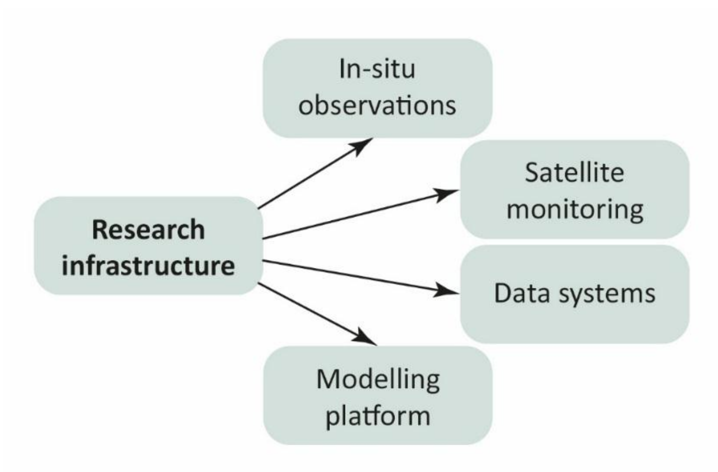


Figure 10 Substructure of Research infrastructure (Focus-2).

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. On the other hand all tools including models and observational/experimental devices need to be developed further in order to answer research questions and solve challenges. The PEEX approach uses research methods including both experimental and modeling tools, and ranging from nanometer and sub-second observations and process studies to global and decadal scale measurement activities, datasets 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 and Baltic countries, Russia and China. The integrated measurements of the hierarchical station network are designed to increase our quantitative process understanding of the land-atmosphere-ocean continuum, and of the impact of anthropogenic activities on the (eco)systems. In the first phase, the land-based station network will be based on existing infrastructure consisting of (i) standard stations including weather stations, (ii) flux (FLUXNET) stations, (iii) flagship stations and (iv) satellite receiving stations. The strategic focus is to ensure the long-term continuation of advanced measurements of aerosols, clouds, GHGs and trace gases in the northern Eurasian area. The preliminary concept of a hierarchical network for aquatic observations in the surrounding seas consist of simple buoys deployed on sea ice in the open sea, sophisticated buoys, research vessels, 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 (incl. carbon, nutrient and water cycles, vegetation dynamics, biotic and abiotic stresses). Ideally, the ground station network will contain one flagship station in all major ecosystems, in practice a station for every 1000-2500 km. 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 cryosphere in the Arctic is changing rapidly. Measurements of the current and past conditions of the cryosphere are made at deep boreholes, permafrost sites, buoy / floating stations in the Arctic Ocean, onboard ships, and through geophysical observations onboard aircraft.

The marine observations to be utilized in PEEX include both *in-situ* and remote sensing observations. *In-situ* measurements are made, among others, of the ocean temperature, salinity, chemical components, and organic matter; of sea ice and snow thickness, temperature, structure, and composition; as well as of the marine atmosphere (temperature, humidity, winds, clouds, aerosols, chemical composition). The remote sensing observations will address the ocean surface temperature, color, and wave field, as well as sea ice properties, including the ice type, concentration, extent, thickness, and albedo, and also biological activity (plankton biomass) parameters. Research based on these observations will be supported by reanalyzes and experiments applying process models, operational models, as well as regional and global climate models. Observations are made at drifting ice stations and research cruises, as well as by autonomous drifting stations/buoys and moorings and (manned and unmanned) research aircraft.

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 communities. The PEEX data will be harmonized with international measurement systems and data formats, in collaboration with existing 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), Integrated Land Information System, AERONET (AErosol RObotic NETwork), NDACC (Network for the Detection of Atmospheric Composition Change, TCCON (Total Column Carbon Observing Network), GAW-WMO (Global Atmosphere Watch Program by World Meteorological Organization), and European research infrastructures 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).

Modeling platform

The PEEX modeling platform (MP) is characterized by multi-scale approach starting from molecular and cell level and ending at a complex integrated Earth system modeling (ESM), in combination with specific models of different processes and elements of the system, acting on different temporal and spatial scales. 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: scenario analysis, inverse modeling, and modeling based on measurement needs and processes. The models are 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 the 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. We lack ways to forward the necessary process understanding effectively to the ESM. Within PEEX we will tackle this issue.

Impact on society (Focus-3)

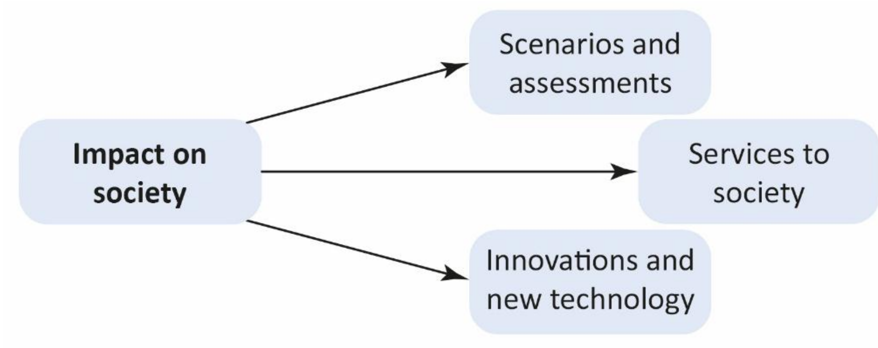


Figure 11 Substructure of the PEEX Impact on society.

Scenarios and assessments

The PEEX research agenda supports planning for climate change adaptation and mitigation. 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 and mitigate to climate change, and which issues can hamper this process.

Services

One of the main outcomes of the PEEX Preliminary Phase is the PEEX observation network, which will fill the current observational gap in the Northern Pan-Eurasian region and in the end prove 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 infrastructures provides a model for the harmonized PEEX data products, and for the calibration of network measurements with international standards. PEEX will be adopt the common European data formats and procedures for the PEEX-RI development. Furthermore, PEEX will actively collaborate in a frame of the circumpolar projects.

The second main area of interest is to 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. The thawing permafrost and extreme weather events both accelerate the risk of natural disasters such as forest fires, floods and landslides, as well as the destruction of infrastructure such as buildings, roads and energy distribution systems. The coherent and coordinated PEEX observation network, together with, the PEEX modeling approach, form the backbone for the next generation early warning systems across the PEEX geographical domain.

New technology

Society and basic 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 new resources back to society. It is crucial to ensure that this cycle remains healthy and is not broken in any place. PEEX is active player in each part of this cycle. Technological development can answer some of the questions arising in F1. However, the whole society, including economic and cultural aspects, must be considered in the search for sustainable answers to grand challenges.

Knowledge transfer

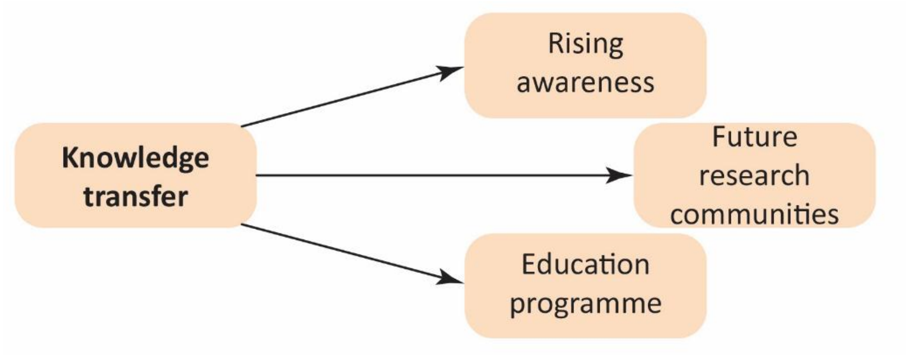


Figure 12 Substructure of the PEEX Knowledge transfer.

Education program

One of the first activities of PEEX will be the establishment of a PEEX education 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.

Research communities

PEEX will contribute to the building of a new, integrated Earth system research community in the Pan-Eurasian region by opening its research and modeling infrastructure, and by inviting international partners and organizations to share in its 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 wellbeing of humans, societies, and ecosystems in the Arctic-boreal region.

Raising awareness

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, Russian and China.

1 OBJECTIVES AND GRAND CHALLENGES

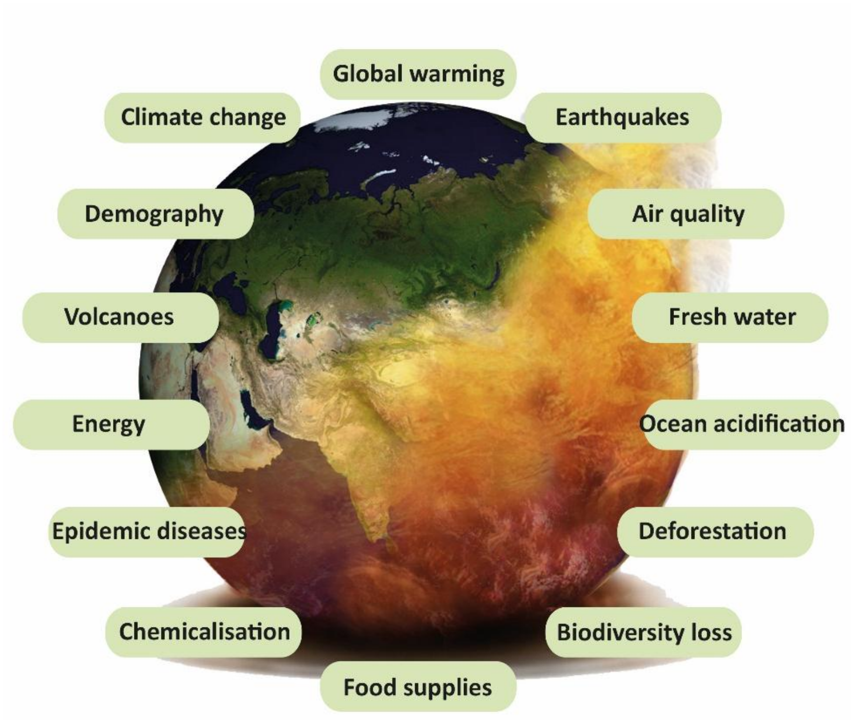


Figure 13 Examples of interlinked grand challenges.

SYNOPSIS Solving any of the Grand Challenges (climate change, air quality, ocean acidification, fresh water, food supplies, Figure 13) requires a multi-scale-multidisciplinary research program linked with fast track policy making. The Pan-Eurasian Experiment (PEEX) contributes to solving global scale grand challenges in the northern Pan-Eurasian context. The PEEX approach emphasizes the converging understanding of physical and socio-economic processes within the Earth system, particularly in the changing pristine and urban environments of the northern (45°N latitude or higher) and Arctic regions. The PEEX initiative aims to be a next-generation natural sciences and socio-economic research initiative having a major impact on the future environmental, socio-economic and demographic development of the Arctic and boreal regions. PEEX also aims to be a science community building novel infrastructures in the Northern Pan-Eurasian region

The Earth system is facing several global-scale environmental challenges, called “Grand Challenges” (Figure 13). Grand challenges are the main factors controlling the human well-being, security and stability of future societies. All the grand challenges are interlinked via complex feedbacks in the Earth system. The dynamics of grand challenges are driven by “global forces” identified as (i) demographics, (ii) increasing demand for natural resources, (iii) globalization and (iv) climate change (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 the climate change including global and regional mean temperature increase.

The Eurasian Pan-Eurasian Experiment (PEEX) is contributing to solving the grand challenges in the Northern Pan-Eurasian context (Figure 14).

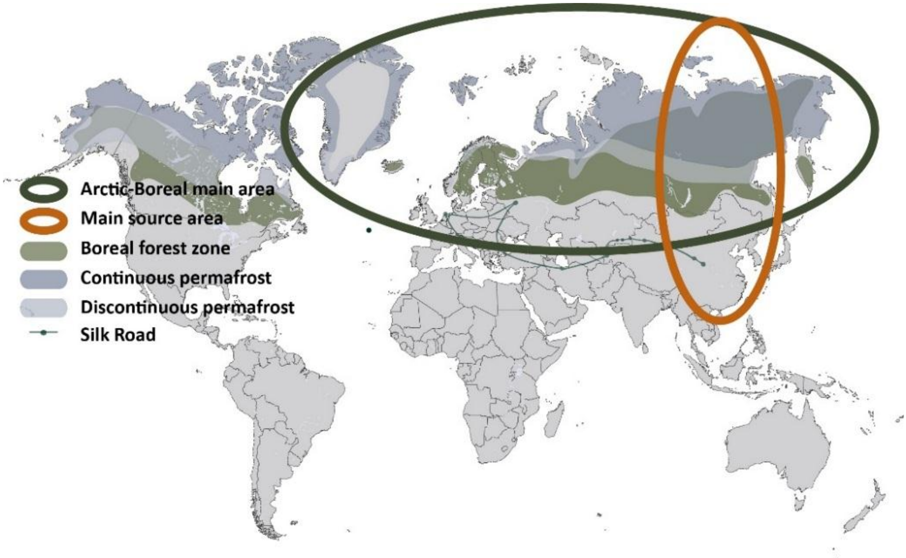


Figure 14 PEEX geographical region encompasses both permafrost and boreal zones.

The PEEX initiative consists of four main focus areas. Each focus area has its own specific objectives:

Focus-1 PEEX research agenda

- To understand the Earth system and the influence of environmental and societal changes in pristine and industrialized Pan-Eurasian environments (system understanding).
- To determine the processes relevant to climate change, demographic development and use of energy resources in the Arctic-boreal regions (process understanding).

Focus-2 PEEX infrastructures

- To establish and sustain long-term, continuous and comprehensive ground-based, airborne and seaborne research infrastructures 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).

Focus-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 and natural resources)
  - Early warning systems for the sustainable development of societies (demography development)
  - Technological innovations needed for coherent global environmental, technological or social processes in an interconnected world (globalization)

Focus-4 PEEX knowledge transfer

- To educate the next generation of multidisciplinary experts and scientists capable of finding tools for solving grand challenges
- To increase public awareness of climate change impacts in the Pan-Eurasian region
- To distribute the new knowledge and data products to scientific communities and the public sector
- To deliver tools, scenarios and assessments for climate policy makers and authorities

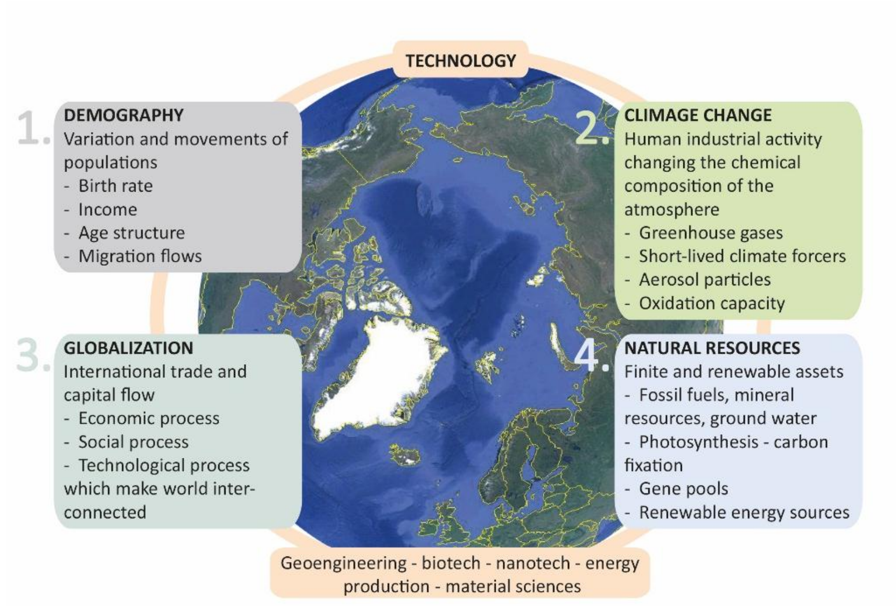


Figure 15 Global forces modifying the northern regions future within next 40 years (adapted from Smith, 2010).

2 MOTIVATION

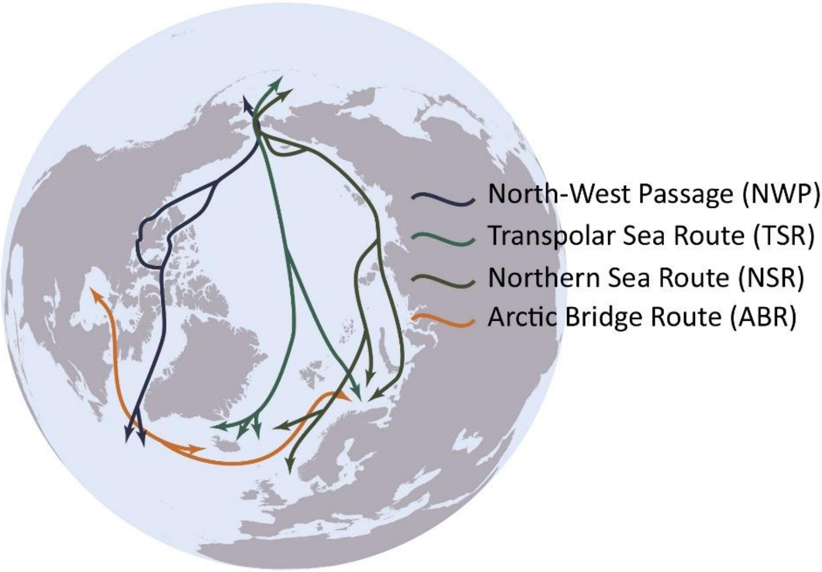


Figure 16 Expected shipping routes in the Arctic (figure adapted from the Arctic Institute).

SYNOPSIS The PEEX initiative is motivated by the fact that the Northern regions – land and ocean areas located at 45°N latitude or higher – will undergo substantial changes during the next 40 years. Even the most moderate climate scenarios predict that the northern high latitudes will warm by 1.5 °C - 2.5° C by the middle of the century, and by 3.5 °C by the end of the century. This is more than twice the global average warming (IPCC, 2013).

Coping with climate change and the transformations of civilizations and ecosystems on a global scale is one of the ultimate challenges of the 21st century. Solving any of the grand challenges, such as climate change, requires a framework where a multidisciplinary scientific approach (i) has the required critical mass and (ii) is strongly connected to fast-track policy making. It is also important to ensure the sustainable development of sensitive environments and societies in the northern regions. This can be done by establishing coherent research infrastructures and educational programs, and by increasing public awareness of environmental related matters.

The northern regions - land and ocean areas located at 45°N latitude or higher - will undergo substantial changes during the next 40 years. The most recent report by the intergovernmental panel on climate change (IPCC, 2013) concludes that this pattern will continue, and that artic regions will warm from 2.2 ± 1.7 °C up to 8.3 ± 1.9 °C by the end of this century, depending on the future emission scenario. It is expected that the northern regions will consequently undergo major changes during the next 40 years (IPCC, 2014).

The Pan-Eurasian Arctic-boreal natural environment will be very an important area for the global climate via the albedo change, carbon sinks and emissions, methane emissions and aerosol production via biogenic volatile organic compounds (BVOCs). Climate change is shaking the dynamics of the whole global climate system, and is also triggering interlinked loops between global forces: demographic trends, the use and demand of natural resources, and globalization. Warming will affect demographic trends by increasing urbanization and migration to northern regions, and by accelerating changes in societal issues and air quality. 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. This will accelerate global trade activities in the Arctic if the northern sea route is opened for shipping between the Atlantic and Asia's Far East. Northern ecosystems and Arctic regions are a source of major natural resources such as oil, natural gas and minerals. The exploitation of natural resources depends on how badly the permafrost thaw will damage infrastructure.

One of the most stimulating visions related to Arctic warming has been the opening of the Northern Sea Route for shipping between the Atlantic and Asia's Far East (Figure 16). 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 in the region. The future role of natural resources of the Arctic Ocean in the global energy market will be significant, as the region may hold 25 % or more of the world's undiscovered oil and gas resources (Yenikeyeff and Krysiek, 2007).

Along with these trends in human activities in the north, ecosystems will undergo significant changes. 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. The latter concerns vast areas of boreal forests and peatlands (Smith, 2010). These ecosystem changes may have unpredictable consequences on *e.g.* food webs or on interactions between different ecosystems and human activities.

In addition to large-scale aspects related to global change, these changes also have a regional societal dimension. This includes *e.g.* the durability of infrastructure (power networks, buildings, ice roads) built on thawing permafrost areas, and issues related to ensuring the living conditions and culture of indigenous people living in the north. A major fraction of the areas critical for permafrost thawing in the Northern Pan-Eurasian Arctic-boreal system is situated within Russia and China, and vast areas of the permafrost region and the boreal forest (taiga) zone are situated in Siberia. The thawing of permafrost and the northward shifting of the taiga zone will have significant consequences for the climate system. The most important driving forces will be the predicted changes in (i) the source and sink dynamics of greenhouse gases and (ii) biogenic volatile organic compounds (BVOC) emissions. The taiga forests and peatland in Siberia currently sequester a significant part of the global GHG fluxes. BVOC are contributing to atmospheric aerosol and cloud formation processes, and the magnitude of these emissions is linked to the total area of boreal forests, and to structural changes of the forest ecosystems. The other geographical area dominating the acceleration of climate change is the Arctic Ocean and its maritime environments. Changes in taking place in the Arctic sea ice will have both short-term and long-term, large-scale effects. The oceanographic changes in the Arctic Ocean, sea ice coverage, Arctic water flows and masses are all teleconnected to global climate and weather dynamics.

3 PEEX RESEARCH AGENDA (F1)

3.1 LARGE-SCALE RESEARCH SCHEMATICS AND QUESTIONS OF THE ARCTIC-BOREAL REGION

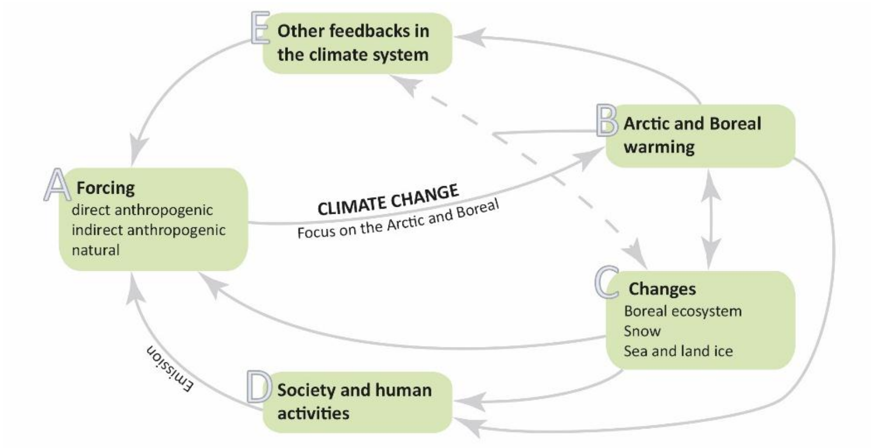


Figure 17 PEEX large-scale schematics.

SYNOPSIS The PEEX research agenda is focused on understanding the complex interlinked land-atmosphere-ocean-society system in the Arctic, boreal and Chinese context. PEEX will study the changes and processes driven by interlinked forces: (i) radiative forcing, (ii) Arctic warming, (iii) changes and feedbacks in the cryosphere, (iv) changes in society and human activities, (v) feedbacks in the climate system, (vi) feedbacks in the biosphere system (Figure 17). This holistic research approach has been adopted from the currently ongoing Nordic Center of Excellence (NCoE) on Cryosphere-Atmosphere Interactions in a Changing Arctic Climate (CRAICC), but has been expanded to cover both Arctic and boreal warming.

Future Arctic climate change, including the role of boreal forests, is a specific issue for northern science communities and societies. There is no clear understanding of why climate change proceeds so fast in the Arctic, and whether or not the amplified Arctic warming will continue at the same rate in the future (Lu and Cai, 2010).

The main components of the system are the Arctic Ocean, different ecosystems of the Northern Pan-Eurasian regions, the northern societies and megacities. Climate change is upsetting the dynamics of the whole global climate system inducing the warming of the Arctic and vast regions of boreal forests. Among the major consequences of warming in the northern latitudes are the changes in the cryosphere and the Arctic Ocean, especially changes in snow and ice coverage. The warming of the northern regions will affect societies and human activities. Economic growth related demographic trends, urbanization, trade and use of natural resources would further increase anthropogenic greenhouse gas emissions and concentration change of SLCF (short lived climate forcers), and thus strengthen the forcing factors in the Arctic-Nordic system.

3.2 LARGE-SCALE RESEARCH QUESTIONS AND KEY TOPICS

The large-scale research questions (PEEX-Q) concerning the main systems and interactions-feedbacks are listed here. Each of the large-scale research questions is introduced as a key topic of the PEEX research agenda.

Land system

Q-1 How can 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: changing land ecosystem processes

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 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 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 changes?
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.

3.3 ARCTIC-BOREAL LAND SYSTEM – KEY TOPICS

3.3.1 Changing land ecosystem processes

SYNOPSIS Climatic conditions influence the structure and functions of all Arctic and boreal ecosystems. In the future, many processes are sensitively responding to climate change, and affecting ecosystem productivity and functions. These changes may lead to unprecedented consequences *e.g.* in the magnitude of the ecosystem carbon sinks, the production of aerosol precursor gases, and the surface albedo.

Q-1 How can the land regions and processes that are especially sensitive to climate change be identified, and what are the best methods to analyze their responses?

Boreal forests are one of the largest terrestrial biomes, and account for around one third of the Earth's forested area (Global Forest Watch, 2002). Nearly 70 % of all boreal forests are located in the Siberian region. The forest biomass, soils and peatlands in the boreal forest zone together constitute one of the world's largest carbon reservoirs (Bolin *et al.*, 2000; Kasischke, 2000; Schepaschenko *et al.*, 2013). This carbon stock has built up over centuries due to rather favorable conditions for carbon assimilation by vegetation, together with simultaneous low temperatures which restrict microbial decomposition. Due to their large forest surface areas and huge stocks of carbon (~320 gigatonnes of carbon; GtC), the boreal and Arctic ecosystems are significant players in the global carbon budget. Further, permafrost, a dominant feature of Siberian landscapes, stores around 1672 GtC (Tarnocai *et al.*, 2009). Boreal forests also form the main vegetation zone in the catchment areas of large river systems, and thus they are an important part of the global water-energy-carbon feedbacks.

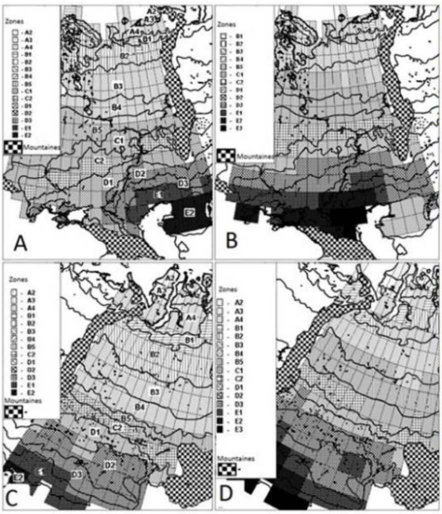
The forest biomass forms a positive climate feedback via the anticipated changes in nutrient availability and temperatures, impacting carbon sequestered both into the aboveground biomass and the soil compartment. The Siberian forests are currently assumed to be a carbon sink, although with a large uncertainty range of 0-1 PgC yr^{-1} (Gurney *et al.*, 2002). However, these ecosystems are vulnerable to global climate change in many ways, and the effects on ecosystem properties and functioning are complicated. While higher ambient CO_2 concentrations and longer growing seasons may increase plant growth and productivity, as well as the storage of carbon to soil organic matter (*e.g.* Ciais *et al.* 2005, Menzel *et al.*, 2006), warming affects respiration and ecosystem water relations in the opposite way (Bauerle *et al.*, 2012; Parmentier *et al.*, 2011). Expected acceleration of fire regimes might also substantially impact the carbon balance in Arctic and boreal regions (Shvidenko and Schepaschenko, 2013).

One example of the potentially large feedbacks is the critical role that permafrost plays in supporting the larch forest ecotone in northern Siberia. The boreal forests in the high latitudes of Siberia are a vast, rather homogenous ecosystem dominated by larch. The total area of larch forests is around 260 million ha, or almost one-third of all forests in Russia. Larch forests survive in the semi-arid climate because of the unique symbiotic relationship they have with permafrost. The permafrost provides enough water to support larch domination, and the larch in turn blocks radiation, protecting the permafrost from intensive thawing during the summer season. The anticipated thawing of permafrost could decouple this relationship, and may cause a strong positive feedback, intensifying the warming substantially.

The ambient temperature, radiation intensity, vegetation type and foliar area are the main constraints for the biogenic volatile organic compounds (BVOCs) (Laothawornkitkul *et al.*, 2009). This makes BVOC emissions sensitive to both climate and land use changes, via *e.g.* increased ecosystem productivity or the expansion of forests into tundra regions. Although the inhibitory effect of CO_2 on the process level may be important, Arctic greening may strongly enhance the production of BVOCs in northern ecosystems (Arneth *et al.*, 2007; Sun *et al.*, 2013). Open tundra may also act as a significant source for BVOCs, especially if the snow cover period changes (Aaltonen *et al.*, 2012; Faubert *et al.*, 2012). This would lead to negative climate feedbacks involving either aerosol-cloud or aerosol-carbon cycle interactions (Kulmala *et al.*, 2013; 2014; Paasonen *et al.* 2013).

In summary, even small proportional changes in ecosystem carbon uptake and in the turnover of soil carbon stocks can switch terrestrial ecosystems from a carbon sink to a carbon source, with consequent impacts on atmospheric CO_2 concentrations. Currently, we do not properly understand the factors influencing carbon storage, or the links between carbon assimilation, transpiration and BVOC production in a changing climate. What is certain is that especially in the high northern latitudes, the changes in these processes may be large, and their impacts may either amplify or decrease climate change.

3.3.2 Ecosystem structural changes and resilience



Tundra belt	
A2	Zone of arctic tundra
A3	Zone of northern standard tundra
A4	Zone of southern bush tundra
Taiga belt	
B1	Zone of forest-tundra
B2	Zone of northern taiga
B3	Zone of middle taiga
B4	Zone of southern taiga
B5	Transition zone from the southern taiga to deciduous forests
Deciduous forest belt	
C1	Zone of deciduous forest
C2	Zone of forest-steppe
Steppe belt	
D1	Zone of northern steppe
D2	Zone of middle steppe
D3	Zone of southern steppe
Desert belt	
E1	Zone of northern desert
E2	Zone of middle desert

Figure 18 Current botanic (A, C) status of 2x2° cells and their potential responses (B, D) to climate change under the climate scenario IPCC A2 (middle of the XXI). A and B are the area of the East European Plain, C and D are the area of the Western Siberia. Figure from

Environmental and geographical consequences of the global warming for the East European Plain and the Western Siberia. Edited by Nikolay Kasimov and Alexander Kislov. Moscow, 2011, 493 p. (Russian language).

SYNOPSIS The PEEX biogeographical domain is characterized by agricultural regions, steppe, tundra, boreal forest, wetlands, Mega-Cities and ice fields. Expected climate change and increasing anthropogenic pressure will cause substantial redistribution of bioclimatic zones (Figure 18) with consequent changes in the structure, productivity and vitality of terrestrial ecosystems. Many of the species found in boreal ecosystems are living at the edge of their distribution, and are susceptible to even moderate changes in their environment. The ecosystem structural changes are tightly connected to adaptation needs, and to the development of effective mitigation and adaptation strategies. Predictions concerning the shifting of vegetation zones are important for estimating the impacts of the region on future global GHG, BVOC and aerosols budgets. Furthermore, natural and anthropogenic stresses such as land use changes and biotic and abiotic disturbances are shaping the ecosystems in the Arctic and boreal regions, and have many important feedbacks to climate. In a warmer climate, northern ecosystems may become susceptible to insect outbreaks, drought, devastating forest fires and other natural disasters. Also human impacts may cause sudden or gradual changes in ecosystem functioning. The ecosystem resilience is dependent on both the rate and the magnitude of these changes. In some cases, the changes may lead to system imbalance and cross a tipping point, after which the effects are irreversible.

Q-2 What are the structural changes and the tipping points[1] of the ecosystem changes in the north?

[1] *Gerald Marten et al.: "an environmental tipping point is a part of the human-environment system that can lever far-reaching change in the system. A change at the tipping point sets in motion mutually reinforcing feedback loops that propel the system on a completely new course."*

Ecosystem structural changes

A large annual variability in climate is characteristic to the northern ecosystems. Climate variability impacts the species distribution and diversity, succession regularities, the structure, growth, productivity, fertility of ecosystems, as well as the interplay between biotic and abiotic stressors on multiple timescales (*e.g.*, Lapenis *et al.*, 2005; Gustafson *et al.*, 2010; Shvidenko *et al.*, 2013). Large vegetation shifts are anticipated in the Arctic-boreal region due to climate change. As a result of warming, the growing season is lengthening, which stimulates ecosystem gross primary productivity (GPP) and implies large increases in the amount of biomass, following an increased carbon uptake capacity. Due to the improved productivity, plant biomass growth is increasing, tree lines are advancing, and previously open tundra is turning into shrubland or forest, a phenomenon called "Arctic greening" (Myneni *et al.*, 1997; Xu *et al.*, 2013). Predictions on the extent and magnitude of this process vary significantly (Tchebakova *et al.*, 2009; Hickler *et al.*, 2012; Shvidenko *et al.*, 2013). It is estimated that the northward shift of bioclimatic zones in Siberia will be as large as 600 km by the end of this century (Tchebakova *et al.*, 2009). Taking into account that the natural migration rate of boreal tree species cannot exceed 200-500 m per year, such a forecast implies major vegetation changes in huge areas of the region. While some other models predict less dramatic changes (Yan & Shugart, 2005; Gustafson *et al.*, 2010), it is evident that all models forecast pronounced changes in the vegetation cover, affecting forest distribution, vitality and productivity, as well as the carbon and water cycles of ecosystems. The shifts in vegetation productivity and distribution will also have large implications for the composition and quantity of biogenic volatile organic compound (BVOC) fluxes (Arneth *et al.*, 2007; Noe *et al.*, 2011; 2012; Walter *et al.*, 2006; Zimov *et al.*, 2006; Schuur *et al.*, 2008).

Peatlands are a typical ecosystem in the high latitudes. They contain 20 to 30 % of the world's terrestrial carbon. While the relatively treeless peatlands occupy a small fraction, about 3 %, of the Earth's land area, they are a globally important carbon storage, and act as small, but persistent sinks of CO_2, and moderate sources of CH_4 (Frolking *et al.*, 2011). The storage of carbon in peat within the top 1 meter layer of soil cover in Russia is estimated at about 115 PgC (Schepaschenko *et al.*, 2013). The degradation of peatlands and their accelerated decomposition are major factors in determining the source and sink strengths of peatland ecosystems. Also, thawing of permafrost peatlands in tundra regions might change tundra ecosystems from a stable state into a dynamically changing and alternating land-water mosaic. The impacts of peatlands on GHG cycles may strongly depend on such changes.

The processes underlying peatland CH_4 emissions are complex, and depend on several climate-, landscape- and vegetation-related variables, such as inundation, depth of water table, vegetation composition, management and soil temperature. Peatlands fell under extensive management already in the distant past (O'Sullivan, 2007). Today, peatland management activities range from drainage and peat harvesting to establishing crop plantations and forests. Complete understanding of the climatic effects of peatland management remains a challenging question (Maljanen *et al.*, 2010).

About 1% of boreal forests burn each year (Gromtsev, 2002; Hytteborn *et al.*, 2005), and this number is expected to increase with climate change. Forest fires induce large changes in ecosystems, *e.g.* the regeneration of forest stands and the disintegration of permafrost, affecting infrastructure such as roads and pipelines (Jafarov *et al.*, 2013). During a fire, soil organic matter is released rapidly to the atmosphere through combustion. In addition to the direct CO_2 emissions, fire affects the ecosystem c and n balance by via the ecological controls of the C and N cycles, as well as the structure and productivity of the post-fire forest. Forest fires also influence albedo, and produce large amounts of globally distributed black carbon.

Surface albedo is affected both by changes in vegetation cover and by cryospheric processes, such as snow and ice cover changes. The surface albedo determines the fraction of incident solar radiation that is reflected back to the atmosphere, and is thus a key parameter in the Earth's radiant energy budget. Changes in vegetation cover can lead to albedo changes *e.g.* due to the lower albedo and therefore higher net absorption of radiation of forests compared to open vegetation. This leads to changes in the net radiation, and thus modifies the local heat and water fluxes, affects the boundary layer conditions, and further also affects the local to larger scale climate (Sellers *et al.*, 1997). Vegetation-related albedo changes, in addition to changes in the vegetation CO_2 sink and BVOC-related aerosol production, lead to potentially large climate feedbacks. However, these feedbacks are currently not well defined.

Modeling the expected large structural changes in vegetation will require the development of a new generation of different vegetation models. The range of such models is large – from landscape models of successions and disturbances, coupled with ecophysiological models including zones of critical changes of climatic and environmental indicators (Gustafson, 2013), to models describing how the microbes in permafrost respond to thaw through processes such as respiration, fermentation, methanogenesis, methane oxidation and nitrification-denitrification.

Ecosystem resilience, tipping points

Ecosystems are not only benefiting from climate change, but may also suffer from increased stresses and deterioration. Resilience means the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and by recovering quickly (Holling, 1973). Such perturbations and disturbances can include stochastic events such as fires, flooding, windstorms or insect population explosions, and human activities such as deforestation or the introduction of exotic plant or animal species. Disturbances of sufficient magnitude or duration can profoundly affect an ecosystem, and may force an ecosystem to reach a threshold beyond which a different regime of processes and structures predominates.

The northern ecosystems have developed during the Holocene under a stable, rather cool or cold climate, with regular seasonal patterns in temperature and precipitation. This is particularly important for boreal forests due to the long period of life (in unmanaged forests) or long rotation periods (in managed forests) of major species with limited acclimation capacity. Very likely, the boreal forests will be affected due to (i) large changes of hydrological regimes over huge territories caused by permafrost melting; (ii) an overall warming in both winter and summer; and (iii) acceleration of disturbance regimes, particularly fire, outbreaks of insects and diseases, coupled with anthropogenic impacts (Krankina *et al.*, 1997; Shvidenko *et al.*, 2013).

Climate warming, precipitation changes during growth periods and permafrost changes will substantially increase water stress, and consequently increase the risk of mortality for trees. This process is already clearly intensified over the entire circumpolar boreal belt (Allen *et al.*, 2010). As a consequence, ecosystems may turn into carbon sources rather than sinks (Parmentier *et al.*, 2011).

In the future, boreal forest diebacks may occur due to mass infections of invasive pathogens or herbivores, such as the autumnal moth, *Epirrita autumnata*, that have previously been climatically controlled by harsh winter conditions. The growth and life cycles of herbivores or their habitat conditions may change in such a way that the outbreak frequencies and intensities of previously relatively harmless herbivore populations increase (Hunter *et al.*, 2014).

At the same time as climate is changing, boreal vegetation is also exposed to increased anthropogenic influences by pollutant deposition and land use changes (Dentener *et al.*, 2006, Bobbink *et al.*, 2010; Savva and Berninger, 2010). Large industrial complexes may lead to local forest diebacks, as has been observed in the Kola region (*e.g.* Tikkanen, 1995; Nöjd and Kauppi, 1995; Kukkola *et al.*, 1997). Societal transformations may lead to abandoning of agricultural land or deterioration of previously managed forests.

There is seldom a single and clear cause for forest dieback, but rather the ecosystems are suffering from multiple stresses simultaneously. This implies that a single stress factor may not be very dramatic for the resilience of the system, but when occurring simultaneously in combination with others, the system may cross a threshold (i.e. tipping point), and this may have dramatic consequences.

3.3.3 Risk areas of permafrost thawing

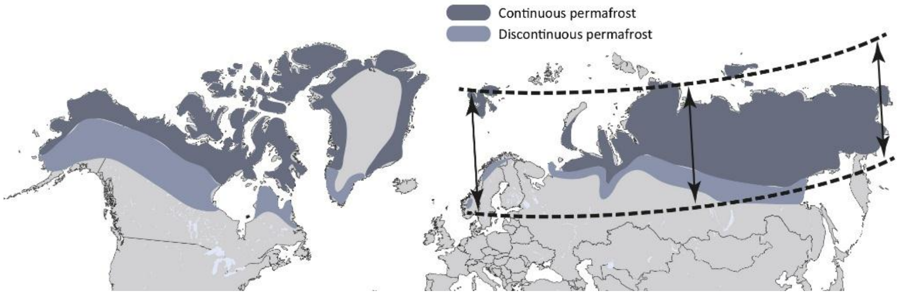


Figure 19 The Arctic permafrost.

SYNOPSIS The major part of the Northern Pan-Eurasian geographical region is covered by continuous permafrost (Figure 19). Even small proportional changes in the turnover of the soil carbon stocks due to permafrost melting will switch the terrestrial ecosystems from carbon sinks to carbon sources. The fate of permafrost soils in tundra is important for global climate with regard to all greenhouse gases. These scenarios underline the urgent need for systematic permafrost monitoring, together with GHG measurements in various ecosystems. The treatment of permafrost conditions in climate models is still not fully developed.

Q-3 How fast will the permafrost thaw proceed, and how will it affect ecosystem processes and ecosystem-atmosphere feedbacks, including hydrology and greenhouse gas fluxes?

Permafrost (ground temperature at or below 0°C for over 2 years) is a very typical characteristic of the Arctic. Permafrost occupies 25 % of the land area in the northern hemisphere, and 50 % of land area in Russia and Canada. Due to climate warming, also permafrost is warming and thawing, with many consequences for carbon and water cycling as well as ecosystem functioning. These feedbacks are currently still insufficiently understood.

The terrestrial biosphere is a key regulator of atmospheric composition and climate via its carbon uptake capacity (Arneth *et al.*, 2010; Heimann and Reichstein, 2008). The Eurasian area holds a large pool of organic carbon both in the soil and in frozen ground, stored during the Holocene and the last ice age, and within the living biota (both above and belowground). There is also a vast stock of fossil carbon in Eurasia. The soil carbon storage in the upper three meters of soil of the circumpolar northern high latitude terrestrial ecosystems is estimated to be between 1400 and 1850 Pg (McGuire *et al.*, 2009; Rarnocai *et al.*, 2009). About 400 Pg of carbon is located in currently frozen soils. This carbon was accumulated in non-glaciated regions during the pleistocene, in what was then steppe-tundra vegetation (Zimov *et al.*, 2006). In addition, *ca.* 250 PgC may be stored in deep alluvial sediments below 3 m in river deltas of the seven major Arctic rivers (Schuur *et al.*, 2008). Due to these large storages, even small changes in processes influencing carbon release and emissions can have significant impact on the behavior of global climate.

In high-latitude ecosystems with large, immobile carbon pools in peat and soil, the future net CO_2 and CH_4 exchange will depend on the extent of near-surface permafrost thawing, the local thermal and hydrological regimes, and interactions with the nitrogen cycle (Tarnocai *et al.*, 2009). The extra heat produced during microbial decomposition could accelerate the rate of change in active-layer depth, potentially triggering a sudden and rapid loss of carbon stored in carbon-rich Siberian pleistocene loess (yedoma) soils (Khvorostyanov *et al.*, 2008).

The permafrost dynamics may affect methane fluxes in many ways. Hot spots such as mud ponds emitting large amounts of CH4 may form when permafrost mires thaw. In contrast, lakes have occasionally disappeared as a result of the intensification of soil water percolation (Smith *et al.*, 2005). The rapid loss of summer ice, together with increasing temperature and melting ice complex deposits, results in coastal erosion, activation of old carbon and elevated CO_2 and CH_4 emissions from sea bottom sediments (Vonk *et al.*, 2012). High methane emissions have been observed from the East Siberian Arctic self (Shakhova *et al.*, 2010).

The connection between the climate and the thermal conditions in the subsurface layers (soil and bedrock) is an extremely important aspect in the coming decades. The warming of the atmosphere will inevitably result in warming of the permafrost layer, and is easily observed in deep borehole temperature data. However, the changes depend on the soil and rock type as well as on the pore-filling fluids. As long as the pore-fill is still ice, the climatic changes are reflected mainly in the thickness of the active layer, and in slow diffusive temperature changes of the permafrost layer itself. In areas where the ground is dominated by low ground temperatures and thick layers of porous soil types (*e.g.*, sand, silt, peat), the latent heat of the pore filling ice will efficiently 'buffer' and retard the final thawing. This is one of the reasons why relatively old permafrost exists at shallow depths in high-porosity soils. On the other hand, quite different conditions prevail in low-porosity areas, *e.g.* in crystalline rock areas.

3.4 ARCTIC-BOREAL ATMOSPHERIC SYSTEM –KEY TOPICS

3.4.1 Atmospheric composition and chemistry

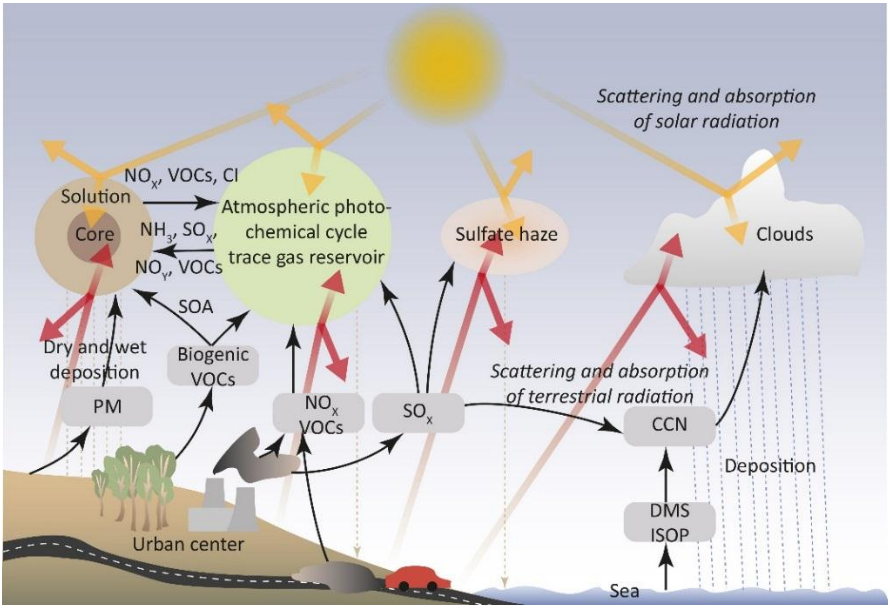


Figure 20 Atmospheric system -interactions. Figure adapted from Zhang (1994) and Zhang (2007).

SYNOPSIS The largest anthropogenic climate forcing agents are greenhouse gases (GHGs) and aerosol particles. Especially in the Arctic, there are also several possible amplifying feedbacks related to aerosols and GHGs, which are expected to result from the changing climate. Furthermore, the Arctic environment is highly sensitive to changes in aerosol concentrations and composition.

Concentrations of aerosols in the Arctic in winter and spring are affected by 'Arctic haze' (Shaw, 1995); a phenomenon suggested to arise from the transport of pollutants from lower latitudes *e.g.* (Stohl, 2006), and further strengthened by the strong stratification of the Arctic wintertime atmosphere (Asmi *et al.*, 2012).

Q-4 What are the critical atmospheric physical and chemical processes with large-scale climate implications?

Atmospheric greenhouse gases and ozone

There is an urgent need to better constrain the source and sink budgets of GHGs (CO_2, CH_4) in the PEEX area, particularly in Siberia, and to quantify the atmospheric impact of CH_4 emissions from the major natural ecosystems (wetlands, permafrost). It also important to identify and observe the anthropogenic sources of short lived pollutants (CO, O_3, BC, fine particles), and to characterize their long-range transport across Eurasia (Figure 20). New data on GHGs are needed to validate atmospheric models and land flux models. To be successful, the PEEX approach requires both ground-based and space-borne instruments over the vast and currently under-documented region of. Local sources, especially forest fires, and their impacts on regional air quality and on the Arctic also need to be characterized.

There are very few measurement programs for documenting tropospheric composition over Siberia (Crutzen *et al.*, 1998; Ramonet *et al.*, 2002; Paris *et al.*, 2008; Sasakawa *et al.*, 2010; Kozlova *et al.*, 2008). Therefore, large uncertainties currently surround our knowledge of biogeochemistry and the distributions/emissions of compounds important for tropospheric chemistry and climate change. Relevant species that require further measurements include CO_2 and CH_4 for biogeochemical cycles, as well as CO, O_3, and aerosols, including black carbon, for tropospheric composition. Other tracers also need further investigation, including the stable isotopic composition of CO_2 and CH_4, required for the attribution of sources and sinks of these species in the studied area.

High latitude biomes influence the global methane budget (Bousquet *et al.*, 2006) in several ways, including wetlands emissions, reactivation of bacterial activity through permafrost melting (Zimov *et al.*, 2006), bubbling in thermokarst lakes (Walter *et al.*, 2006) and potential destabilization of methane hydrates in coastal permafrost. In a warming climate, these altered processes are expected to feed back into the global radiative forcing, and thus further enhance climate change. Our current understanding of the extent and amplitude of these sources, as well as the large-scale driving factors, remain highly uncertain (Bloom *et al.*, 2010). Anthropogenic emissions of CH_4 from leakages of natural gas pipelines are also not well quantified. In addition, as northern regions of Russia warm, there is likely to be additional exploitation of natural gas reserves. As a result, and due to the lack of regional observations, it can only be conjectured from zonal gradients that the recently resumed increase in global atmospheric CH_4 concentrations was initiated by unusually high temperatures at high northern latitudes in 2007 (Dlugokencky *et al.*, 2009).

Despite Siberia's vast dimensions and importance in the climate system, little is known about whether and how the regional O_3 budget differs from the rest of the northern hemisphere (Berchet *et al.*, 2013). For example, O_3 production in boreal wildfire plumes seems to be weaker, or even turn into net destruction, compared to fire plumes at lower latitudes (Jaffe and Wigder, 2012). This may be due to lower NO_X emissions and/or more sequestration of NO_X as PAN (peroxyacyl nitrates), although pan can produce O_3 downwind. Also, given their importance for air quality and the global greenhouse gas budget, more atmospheric measurements of O_3, its precursors and other pollutants over Siberia are needed (see Elansky, 2012). These data are particularly useful for the validation of atmospheric chemistry models and satellite products. Emissions of NO_X and VOC (volatile organic compounds) from anthropogenic and biogenic sources are responsible for O_3 production and/or destruction downwind of source regions (review in HTAP, 2010). Observations in the Arctic and sub-Arctic areas have revealed production of O_3 in pollution and biomass burning plumes during transport (*e.g.* Oltmans *et al.*, 2010; Jaffe and Widger, 2012; Thomas *et al.*, 2013). Ozone destruction was also reported in some plumes from biomass burning or anthropogenic pollution (*e.g.* Verma *et al.*, 2009; Alvarado *et al.*, 2010). Ozone is lost by photochemical destruction following photolysis, and subsequent reaction of the formed excited-state atomic oxygen with water vapor. Halogen oxidation in the Arctic lower troposphere (Gilman *et al.*, 2010; Sommar *et al.*, 2010) can also lead to significant O_3 destruction, but this is generally confined to the Arctic boundary layer in springtime. Another major sink for O_3 is dry deposition on leaves via stomatal exchanges, which is harmful for vegetation.

<u>Examples of research questions – GHGs</u>

What are the main anthropogenic sources of CO_2, aerosol particles and their precursors in Pan-Eurasia? How they are distributed over the territory, and how they are changing in time?

What are the climatic parameters controlling the seasonal and inter-annual variability of regional CO_2 concentration in the atmosphere?

Atmospheric aerosols

From a climate perspective, the most important natural aerosol type over most of Eurasia is secondary organic aerosol (SOA) originating from atmospheric oxidation of biogenic volatile organic compounds (BVOC) emitted by boreal forests and possibly other ecosystems. Studies conducted in the Scandinavian part of the boreal zone indicate that new-particle formation (NPF) associated with BVOC emissions is the dominant source of aerosol particles and cloud condensation nuclei during summer (Mäkelä *et al.*, 1997; Kulmala *et al.*, 2001; Tunved *et al.*, 2006; Dal Maso *et al.*, 2007). Secondary organic aerosols associated with BVOC emissions are expected to induce large indirect radiative effects over the boreal forest zone (Spracklen *et al.*, 2008; Tunved *et al.*, 2008; Lihavainen *et al.*, 2009), provided that the findings made over Scandinavia are valid over larger spatial scales. Continuous aerosol measurements carried out in recent years at two west Siberian stations has revealed both the frequency and the seasonal dependence of the NPF events (Arshinov *et al.*, 2012). In Siberia, NPF events take place on about one-quarter of all days, being most frequent during spring (from March to May) and early autumn (with a secondary frequency peak in

September). The observed seasonal pattern of event frequencies in Siberia is similar to the one observed at Nordic stations (Dal Maso *et al.*, 2007).

Other important natural aerosol types in the PEEX domain are sea spray, mineral dust and primary biogenic aerosol particles. Sea spray makes an important contribution to the atmospheric aerosol over the Arctic Ocean and its coastal areas, and influences cloud properties over these regions. The climatic effects of sea spray are expected to change in the future as a result of changes in the sea ice cover and ocean temperatures (Struthers *et al.*, 2011). Mineral dust particles affect regional climate and air quality over large regions in Asia, especially during periods of high winds and moderate precipitation. Mineral dust and PBAP particles are also effective ice nuclei (Hoose and Möhler, 2012), and have the potential to influence the radiative and other properties of mixed-phase cold clouds in the PEEX domain.

The changes in emissions of anthropogenic aerosols and their precursors in the PEEX domain have been extensive during the last decades (Granier *et al.* 2011), and this has almost certainly contributed to the very different regional warming patterns over these areas (*e.g.* Shindell and Faluvegi 2009). The main aerosol constituents in this context are primary carbonaceous particles, consisting of organic and black carbon, as well as secondary sulfate particles produced during the atmospheric transport of sulfur dioxide. Anthropogenic aerosols cause large perturbations to the regional radiation budget downwind of major source areas in the PEEX domain, and the resulting changes in cloud properties and atmospheric circulation patterns may be important even far away from these sources (Koch and Del Genio, 2010; Persad *et al.*, 2012). In the snow-covered parts of Eurasia, long-range transported aerosols (see Figure 21) containing black carbon and deposited onto snow tend to enhance the spring and early-summer melting of the snow, with concomitant warming over this region (Flanner *et al.*, 2009; Goldenson *et al.*, 2012).

Aerosols emitted by forest fires are a special case in the PEEX domain, since the strength of this source type depends on both climate change and human behavior (Pechony and Shindell, 2010), and since particles emitted by these fires have potentially large radiative effects over the domain (Randersson *et al.*, 2006).

Atmospheric transport of pollutants

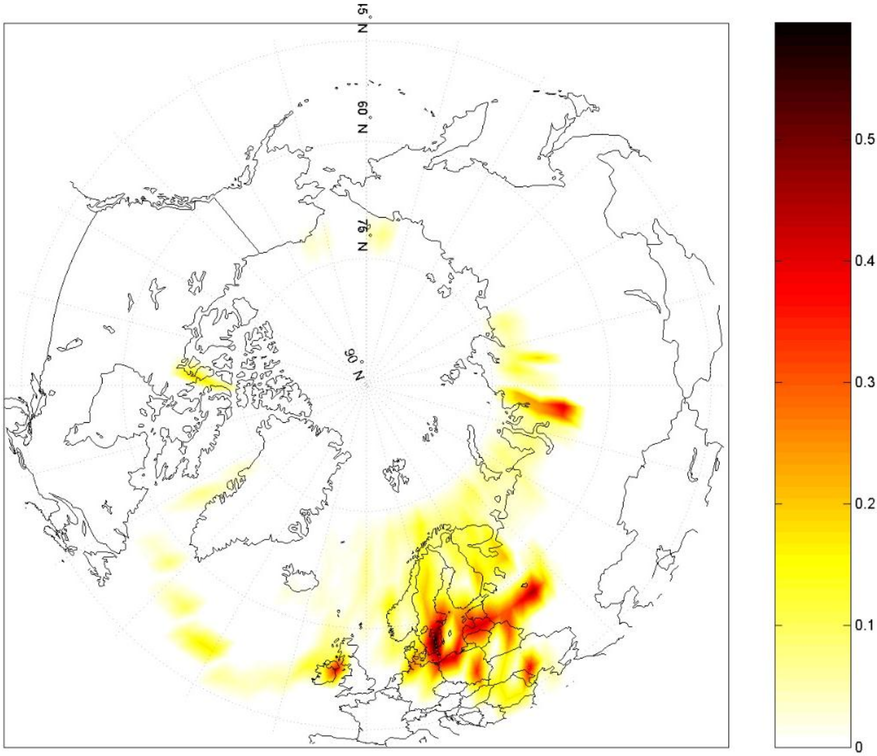


Figure 21 Relative probability for contribution to Arctic BC, observed at Zeppelin station. BC source regions determined by a PSCF model and BC measurements at Zeppelin station during summer months (May to October), 2001-2007. Figure from Kostas Eleftheriadis.

Atmospheric pollutants released by human activities in mid-latitude industrialized regions of the northern hemisphere are quickly moved over long distances by atmospheric transport mechanisms. Of particular interest is the transport of these pollutants to Arctic areas (Figure 21), where they can influence the radiative budget and climate by various ways (Warneke *et al.*, 2009). Inter-continental pollution transport has also become of increased concern due to its potential influence on regional air quality. The impact and influence of China and its polluted megacities on Arctic and boreal areas is one of the key topics. To understand the atmospheric transport the station network coupled with regional and chemical transport models and remote sensing is needed.

The main pollution transport pathways differ qualitatively between North Asia (including Siberia), western Europe and North America. Model simulations show that European pollutants are predominantly dispersed eastwards over Siberia in summer, or north-eastwards towards Siberia and the Artic in winter (Stohl and Eckhardt, 2004; Wild *et al.*, 2004; Duncan and Bey, 2004). Emissions from Europe remain mostly below 3000 m during transport eastwards, and model studies undertaken as part of the task force on hemispheric transport of atmospheric pollutants (TF-HTAP), under the auspices of the convention on long-range transport of air pollutants (CLRTAP), have shown that European pollution is a major contributor to background pollutant levels over Asia (*e.g.* Fiore *et al.*, 2009).

While pollutant export from North America and Asia has been characterized by intensive field campaigns (Fehsenfeld *et al.*, 2006; Singh *et al.*, 2006), the export and long-range transport of European pollution across Siberia has received very little attention. Satellites provide information about spatial distributions, but satellite retrievals often have low sensitivity in the lower troposphere (Pommier *et al.*, 2010), making the validation against *in-situ* observations imperative. In addition, emissions from forest fires (van der Werf *et al.*, 2006) and from agricultural fires in southern Siberia, Kazakhstan and Ukraine (Korontzi *et al.*, 2006) in spring and summer are large sources of trace gases such as CO (Nédélec *et al.*, 2005), as well as aerosols. These can have a significant impact on the chemical composition of the atmosphere over Siberia, and more generally on the CO budget of the northern hemisphere (Wotawa *et al.*, 2001).

3.4.2 Urban air quality, megacities and boundary layer characteristics

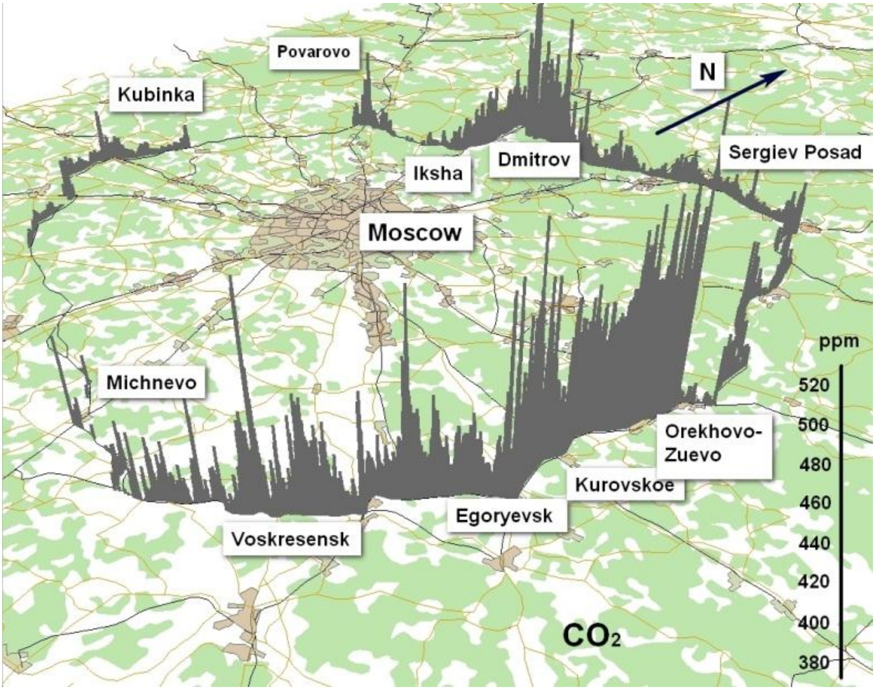


Figure 22 Example of CO_2 concentrations in the Moscow megacity surroundings. Figure from Nikolay Elansky.

SYNOPSIS PEEX urban environments are mainly characterized by cities in Russia and China with heavy anthropogenic emissions from local industry, traffic and housing, and by the megacity regions like the ones of Moscow and Beijing with alarming air quality levels (Figure 22). Bad air quality has serious health effects, and also damages ecosystems. Furthermore, atmospheric pollutants and oxidants (SO_2, O_3, NO_X, BC, sulfate, secondary organic aerosols) play a central role in climate change dynamics via their direct and indirect effects on global albedo and radiative transfer.

Q-5 What are the key feedbacks between air quality and climate at northern high latitudes and in China?

Climate-relevant major national emission sources in the different Pan-Eurasian regions are important objects for assessment, with special emphases on Arctic pollution sources such as diesel stations, gas flares, and shipping.

Russian region

Among all Russian and European cities, urban air quality in several Siberian cities (*e.g.* Norilsk, Barnaul and Novokuznetsk) is especially alarming. In Siberian cities, the air quality is strongly linked to climatic conditions typical for Siberia. Stable atmospheric stratification and temperature inversions are predominant weather patterns for more than half of the year. This contributes to the accumulation of different pollutants in the low layers of the atmosphere, and thus increases their impact on ecosystems and humans. In addition to the severe climatic conditions, man-made impacts on the environment in industrial areas and large cities continue to increase.

The main atmospheric pollution sources in Siberia can be divided into anthropogenic (industrial, transport, combustion, *etc*.) and natural (biogenic emissions, wild fires, dust storms, sea aerosols, volcano eruptions, pollen emission, *etc*.) sources, and further characterized by different pollutant types, characteristics and time dynamics, including local, regional, and outside sources, and accidental releases. The main pollutants can be divided into toxic, climate-affecting and ecosystem-damaging gases and aerosols. The main acidifying compounds in atmospheric deposition are SO_2, sulfate (SO_4^{2-}) and NO_X. Sulfur dioxide emissions in land areas are mainly associated with point sources such as power plants, pulp and paper industry, non-ferrous metal smelters, and oil and gas processing. Oil and gas production involves the emission of exhaust gases containing CO_2, NO_X, SO_X and volatile organic compounds (VOC). Actually all these pollutants are interlinked and the whole system is very non-linear.

China region

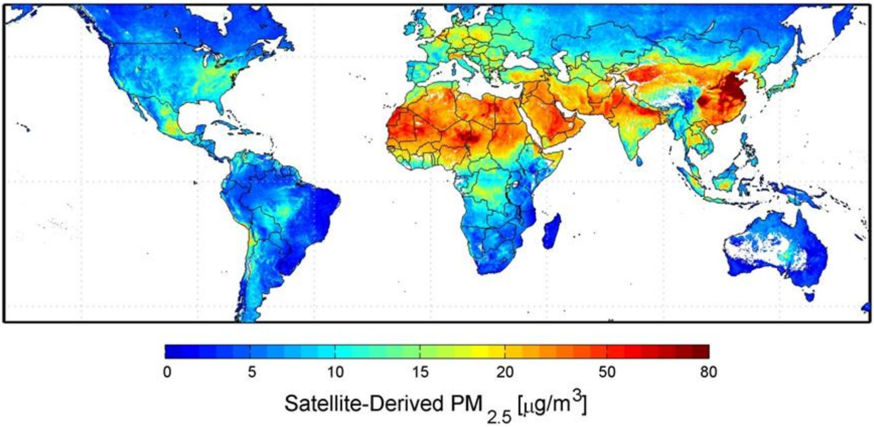


Figure 23 Global distribution of PM2.5 (van Donkelaar et al., 2010).

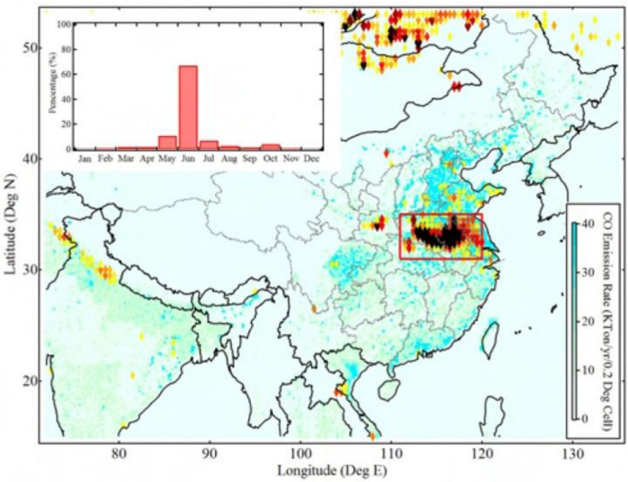


Figure 24 Map showing the anthropogenic emission inventory of CO (Zhang et al., 2009) and averaged active fire data during 2002-2012 over Asia, based on Modis collection 5 active fire product. The upper left corner shows the seasonal variation of the monthly percentage of active fires during the 11 year period. Note: the color (from yellow to black) and size of rhombuses represent the intensity of fires per grid (Ding et al., 2013b).

Asia is currently one of the main regions still suffering from heavy air pollution (Figure 23). Air pollution in monsoon Asia has two main characteristics. First, the total pollutant emission rate from fossil fuel (FF) combustion sources is very high, leading to a high concentration of primary and secondary pollutants in Asia, especially in eastern China and northern India. Observations show that Asia is the only region where the emissions of key pollutants, such as NO_X (Ritcher *et al.*, 2005) and O_3 (Ding *et al.*, 2008; Wang *et al.*, 2009) are still increasing. Second, in addition to the anthropogenic FF combustion pollutants, monsoon Asia is also influenced by intensive pollution from seasonal biomass burning and dust storms. For example, intensive forest burning activities often take place in south Asia in spring and in Siberia in summer, and intensive man-made burning of agricultural straw take place in the north and east China plains in June (Figure 24). Dust storms frequently occur in the Taklimakan and Gobi deserts in northwest China, and the dust is often transported over eastern China, southern China, the Pacific Ocean and even the entire globe (Nie *et al.*, 2014). These biomass burning or mineral dust aerosols have been found to cause complex interactions in the climate system, after they are mixed with the anthropogenic pollutants (Ding *et al.*, 2013; Nie *et al.*, 2014).

China's air pollution in 2013 was at its worst for some 52 years, with 13 provinces hitting record-high levels of air pollution, according to the ministry of environmental protection. Nearly half of China has been hit by smog, with the south eastern regions experiencing severe conditions. Increasingly many cities are now monitoring air quality in real time using meteorological towers and remote sensing from satellites to track pollutants. In Beijing, concentrations of fine particles in the atmosphere have been found to be more than 10 times the safe level recommended by the WHO. This has prompted authorities to take measures such as limiting industrial emissions and reducing traffic across the nation. In these cities, the haze is also so thick that it often blocks out the sun in winter, reducing natural light and warmth significantly. As a result, local temperatures drop, households use more energy for heating, and pollution gets worse, causing respiratory diseases and eventually the hospitalization of even more people. The country's five-year action plan has provisions to improve environmental technology, planning and regulation. The plan aims at reducing heavy pollution by a large margin, and at improving air quality in the Beijing-Tianjin-Hebei province, the Yangtze River Delta and the Pearl River Delta.

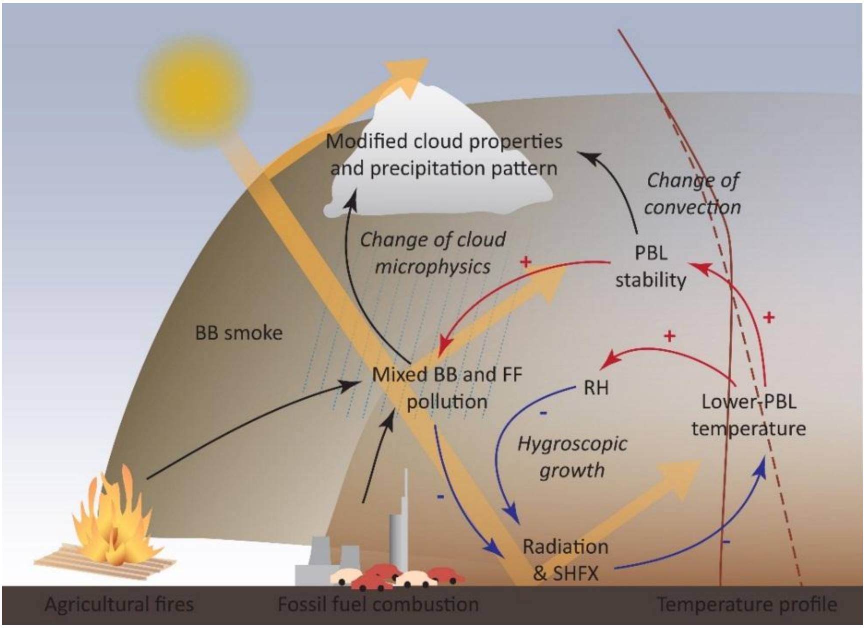


Figure 25 Schematic figure of the interactions of air pollution, planetary boundary layer dynamics, aerosols, radiation and cloud properties under a mixture of agricultural burning plumes and fossil fuel combustion pollutants (Ding et al., 2013b).

The worst air pollution episodes were mostly associated with stagnant weather conditions and a lower planetary boundary layer (PBL), which promotes the accumulation of intensively emitted pollutants at the ground surface. However, studies (*e.g.* Ding *et al.*, 2013b) show that the lower planetary boundary layer also is a result of the heavy pollution through its direct or indirect effects on solar radiation and hence the surface sensible heat flux. The boundary layer - air pollution feedback will further decrease the height of the PBL, and result in a more polluted PBL (Ding *et al.*, 2013b; Wang *et al.*, 2014). Therefore, considering the complex land surface types (city clusters surrounded by agriculture areas) and pollution sources (FF, BB and dust *etc.*) in the China PEEX domain, improving our understanding of this feedback is very important for the forecasting of extreme air pollution episodes (Figure 25). It is also important for long-term policy making. To understand this topic, more vertical measurements using aircraft, balloons and remote sensing techniques, as well as advanced numerical models including all relevant processes and their couplings, are needed.

3.4.3 Weather and atmospheric circulation

Figure 26 The atmospheric dynamics in the Arctic-boreal region are undergoing major changes. Photo from Ella-Maria Kyrö.

SYNOPSIS Changes in atmospheric dynamics taking place in the Arctic and boreal regions (Figure 26) have severe impacts on (i) short-term predictions of physical conditions in the domain, and also beyond the domain due to non-linear multi-scale interactions in the atmosphere and closely coupled sub-systems, and on (ii) long-term predictions and projections concerning the bio-geochemical systems in the domain, and world-wide.

Q-6 How will atmospheric dynamics (synoptic scale weather, boundary layer) change in the Arctic-boreal regions?

Planetary and synoptic scale weather

The driving motivation for better predictions and understanding of high impact weather is to mitigate economic and human losses from weather-related natural hazards. The key issues here are the reliability of weather forecasts, and the extension of the time-range of useful forecasts. In Europe, this range is currently on average about 8−9 days, which allows reliable early warnings to be issued for weather related hazards, such as wind storms and extreme precipitation events with flash floods. The time-range of useful forecasts has typically increased by a day per decade over the past three decades (Uppala *et al.*, 2005). The aim of PEEX in this topic is to enhance the scientific and technical basis for maintaining and developing these capabilities across the study domain. The challenges are related to the ongoing environmental change and its impact on the occurrence and predictability of weather.

Skill in predicting weather-related natural hazards can be attributed to all components of numerical forecasting systems: formulation of the prediction model, exploitation of observations, and probabilistic aspects of forecasting. Improving forecast skill calls for a balanced research program to cover all these aspects. Improvements in prediction model formulation include issues such as more accurate numerical methods to solve the underlying set of thermo-dynamic equations, and improved parameterizations of sub-grid scale processes. PEEX provides a unique opportunity to better understand and quantify near-surface physical and bio-geochemical processes, and thus improve the scientific basis for model development.

Weather prediction is predominantly an initial value problem, and the initial state for the prediction model is generated by data assimilation of observational information into the model initial state. Volumes of observational data used daily in operational numerical weather prediction centers are staggering: some 50-100 million individual measurements from all possible *in-situ* and remote sensing instruments world-wide are transmitted and used in near-real time. Observation modeling ("virtual instrumentation") is a cornerstone in utilizing all these measurements in data assimilation. For PEEX, this poses a special challenge. It is crucial that observational data generated in the region are transmitted without delay to the global telecommunication system for use in operations. This should be supported by activities directed towards a better understanding of the measurements by observation modeling.

Probabilistic aspects of forecasting address the fact that proper risk assessment of hazardous events cannot be based on a single forecast. It has to be accompanied by some probability of the event, so that users can decide the risk they are prepared to take, depending on how likely they are going to be affected by the event, and act accordingly (Palmer and Slingo, 2011). The development of more accurate prediction tools supports more accurate data assimilation and probabilistic forecasting. This, in turn, enables better characterization of uncertainties, benefitting the users of the forecast products, and also, in return, accelerating model development as uncertainties are better known.

The ongoing environmental change and its amplification in the PEEX domain pose special challenges to the prediction of weather-related hazards, and also longer-term impacts. This line of thinking can be illustrated by considering the recent changes in the Arctic sea-ice. First, they have been much more rapid than models and scientists anticipated about ten years ago. Second, the sea-ice changes have no doubt impacted the weather conditions in the northern European region. For instance, increased winter-time snowfall in Scandinavia during 2010-2013 can be partly attributed to the thermal forcing of the increasingly open sea surface in the Arctic Ocean, and its impact on atmospheric circulation upstream in the Atlantic sector. This mechanism alters movements of weather patterns, and undermines preparedness to natural hazards based on past experience. It is thus vital to enhance routine observations, data assimilation techniques, and prediction models in order to properly monitor the physical state of the environment. Longer-term impacts of the reduced ice cover are largely unknown, because the scientific community has had only little time to create new knowledge on essential climate variables across the domain. To improve preparedness, new observational evidence is thus needed to reduce uncertainties in the system dynamics both on short and longer time-scales.

Near-surface weather

The main impacts of weather-related natural hazards are felt due to near-surface weather, which is particularly sensitive to conditions in the lower boundary layer and surface, such as soil temperature and moisture. The ongoing global change affects surface conditions in the Arctic-boreal region, and this is naturally linked to changes in atmospheric circulation.

For better predictions of hazardous near-surface weather, awareness of these important linkages and how they are implemented in prediction models is needed. In the development of prediction models, the surface-atmosphere coupling is mainly built into the physical parameterizations. These need to be continuously improved and optimized for high-resolution models. Boundary layer processes are particularly important, especially in stable conditions, and the representation of boundary layer clouds, and their further coupling to convection, remains an important research topic. Refined models also need improved data assimilation systems. Linking model improvements into data assimilation of cloud and precipitation is largely an open question, which calls for further research. With higher resolution modeling, the surface conditions (land use type, fraction of water, vegetation state, snow cover, *etc*.) Become very important. Investigations on how to consistently couple surface and upper-level data assimilation and modeling remain high-priority research issues. In summary, PEEX can offer unique new knowledge on near-surface conditions in the study domain. The research community needs to respond by a development effort to improve the predictive skill and power concerning near-surface weather parameters, on time-scales from daily and weekly to seasonal, annual and beyond.

Boundary layer dynamics

Most of the land-atmosphere-ocean processes take place in the lowest part of the troposphere, in the planetary boundary layer (PBL). Quantification of the behavior of the PBL over the Pan-Eurasian region is needed in the analysis of the spatial and temporal distribution of surface fluxes, in predictions of microclimate and extreme weather events, and in the modeling of clouds and air quality.

Shallow, stably-stratified PBLs are typical in northern Scandinavia and Siberia, especially in winter, and are extremely sensitive even to weak perturbations.

Atmospheric planetary boundary layers (PBLs) are strongly turbulent layers immediately affected by dynamic, thermal and other interactions with the Earth's surface. PBLs are subject to diurnal variations, absorb surface emissions, control microclimate, air pollution, extreme colds and heat waves, and are sensitive to human impacts. Very stable stratification in the atmosphere above the PBL prevents compounds produced by surface fluxes or emissions from efficiently penetrating from the PBL into the free atmosphere. Therefore, the PBL height and turbulent fluxes through the PBL upper boundary control local features of climate and extreme weather events (*e.g.*, heat waves associated with convection, or strongly stable stratification events triggering air pollution). This concept (equally relevant to the hydrosphere) illustrates the challenge and importance of modeling and monitoring the PBL height.

The PBL height varies from dozens to thousands of meters. The PBL also controls the dispersion and transport of atmospheric admixtures, as well as extreme cold and heat periods (Zilitinkevich, 1991; Zilitinkevich *et al.*, 2007; Zilitinkevich and Esau, 2009). A comprehensive inventory of the planetary boundary layer (PBL) height over Eurasia will be carried out under PEEX, as the PBL is the layer where most of the basic observations will be performed, and also contains the weather the human population is exposed to.

Shallow, stably stratified PBLs, typical of winter time in northern Scandinavia and Siberia, are especially sensitive to even weak changes. They therefore deserve particular attention, especially in conditions of environmental and climate change (Zilitinkevich and Esau, 2009). Unstably stratified PBLs interact with the free atmosphere mainly through turbulent ventilation at the PBL upper boundary (Zilitinkevich, 2012). This mechanism, still insufficiently understood and poorly modeled, controls the development of convective clouds, dispersion and the deposition of aerosols and gases, which are essential features of hot waves and other extreme weather events.

The traditional view of the atmosphere-earth interaction as fully characterized by the surface fluxes is incompatible with the modern concept of a multi-scale climate system, where PBLs couple the geospheres, and regulate local features of the climate. In this context the PBL height and the turbulent fluxes at the PBL upper boundary play important roles. Good knowledge of global atmosphere-earth interactions requires investigation, observation and monitoring of all these parameters.

Upper atmosphere

The development of diagnostic and modeling methods for aero-electric structures is important for a study of both convective and electric processes in the lower troposphere (Shatalina *et al.*, 2005; 2007). Convection in the PBL leads to the formation of aero-electric structures, manifested in ground-based measurements as short-period electric-field pulsations with periods from several to several hundreds of seconds (Anisimov *et al.*, 1999; 2002). The sizes of such structures are determined by the characteristic variation scales of aerodynamic and electrodynamics parameters of the atmosphere, including the PBL and surface-layer height, as well as the inhomogeneities of the ground (water) surface. Formed as a result of convective processes and the capture of positive and negative charged particles (both ions and aerosols) by convective elements (cells), aero-electric structures move with the air flow along the Earth's surface. The further evolution of convective cells results, in particular, in cloud formation.

The global electric circuit (GEC) is an important factor connecting solar activity and upper atmospheric processes with the Earth’s environment, including the biosphere and the climate. Thunderstorm activity maintains this circuit, whose appearance is dependent on atmospheric conductance variations over a wide altitude range. The anthropogenic impact on the GEC through aviation, forest fires and electromagnetic pollution has been noted with great concern, and the importance of lightning activity in climate processes has been recognized. The GEC forms due to two reasons: the continuous operation of ionization sources, which provide an exponential growth of conductivity in the lower atmosphere, and the continuous operation of thunderstorm generators, providing a high rate of electrical energy generation and dissipation in the troposphere. Therefore, the

GEC is influenced by both geophysical and meteorological factors, and can serve as a convenient framework for the analysis of possible inter-connections between atmospheric electrical phenomena and climate processes. Further exploration of the GEC as a diagnostic tool for climate studies requires accurate modeling of the GEC stationary state and its dynamics. Special attention should be paid to the observations and modeling of generators (thunderstorms, electrified shower clouds, mesoscale convective systems) in the global circuit.

3.5 ARCTIC-BOREAL AQUATIC SYSTEM – KEY TOPICS

3.5.1 The Arctic Ocean in the climate system

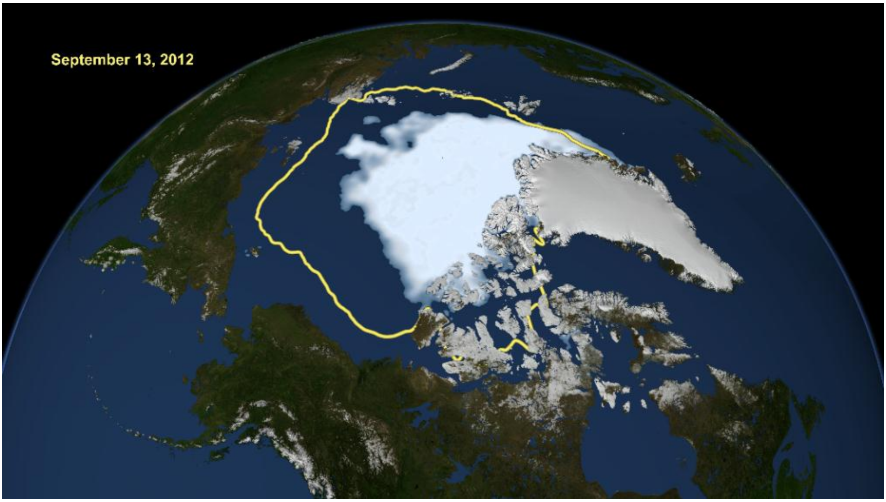


Figure 27 Record minimum in the Arctic sea ice in 2012. (NASA/Goddard Space Flight Center Scientific Visualization Studio. The Blue Marble data is courtesy of Reto Stockli (NASA/GSFC).

SYNOPSIS The Arctic Ocean plays an important role in the climate system. The essential processes related to the interaction between the ocean and the other components of the Earth system include the air-sea exchange of momentum, heat, and matter (*e.g.* moisture, CO_2, and CH_4), and the dynamics and thermodynamics of sea ice. the major issues to be studied are (i) the role of the ocean in the Arctic amplification of climate change, (ii) reasons for the Arctic sea ice decline, (iii) greenhouse gas exchange between ocean and atmosphere, and (iv) various effects that the sea ice decline have on the ocean, surrounding continents and aerosol budgets.

Q-7 How will the extent and thickness of the Arctic sea ice and the terrestrial snow cover change?

The Arctic Ocean occupies a roughly circular basin, and covers an area of about 14,056,000 km^2. The oceanographic changes in the Arctic seas – sea ice coverage, Arctic water currents and masses – are teleconnected to the global climate and weather dynamics. The Arctic Ocean can influence mid-latitude weather and climate. The warmer and moister atmosphere of the ice-free Arctic during autumn has been associated with enhanced autumn snow cover in Asia (Park *et al.*, 2013).

Many of the processes considered responsible for the Arctic amplification of climate warming are related to the ocean. Among these, the snow/ice albedo feedback has received the most attention (*e.g.* Flanner *et al.*, 2011). The feedback is largest when sea ice is replaced by open water, but the feedback starts to play a significant role already in spring, when the snow melt on top of sea ice starts. This is because of the large albedo difference between dry snow (albedo about 0.85) and wet, melting, bare ice (albedo about 0.40). More work is needed to quantitatively understand the reduction of snow/ice albedo during the melting season, including the effects of melt ponds and pollutants in the snow. Other amplification mechanisms related to the ocean include the increased fall-winter energy loss from the ocean (Screen and Simmonds, 2010). Furthermore, the melting of sea ice strongly affects (a) evaporation, and hence the water vapor and cloud radiative feedbacks (Sedlar *et al.*, 2011), and (b) the PBL thickness, which controls the sensitivity of the air temperature to heat input into the PBL (Esau and Zilitinkevich, 2010). The relative importance of the mechanisms affecting the Arctic amplification of climate warming are not well known, but will be studied in PEEX.

The rapid decline of Arctic sea ice cover (Figure 27) has tremendous effects on navigation and exploration of natural resources. To be able to predict the future evolution of the sea ice cover, the first priority is to better understand the reasons behind the past and ongoing sea ice evolution. Several processes have contributed to the decline of Arctic sea ice cover, but the role of these processes needs better quantification. PEEX will conduct further studies on the impacts of changes in cloud cover and radiative forcing (Kay *et al.*, 2008), atmospheric heat transport (Ogi *et al.*, 2010) and oceanic heat transport (Woodgate *et al.*, 2010). In addition, as the ice thickness has decreased, the sea ice cover becomes increasingly sensitive to the ice-albedo feedback (Perovich *et al.*, 2008). Other issues calling for more attention include the reasons for the earlier onset of the spring melt (Maksimovich and Vihma, 2012), the changes in the phase of precipitation (Screen and Simmonds, 2011), and the large-scale interaction of sea ice extent, sea surface temperature distribution and atmospheric dynamics (cyclogenesis, cyclolysis and cyclone tracks).

In addition to thermodynamic processes, another factor affecting the sea ice cover in the Arctic is the drift of sea ice. The momentum flux from the atmosphere to the ice is the main driver of sea-ice drift, which is poorly represented in climate models (Rampal *et al.*, 2011). This currently hinders a realistic representation of sea-ice drift patterns in large-scale climate models. Furthermore, the progressively thinning ice pack is becoming increasingly sensitive to wind forcing (Vihma *et al.*, 2012). PEEX will address the main processes that determine the momentum transfer from the atmosphere to the sea ice, including the effects of atmospheric stratification and sea ice roughness.

To better understand the links between the Arctic Ocean and terrestrial Eurasia, there is particular need in PEEX to study the effects of Arctic sea ice decline on Eurasian weather and climate. Several recent studies suggest that the strong sea ice decline in the Arctic has been favoring cold, snow-rich winters in Eurasia (Honda *et al.*, 2009; Petoukhov and Semenov, 2010). Some studies have also suggested a link between the sea ice decline and increased autumn snowfall in Siberia, which also tends to favor hard winters (Cohen *et al.*, 2012).

Another poorly studied problem related to the Arctic Ocean is the role of sea ice as a source of aerosol precursors, and in gas exchange between the ocean and the atmosphere. Preliminary results of field studies at the drifting "North Pole" station (Makshtas *et al.*, 2011) showed that the shrinking sea ice cover could be the reason for increasing CO_2 uptake from the atmosphere in the annual cycle, and for the growth of the seasonal amplitude of CO_2 concentrations in the Arctic.

Climate models project that air temperatures and precipitation will increase over the Arctic Ocean, this may also have important effects on the structure of sea ice. Increased snow load on a thinner ice tends to cause ocean flooding, which results in the formation of snow ice. Increased snow melt and rain, on the other hand, results in increased percolation of water to the snow-ice interface, where it refreezes, forming super-imposed ice (Cheng *et al.*, 2006). Snow ice and super-imposed ice have granular structures, and differ thermodynamically and mechanically from the sea ice that currently prevails in the Arctic.

The changes in the Arctic Ocean have also opened some, albeit limited, possibilities for seasonal prediction. These are mostly related to the large heat capacity of the ocean: if there is little sea ice in the late summer and early autumn, this tends to cause large heat and moisture fluxes to the atmosphere, favoring warm, cloudy weather in late autumn and early winter (Stroeve *et al.*, 2012). On the other hand, the reduction of sea ice thickness may decrease the possibilities for seasonal forecasting of ice conditions in the most favorable navigation season in late summer - early autumn. This is because thin ice is very sensitive to unpredictable anomalies in atmospheric forcing. For example, in August 2012 a single storm caused a reduction of the sea ice extent by approximately 1 million km^2.

3.5.2 Arctic marine ecosystem

Figure 28 Arctic sea ice north of Svalbard. Photo Ella-Maria Kyrö.

SYNOPSIS The ice cover of the Arctic Ocean (Figure 28) is undergoing fast changes, including a decline of summer ice extent and ice thickness. This results in a significant increase of the ice-free sea surface in the vegetation season, and an increase in the duration of the season itself. This could result in a pronounced growth of the annual gross primary production (GPP) and phytoplankton biomass. Higher GPP may in turn cause (i) an increase in CO_2 fluxes from the atmosphere to the ocean and (ii) an increase in the overall biological production including the production of higher trophic level organisms and fish populations. An increase in surface water temperature may "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 to an increase in the amount of fresh water and allochthonous materials annually delivered to the artic shelves, and further to the Arctic Basin. All these processes may impact the Arctic marine ecosystems and their productivity, as well as key biogeochemical cycles in the region. One of the most important potential changes in the marine Arctic ecosystems is related to the progressive increase of the anthropogenic impacts of oil and natural gas drilling and transportation over the shelf areas, via the long-term backwash effect.

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 ice cover of the Arctic Ocean is undergoing fast changes, including the decline of summer ice extent and ice thickness. Since the late 1970s and early 1980s, the Arctic summer ice sheet has diminished by around 3.0-3.5 million km^2 (National Snow and Ice Data Center, USA). In September 2012, 40 % of the central Arctic basin was open water. In august of 2007 and 2012 (the warmest years of the past decade in the Arctic), the Kara Sea South border of the permanent ice covered area – one of the key Arctic areas – was found some 700-750 km to the north from its mean position during the 1970-2000 period. This is equal to the distance from Moscow to St. Petersburg. Theoretically, the appearance of new ice-free areas should result in a pronounced growth of the annual gross primary production (GPP) and phytoplankton biomass in these areas. Another concern is a loss of ice-rich algae communities, associated with the low ice sheet surface (Bluhm *et al.*, 2011). The input of these communities to the GPP, primary producer biomass, CO_2 consumption/flux and biomass sedimentation may be comparable to (or even exceed) that of the plankton algae which we expect to bloom in ice-free areas.

Another problem is related to the increase (by 1 to 2 months) of the ice-free season in areas which were normally free of ice even before the pronounced climate signal was seen in the Arctic. These areas are mostly the Arctic margin seas. It does not seem probable that these areas will exhibit high volumes of additional GPP, because of strong nutrient limitations after the end of the spring bloom, and because of the low activity of bacterioplankton (slow nutrient regeneration) due to low temperatures (Makkaveev *et al.*, 2010; Sazhin *et al.*, 2010). High GPP in the second part of the vegetation season may be found only in the (quite limited) areas impacted by riverine inflow in the Arctic, or in areas of active vertical water transport (Sergeeva, 2013). Some of these areas we know (Hill and Cota 2005; Sergeeva, 3013), but most remain unknown. It is thus evident that the estimates of CO_2 fluxes, and the role of the Arctic as a possible CO_2 sink in the context of climate change, have significant uncertainties.

The third important question is how the climatically induced increase in GPP and phytoplankton biomass influences the productivity of higher trophic levels of the Arctic ecosystem, including populations of interest to humans. If we consider typical Arctic ecosystems (excluding the Barents Sea as it is mainly influenced by the Atlantic) we found that the most important primary consumers are large-sized herbivorous copepods, which have lifecycles synchronized with the seasonal algae bloom (Kosobokova, 2012). Populations of these copepods leave the upper productive layers of the water column in the middle of vegetation season or a little bit later, and descend deeper. Currently, we are now aware of a mechanism by which a small increase in the amount of available food in the second part of vegetation season could significantly influence this key component of the pelagic ecosystem. Another important component of the consumer community is the small-sized herbivorous copepods, which are important especially in shelf ecosystems. Theoretically, an increase in the available phytoplankton production in fall, together with an increase in the sea temperature, may influence the populations of small-sized copepods, and increase their role in mass and energy flow in the ecosystems. Unfortunately, current understanding of the role of small copepods in the Arctic ecosystems is limited (Arashkevich *et al.*, 2010).

Increases in Artic sea temperature may possibly lead to alien populations from neighboring regions penetrating the Arctic ecosystem, forming rich regional populations, and changing the structure and functioning of native ecosystems. Recently, we observed an example of this: the Alaskan pollock in the western Arctic. A regime shift, including a 1.50 °C water temperature increase, occurred in the Bering Sea in the mid-1970s. This allowed the pollock to penetrate the Arctic ecosystem, and occupy a place as a key-stone species for several years, supporting one of the world largest regional fish harvests (Shuntov *et al.*, 2007). The Bering Sea ecosystem is very rich compared to the Arctic ecosystems.

Currently, we are not aware of food sources sufficient for supporting massive invader populations even in case of climate-induced changes in the ecosystem. However, the appearance of aggressive alien species even in low numbers may dramatically impact the sensitive Arctic ecosystem. In any case, the problem is very important, and also related to the regulation of international fisheries regulation in the Arctic under future ecosystem changes.

Climate warming in the Arctic and adjacent boreal areas will change riverine discharge to the Arctic shelves. This will increase the impact of climate warming on the Arctic marine ecosystems. Degradation of permafrost, soil erosion, changes in snow cover and summer precipitation may all lead to changes in flood timing, and also to an increase in the amount of fresh water and allochthonous materials, including organic matter and nutrients, annually delivered to the artic shelves, and further to the Arctic basin. Increased anthropogenic activities over the drainage areas, as well as unpredictable anthropogenic catastrophes, will result in the quick delivery of pollutants and other anthropogenic signals to the Arctic via the river streams. We have only recently begun to understand the processes which regulate freshwater-marine ecosystems interactions in estuarine zones (Flint, 2010). The mechanisms which determine the impact of riverine waters over the Arctic shelves and the central deep-basin, and their dependence on specific climatic forces, are also still poorly understood. The estuaries of large Siberian rivers are key places for the location of flagship-stations or permanent observation points in the PEEX program.

The progressive increase of all forms of anthropogenic impacts associated with oil and natural gas drilling and transportation over the Arctic shelf areas is a major reason for concern for marine Arctic ecosystems today and in the future. This concern is related to both economics and climate. The warmer and more open the Arctic Ocean becomes, the more oil- and gas-related activities will occur. Anthropogenic impacts associated with the oil and gas industries will have long-term effects because of the high sensitivity of the Arctic ecosystems. At least one flagship-station or observation point should be located in an Arctic area with a high concentration of oil and gas industry.

The listed problems and processes are of utmost importance for understanding the coming evolution of the Arctic natural system, and the impacts of climate change and increasing anthropogenic activities on the Arctic marine ecosystems. There is a risk of irreversible changes in marine Arctic productivity, key biogeochemical cycles, and the potential for CO_2 absorption by marine ecosystem. Processes involving the Arctic may also affect adjacent boreal areas.

Climate feedbacks between the aquatic and atmospheric systems

The layered, stratified structure of the water column is a key characteristic of all aquatic ecosystem types: marine, brackish and freshwater. This structure originates from the dependence of water density on temperature, and on ions dissolved in the water. Water columns thus become layered according to temperature, as well as according to the concentrations of various chemical compounds. In general, ion concentrations are high in oceans, but low in fresh waters. Acidity (pH) is usually higher in marine environments than for instance in lakes, which in the boreal zone are naturally acidic. The values of pH are important for the inorganic carbon system, since pH determines the relative concentrations of dissolved CO_2, bicarbonates and carbonates. Oxygen, which can originate either from the surface water-atmosphere-gas exchange or from photosynthesis, is utilized in all respiration. Layering is not only important for biological processes, but also greatly affects heat exchange and thus the energy budgets of aquatic ecosystems.

Cyanobacteria and algae synthesize sugars by photosynthesis, utilizing solar energy and inorganic carbon dissolved in the water. All photosynthetic organisms can use CO_2 as a carbon source, but some are adapted to take advantage of dissolved bicarbonates as well. Bicarbonates can be taken up and converted to CO_2 by the carbonic anhydrase enzyme. Low CO_2 concentrations in water can limit photosynthesis in the same way as light and nutrient shortages. Hence, the growth of phytoplankton as well as the so-called biological pump – important in aquatic carbon sequestration in stratified aquatic ecosystems – are negatively affected by low CO_2 levels. Due to its strong dependence on the dissolved carbon source, photosynthesis generates clear temporal as well as spatial – especially vertical – variations in CO_2 concentration in the water. All aquatic life, including large predators such as sharks and orcas, giant plankton feeding whales in oceans, and freshwater seals in lakes, is based on photosynthesis by prokaryotic cyanobacteria or eukaryotic algae, which provides the primary source of material and energy for the ecosystem.

As a result of photosynthesis, algae synthesize a large array of organic compounds, including atmospherically important VOCs. Algae produce large amounts of DMSP, a precursor of DMS known to be an important sulfur-containing compound in atmospheric aerosol formation. Since the intracellular DMSP concentrations in algae vary, it is obvious that DMSP is physiologically as well as ecologically controlled, although the ultimate purpose for its synthesis is still unknown.

The dissolution and evaporation of CO_2 and DMS depend on temperature, with high temperatures enhancing evaporation and slowing down dissolution. The atmospheric CO_2 concentration, and the CO_2 concentration of the air that is in equilibrium with the water CO_2 concentration, determine the evaporation and dissolution rates of CO_2. VOC and DMS molecules evaporate from sea water depending to the temperature, and their concentration in the water. Photosynthesis and the synthesis of VOCs and DMS generate strong temporal and spatial variations in the surface concentrations of climate-relevant compounds in the oceans. These concentrations are the driving forces for the fluxes of compounds between water and the atmosphere.

Examples of research questions: marine ecosystems

How will Arctic sea ice extent, snow cover and permafrost change in a changing climate, and what are their connections to the climate system?

How will climate change influence fresh water and allochthonous materials delivery to marine Arctic through the river inflow, and what are the corresponding impacts on the Arctic marine ecosystems?

What are the effects of Arctic warming and seasonal ice shrink on the Arctic marine ecosystems, mainly on the primary production (the extent of the phytoplankton vegetation season and the corresponding carbon sink) and the productivity of upper trophic level populations including key species?

What are the joint effects of Arctic warming, pollution load and acidification on the Arctic marine ecosystem, mainly on the primary production (algal blooms and the consequent carbon sink through sedimentation)?

3.5.3 Lakes and large-scale river systems

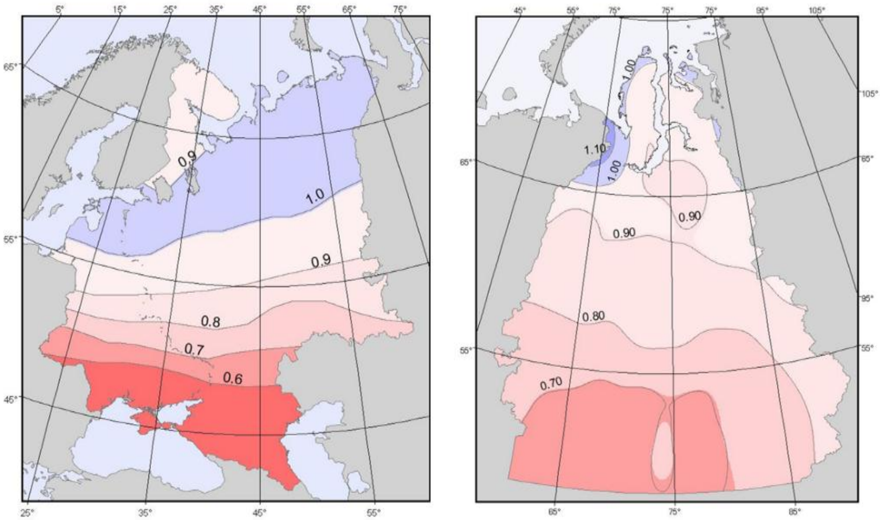


Figure 29 Relative changes (within the area of the East European Plain (left) and Western Siberia (right)) of the annual rivers runoff for the middle of the 21st century (reference volume is the values for current climate). Figures from Kasimov and Kislov, 2011.

SYNOPSIS The gradient in water chemistry from the tundra to the steppe zones in Siberia can provide insight into the potential effects of climate change on water chemistry. In the last century, long-range trans-boundary air pollution has led to changes in the geochemical cycles of S, N, metals and other compounds. Furthermore, northern pan-Eurasian methane originates from random bubbling in disperse locations. Permafrost melting may accelerate emissions of methane from lakes. Furthermore, there is a risk of increasing toxic blooms. In China, pollution and the shortage of water resources has become worse during the last decades. The conservation of water resources has become crucial for society.

Q-9 What is the future role of the 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)?

Water systems and GHG

The enhanced decomposition of soil organic matter may significantly affect the transport of terrestrial carbon to rivers, estuaries and the coastal ocean. The contribution of this process to the global and regional carbon budgets is unknown. The role of aquatic systems as a net sink or source for atmospheric CO_2 is presently under debate. When precipitation or other processes transport large volumes of organic matter from land into nearby lakes and streams, the carbon content of this matter effectively disappears from the carbon budget of the terrestrial ecosystem. Thus, the biological processes taking place in the terrestrial ecosystem (*e.g.* photosynthesis, respiration and decomposition) and in the aquatic ecosystem are interlinked. The higher temperature response of aquatic ecosystems compared to terrestrial ecosystems indicates that a substantial part of the carbon respired or emitted from the aquatic system must be of terrestrial origin (Yvon-Durocher *et al.*, 2012).

The Northern Pan-Eurasian region is characterized by thaw lakes, which comprise 90% of the lakes in the Russian permafrost zone (Romanovskii *et al.*, 2002). The Siberian lakes, which are formed in melting permafrost as the temperatures rise, have long been known to emit methane. The latest observations of the lakes in the permafrost zone of northern Siberia indicate that they are belching out much more methane into the atmosphere than previously thought. Rather than being emitted in a constant stream, 95 % of the methane comes from random bubbling in disperse locations. In coming decades, this could become a more significant factor in global climate change (Walter *et al.*, 2006).

Water systems and pollution

The Siberian lakes situated in tundra and forest-tundra zones are in general poorly studied. In their natural state, their productivity is low, but their ecosystems are highly sensitive to external influences. Profuse blooming of cyanobacteria is usually associated with industrial effluents and nutrient run-off. An assessment is needed of the impact of climate change in the northern pan Eurasian region on increasing water trophicity, accompanied by blooms of cyanobacteria.

The water chemistry in small lakes along a transect from boreal to arid eco-regions in European Russia is determined by a combination of physical, chemical, and biological processes occurring both in the lakes themselves, as well as in their catchment areas. In the last century, long-range trans-boundary air pollution has led to changes in the geochemical cycles of S, N, metals and other compounds in many parts of the world (Schlesinger, 1997; Vitousek *et al.*, 1997a,b; Kvaeven *et al.*, 2001; Skjelkvåle *et al.*, 2001). In the last decade, the combined effects of air pollution and climate warming have received increasing attention (Skjelkvåle and Wright, 1998; Schindler *et al.*, 2001, Alcamo *et al.* 2002, Sanderson *et al.* 2006, Feuchtmayr *et al.*, 2009; Sereda *et al.*, 2011). The water chemistry of small lakes without any direct pollution sources in the catchment area can be expected to reflect regional characteristics of water chemistry, as well as global anthropogenic processes such as climate change and long-range air pollution (Müller *et al.*, 1998; Moiseenko *et al.*, 2001; Battarbee *et al.*, 2005).

The problem of environmental pollution includes as a central component the waterborne spreading of nutrients and pesticides from agricultural areas, heavy metals often originating from mining areas, and other elements and chemicals, such as persistent organic pollutants from urban and industrial areas. Shifts in downstream loads cause changes in the river and delta dynamics. The current ground-based stream flow-gauging network does not provide adequate spatial coverage for many scientific and water management applications, including the verification of the land-surface runoff contribution to the recipients of intra-continental runoff. Special field laboratories, with joint observation and modeling capabilities in hydrometeorology, sedimentology and geochemistry, are needed to understand the spreading of tracers and pollutants as part of current and future global environmental fluxes (see also Figure 29).

One example is the Selenga river basin. The basin is located in the center of Eurasia, extends from Northern Mongolia into southern Siberia (Russia), and has its outlet at Lake Baikal. The Selenga river basin and lake Baikal are located in the upstream part of the Yenisey River system, which discharges into the Arctic Ocean. Lake Baikal has the largest lake volume in the world at about 23000 km^3 (comprising 20 % of all unfrozen freshwater in the world), hosts a unique ecosystem (Granina, 1997), and is an important regional water resource (Garmaev and Khristoforov, 2010; Brunello *et al.*, 2006). There are numerous industries and agricultural activities within the Selenga river basin, which affect the water quality of the lake and its tributaries. Mining is well-developed in the region (*e.g.* Korytnjy *et al.*, 2003; Karpoff and Roscoe, 2005; Byambaa and Todo, 2011), and heavy metals accumulate in biota and in sediments of the Selenga River delta and Lake Baikal (Boyle *et al.*, 1998; Rudneva *et al.*, 2005; Khazheeva *et al.*, 2006).

Water systems of China

In China, the river systems are dominated by rivers flowing from the Tibetan plateau to the Pacific Ocean. Yangtse is the longest river in China, and flows from Tibetan plateau to Shanghai. The Yellow river is the second longest in China, and it is characterized by seasonal flooding which causes great economic and societal loses. The Amur River forms the northern border with Russia. The Haihe River flows through Beijing to Tianjin, and is under heavy stress from the highly populated and industrialized capital metropolitan region. Only one river from China flows to the Arctic Ocean: the Ertix River, which flows to the north through Kazakhstan, across Siberian Russia, finally joining the Ob River which flows to the Arctic Ocean.

Climate and environmental changes during the last decades have caused changes in the distribution of water resources in China. The available water resources from the river system in northern China have decreased, and are expected to deteriorate further, whereas in southern China the available water resources have slightly increased (Mo, 2008). Especially regional flooding and droughts are expected to increase. The situation is not much better in coastal regions, where sea level rise is causing seawater intrusion, soil salinization and coastal erosion. These changes are inhibiting service functions and biodiversity in coastal zones from north to south, and are predicted to continue and become worse in the future.

Water conservation has received increasing attention in China, and multiple new projects have been initiated recently. Especially the construction of water transfer, reservoir and irrigation schemes have received much attention, because central and western regions of China are suffering from water shortages. These projects are expected to improve water usage and security, especially in agricultural activities, and to provide sufficient water resources for local societies (Mu, 2014).

Direct consequences of climatic changes and toxic water blooms

One direct consequence of climate change is the avalanche reproduction of toxigenic cyanobacteria (*Nodularia, Microcystis, Anabaena, Aphanizomenon, Planktonthrix*) and diatoms (*Pseudo-nitzschia*). This occurs in ponds, lakes, reservoirs and bays of the sea. Decay of cyanobacteria (*Nodularia, Microcystis, Anabaena, Aphanizomenon, Planktonthrix*) and diatoms (*Pseudo-nitzschia*) excrete especially dangerous carcinogens and neurotoxins into the water. The toxicity of some cyanotoxins exceeds the toxicity of currently banned warfare agents. Antidotes to these toxins do not exist at the moment.

3.6 SOCIO-ECONOMIC SYSTEM – KEY TOPICS

3.6.1 Natural resources and anthropogenic activities

Land use and land cover changes

SYNOPSIS Siberia is a treasure chest of natural resources for Russia, containing 85 % of its prospected gas reserves, 75 % of its coal reserves and 65 % of its oil reserves. Siberia has more than 75 % of Russia's lignite, 95 % of its lead, approximately 90 % of its molybdenum, platinum, and platinoides, 80 % of its diamonds, 75 % of its gold and 70 % of its nickel and copper. (Korynty, 2009). The industrial development of Siberia should be considered one of most important drivers of future land use and land cover changes in Russian territory. In China anthropogenic activities has focused until now on eastern part of the country where urbanization has been intense, and its natural resources has been heavily utilized. Now the government of China is shifting development focus on the western part of the country where pristine environment is still found. Sustainable development of natural resources utilization in the west is important aspect for the future development of China.

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?

During the 20th century, a considerable transformation of landscapes in the tundra and taiga zones in northern Eurasia has occurred as a result of various industrial, socio-economic and demographic processes, leading to the industrial development of previously untouched territories (Bergen *et al.*, 2013). This has led to a decrease in the rural population and, mostly after the 1990s, to decrases in agricultural activity. There has also been a significant reduction in agricultural land use (in some marginal areas of small-scale or subsistence agriculture by up to 70 %), and its partial replacement by zonal forest ecosystems (Lyuri *et al.*, 2010). As a result, these areas have become active accumulators of atmospheric CO_2 (Kalinina *et al.*, 2009). These new forests ("substituting resources") could form the basis for sustainable development in these regions, if relevant management programs for the forests re-established on abandoned lands are be implemented.

Inventory of Russian forests

The dynamics of major classes of land cover, particularly forests, are documented since 1961, when the results of the first complete inventory of Russian forests were published. According to official statistics, the area of forests in Asian Russia increased by around 80 million ha during 1961-2009 (most of this before the middle of the 1990s). This large increase is explained by (i) improved quality of forest inventories in remote territories, (ii) natural reforestation (mostly during the soviet era as a result of forest fire suppression), and (iii) encroaching forest vegetation in previously non-forested land. Based on official statistics, the area of cultivated agricultural land in the region decreased by around 10 million ha between 1990 and 2009. After the year 2000, the forested area in Siberia decreased, mostly due to fire and the impacts of industrial transformations in high latitudes (Shvidenko and Schepaschenko, 2014). A critical decrease in the forest area has also been observed in the most populated areas with intensive forest harvesting (particularly in the southern part of Siberia and the Far East. For example, in the Krasnoyarsk Krai, the total area of forests decreased by 5 %, while that of mature coniferous forests decreased by 25 %. Overall, the typical processes in these regions are (Shvidenko *et al.*, 2013):

- A dramatic decline in the quality of forests (decrease of the area of conifer forests; substantial reduction in the area of forests of high productivity; the lack of ecological technology and the use of logging machinery leading to the destruction of logged areas; ineffective use of harvested wood, *etc*.);

- Unsustainable use of forest resources in northern regions with undeveloped infrastructure;
- Insufficient governance and forest management in the region – frequent occurrence of illegal logging, natural and human-induced disturbances, *etc*.

Future land use and land cover changes will crucially depend on how successfully the strategy of sustainable development of northern territories is developed and implemented. An effective system for the adaptation of boreal forests to global change needs to be developed and implemented in the region. An "ecologization" of the current practices of industrial development of previously untouched territories would allow for a substantial decrease in the physical destruction of landscapes, and halt the decline of surrounding ecosystems due to air pollution and water and soil contamination.

The expected changes in the climate and environment will have multiple and complicated impacts on ecosystems, with consequent land cover changes. The alteration of fire regimes and the thawing of permafrost will intensify the process of "green desertification" in a large area. Climate warming will have multiple effects on soil-vegetation-snow interactions. For example, in a warmer climate, mosses and other vegetation grow faster, providing better thermal insulation of the permafrost in summer, and better feeding conditions for reindeer. However, snow can also more easily accumulate on thicker vegetation, thus protecting deeper soil from cooling during the winter (Tishkov, 2012).

Both Russia's north and east possess abundant mineral resources (Korytnyi, 2009). The resource orientation of northern and eastern Russia's economy, which has not changed for centuries, increased in the post-Soviet period, and has been influenced primarily by the product market. It is also expected that the natural resource development sector (extraction and exploration of natural resources in the region, including the forest industry in areas with sufficient infrastructure) will continue to dominate the economy in the majority of these territories for the next decades. However, serious socio-ecological problems remain, including a social and ecological conflict between industrial exploitation of natural resources and traditional forms of nature management, such as reindeer herding. It is difficult to mitigate the negative impacts of resource utilization.

Examples of research questions: land use – land cover changes

How will climate change impact future land-use in the high latitudes? How much will this impact the Earth's climate system?

How should the appropriate classes of integrated models be improved in order to describe the specific features of high-latitude regions?

What are the connections between land use, land cover and biomass burning in pan-Eurasia?

What are the regional and global climate and air quality effects of biomass burning in Siberia?

What are the current and future effects of biomass burning / wild forest fires / ship emissions on radiative forcing and atmospheric composition in the Arctic and in Siberia?

Urbanization in China

China has experienced fast urbanization in the past few decades. Because of the rapid increase in population, and also in the fraction of the population working in cities, the number and total area of cities in China has increased dramatically. This development has been especially rapid in the eastern and southern coast areas, such as the Jingjinji-Hebei area, the Yangtze River Delta and the Pearl River Delta. Urbanization has a significant impact on radiation transfer via changes in the surface albedo (Figure 30). Therefore, fast urbanization introduces not only air pollution issues, but also other problems such as the urban heat island effect. Studies have reported very significant urban heat island effects in Chinese cities (*e.g.* Zhou *et al.*, 2004), and other studies show that urbanization may influence precipitation significantly (*e.g.* Wang *et al.*, 2014). In summer, the higher air temperature in cities may also lead to higher electricity consumption for air-conditioners. This may produce more air pollutants and carbon emissions. Also, the urban heat islands increase the probability of heat waves in summer, and may thus have negative effects on human health.

Since China is still undergoing fast development of cities and towns in the next 1-2 decades, urbanization and its impact on regional climate and sustainability is one of the important concerns for the PEEX China domain. It is also important to use present experience from the east in sustainable development of the west.

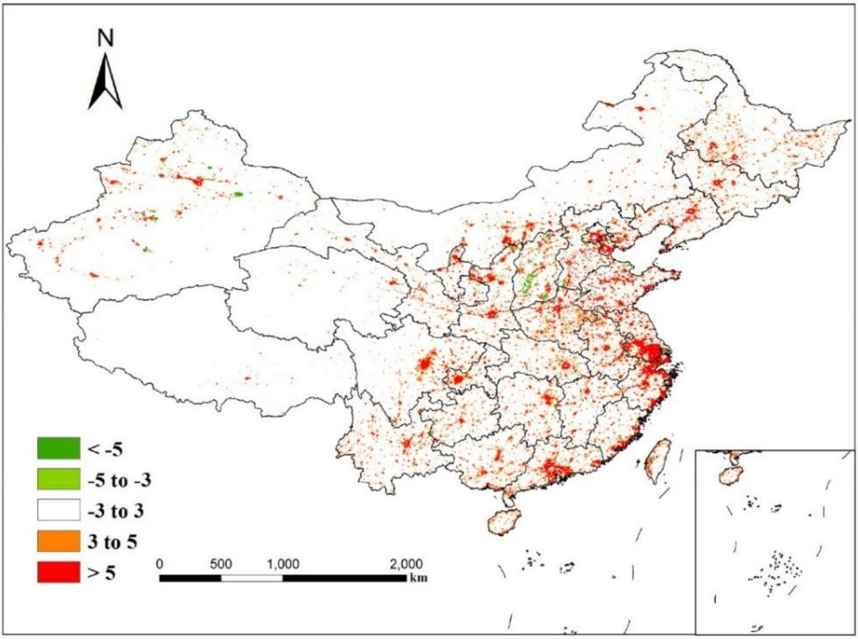


Figure 30 Change in brightness between 1992-1996 and 2008-2012. Note: red colors indicate the development of urban areas in China. Figure from Han et al., 2014.

Energy production

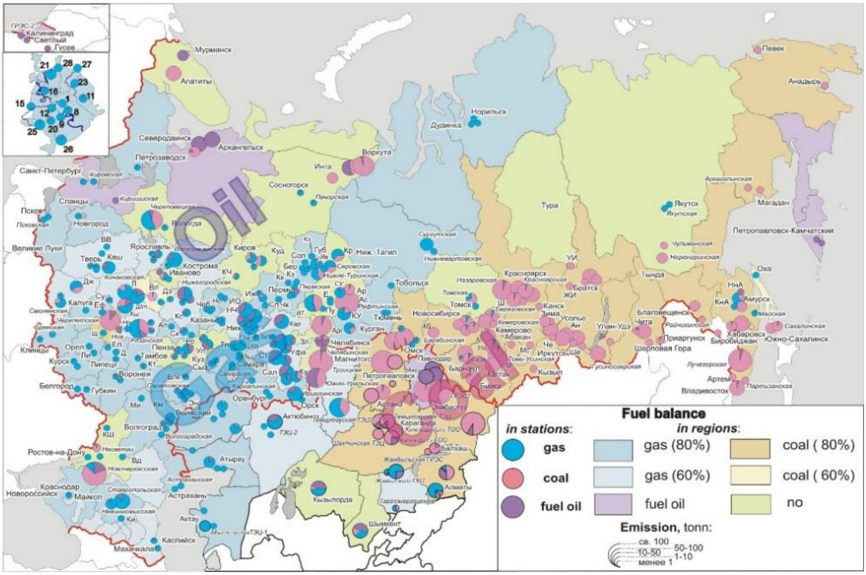


Figure 31 Fuel balance for power generation in Russia. Figure from Bitukova et al., 2010.

In Russia certain features of the fuel balance has led to increased pollution. On average, specific emissions in northern and eastern cities of Russia, where coal accounts for most of the power generation (Figure 31), are 3 times higher than in cities where power is generated mainly from gas or fuel oil. Geographical location, undeveloped infrastructure, harsh climate and coal burning are the main reasons for increased levels of anthropogenic pollution in these areas.

A crucial factor in greenhouse gas emission dynamics from energy production is the fuel balance. In small towns, low-capacity boiler rooms are the main source of emissions. Usually, the lack of financial resources leads to the use of low-quality coal and obsolete boilers. In the steppe zone of Asian Russia, Mongolia, Kazakhstan and Buryatia, the main source of emissions is the burning of harvest residuals.

The dynamics of GHG emissions in Russia are largely determined by the economic conditions of production. The economic crisis in 1990-1998 slowed down environmental degradation: emissions generally decreased by 40 %. However, the underlying environmental problems not only remained unresolved, but significantly deepened, and turned into systemic problems. The most polluting industries were more resistant to the decline in production. Technological degradation took place, cleaning systems were eliminated, and production shifted to part-time, and thus inefficient capacity utilization. Significant amounts of pollution continued to be emitted from the domestic sector. Emissions decreased in most regions of the country, and in 83% of the cities, but much more slowly than production. As a result, the specific emissions (per product cost at comparable prices) had grown by the end of the 1990s in all categories of cities, except cities with more than 1 million inhabitants (Bityukova *et al.*, 2010). All this can cause negative impacts on ecosystems. For example, there are about 2 million ha of technogenic deserts around Norilsk. Norilsk is probably the biggest smelter in the world, and produces more than 2 million tons of pollutants per year (Groisman and Gutman, 2013).

The amount, precise composition and dynamics of emissions are thus largely determined by factors inherited from the period of rapid industrialization, and from projects carried out over 50 years ago. This combination gives rise to large regional sources of emissions in a variety of cities. The fuel balance of energy production and utilities creates a common background contamination, with industrial specialization, and the age and quality of industrial assets, also playing a role. The institutional environment and the policies of regional authorities determine the rate of asset modernization, which runs at different speeds and sometimes even in different directions. Industry is the most dynamic and often the most modernized factor in the regional environmental situation. However, environmental problems are often systemic, because elevated levels of anthropogenic emissions often coincide with regions where also the natural conditions increase pollution. This leads to a high potential for pollution of the atmosphere.

Energy production in China

China remains highly dependent on its coal reserves for domestic energy production. It has been estimated that coal accounts for approximately 85 % of China’s energy reserves. China's annual total energy consumption is approximately 3070 Mtoe (millions of tons of oil equivalent), of which 2050 Mtoe is produced using coal (IEA, 2014). Oil consumption has risen steadily, but is still only around 480 Mtoe. Biofuel and waste production is the third largest energy source at 215 Mtoe. Other energy sources such as gas, hydro and nuclear are still minor forms of production. Because China has limited oil supplies, it has invested in technologies to produce petroleum from other sources, especially from coal via coal-to-liquids production. This dependence on coal is the main reason for the prevalent smog problem in eastern China, as many coal-fired power plants and industrial furnaces are still using old technologies with inadequate filtering techniques. The increased traffic in China's megacities also reduces local air quality. Thus, modernization of local transportation is sorely needed. Modern cleantech solutions are urgently needed in energy production, as well as in transportation, in order to decrease impacts of pollution on society.

3.6.2 Natural hazards

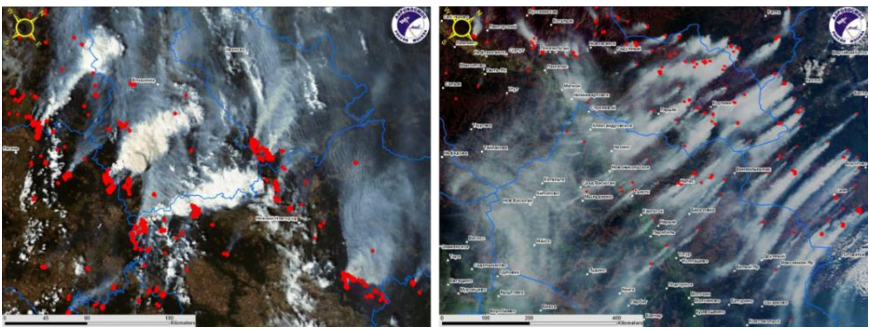


Figure 32 Fires in Central Russia (left) and Siberia and Urals (right). Figures from Valery Bondur / AEROCOSMOS.

SYNOPSIS The frequency and intensity of weather extremes have increased substantially during the last decades in Europe, Russia and China. Further acceleration is expected in the future. The evolving impacts, risks and costs of weather extremes on population, environment, transport and industry have so far not been properly assessed in the Northern latitudes of Eurasia. Important research topics include: analysis and improvements in forecasting of extreme weather conditions/events; examination of the effect of wildfires (Figure 32) on radiative forcing and atmospheric composition in the region; examination of the impacts of weather extremes on major biogeochemical cycles; studying the impacts of disturbances in forests on the emissions of BVOC and VONs (volatile organic nitrogen).

Q-11 How do 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?

The northern Eurasian territory is prone to natural hazards. In the future, the frequency of natural hazards is likely to further increase due to climate change and the consequent transformations in land cover (IPCC, 2007). The number of large hydrometeorological events in Russia that cause substantial economic and social losses has increased by around a factor of 2 times from 2001 to 2011 (state report, 2011). The main hazards are related to atmospheric processes on various temporal and spatial scales: for example strong winds, floods and landslides caused by heavy precipitation, fires caused by drought and extreme temperatures. High temperatures and long droughts can substantially decrease productivity and cause die-backs in dark coniferous forests. Hurricanes occur fairly often in the forest zone. For example, a hurricane destroyed about 78000 ha of forest in the Irkutsk region in July 2004 (Vaschuk and Shvidenko, 2006). However, there are no reliable statistics on many types of natural hazards.

To build scenarios of the future frequency and properties of weather-related hazards, one should first analyze the atmospheric mechanisms behind the circulation structures responsible for these hazards: the cyclones (mostly responsible for relatively rapid hazards such as strong winds and heavy precipitation) and anticyclones (responsible for slow large-scale hazards such as drought and fires). Studying the cyclone/anticyclone tracks, frequency and intensity can provide a statistical basis for understanding the geographical distribution and properties of the major atmospheric hazards and extremes (*e.g.* Shmakin and Popova, 2006). For future climate projections, atmospheric hazards and extremes should be interpreted from the viewpoint of cyclone/anticyclone statistics, and possible changes in the cyclone/anticyclone geography and frequency should be analyzed.

Fires are the most important natural disturbances in the boreal forests. Fires strongly determine the structure, composition and functioning of the forest. Each year, about 0.5−1.5 % of the boreal forest burns. Since boreal forests cover 15 % of the Earth's land surface, this is a significant area (Kasischke, 2000; Conard *et al.*, 2002). Climate change already substantially impacts fire regimes in northern Eurasia. More frequent and severe catastrophic (mega-) fires have become a typical feature of the fire regimes. Such fires envelope areas of up to a hundred thousand hectares within large geographical regions, lead to the degradation of forest ecosystems, decrease the biodiversity, may spread to usually unburned wetlands, cause large economic losses, deteriorate life conditions and health of local populations, and lead to “green desertification” - irreversible transformation of the forest cover for long periods (Shvidenko and Schepaschenko, 2013). Megafires also lead to specific weather conditions over the affected area that are comparable in size with large-scale pressure systems (~30 million ha and more). In 1998-2010, the total burned area in Russian territory is estimated at $8.2 \pm 0.8 \cdot 10^6$ ha; about two thirds of this area consisted of boreal forests. For this period, the fire carbon balance (total amount of carbon in the burnt fuel) is estimated at 121 ± 28 Tg C year^{-1} (Shvidenko *et al.*, 2011). Current model projections suggest that the number of fires will double by end of the century. The extent of catastrophic fires escaping from control and the fire intensity are also projected to increase. Due to deep soil burning, carbon emissions from fires are predicted to increase by a factor of 2 to 4 (Gromtsev, 2002; Malevsky-Malevich *et al.*, 2008; Flanningan *et al.*, 2009; Shvidenko *et al.*, 2011). During and after fires significant changes take place in the forest ecosystem, including the soil. These changes include:

- A significant amount of biomass is combusted, and large amounts of carbon and nitrogen are released to the atmosphere in the form of carbon dioxide, other gases or particles (Harden *et al.*, 2000);
- Fire alters the microbial community structure in the soil, as well as the structure of the vegetation (Dooley and Treseder, 2012);
- Fires determine the structure of the vegetation, succession dynamics and the fragmentation of forest cover, tree species composition, and the productivity of boreal forests (Gewehr *et al.*, 2013)
- Fire is a crucial driver controlling the dynamics of the carbon stock of boreal forests (Jonsson and Wardle, 2010).

Disturbances resulting from fire, pest outbreaks and diseases also have substantial effects on the emissions of BVOCs and volatile organic nitrogen compounds (Isidorov, 2001), and consequently on atmospheric aerosol formation. The acceleration of fire regimes will also affect the amount of black carbon in the atmosphere, and thus has an effect on the albedo of the cryosphere.

The importance of weather extremes for the functioning and survival of northern ecosystems, and their impacts on the environment and populations of the regions, give rise to a large number of research questions within the PEEX research agenda. These include (i) analysis and improvements in forecast of extreme weather conditions/events, (ii) examination of the effect of wildfires on radiative forcing and atmospheric composition in the region, (iii) examination of the impacts of weather extremes on major biogeochemical cycles, (iv) investigation of methods for including extreme effects in Earth system models, and (v) studying the impacts of disturbances in forests on emissions of BVOC and volatile organic nitrogen.

Health issues

In Russia, about 60 % of gross emissions into the atmosphere are emitted from stationary sources, i.e., industry and heating systems for public services. This figure is the most reliable value for emission processes in 1100 Russian cities, with a total population of over 95.4 million. Analyzes of the emission dynamics in Russian cities, which are the main sources of emissions, are extremely important for identifying factors contributing to pollution (Bityukova and Kasimov, 2012).

The quantification of the anthropogenic impacts on air quality, as well as the long-term climate impacts, is one of the research topics in PEEX. The Siberian region contains several major production centers for copper, nickel and other non-ferrous metals: Krasnoyarsk, Murmansk, Orenburg and Bratsk. The environmental impacts of these sites are a reason for great concern. Siberia also contains several large centers with coal-fired power generation, such as Troitsk in the Chelyabinsk region, as well as petrochemical and oil refining industries (Omsk, Angarsk, Ufa), and areas where oil extraction is just commencing (Tomsk region).

Climate change needs to be considered together with other known population health risk factors, including environment pollution, food security problems and the deterioration of drinking water quality. Published studies show that climate change influences human health through both direct and indirect mechanisms. In particular, climate change leads to changes in the borders of vegetation zones (Malkhazova *et al.*, 2012). This can lead to changes in the spreading areas of infectious diseases, and change the general epidemiological situation. These are among the most important indirect health-related consequences of climate change (Malkhazova *et al.*, 2013).

Health and air quality in China

The fraction of the population living in urban areas exceeded 50 % in mainland China for the first time in 2011. The total area of the urban regions also exceeded half of China's total land area (International Eurasian Academy of Sciences IEAS, 2012). China's large-scale and high-speed urbanization and industrialization is unique in history. Therefore, solutions for dealing with the negative impacts of this process do not yet exist. At the present, air pollution is severe in around 20 % of the cities in China, and especially PM2.5 air pollution has become obvious. In China, the prevalent air pollution conditions have been estimated to lead to the premature death of up to 2 million people annually (IHME, 2013; Yang *et al.*, 2013), and to shorten life expectancies on average by 5.5 years (Moller *et al.* 2008). Outdoor-to-indoor transport of air pollutants plays a major role in air quality -related mortality, since people spend more than 90 % of their time indoors (Monn and Becker, 1999; Smith *et al.*, 2000; Ding *et al.*, 2012; Anenberg *et al.*, 2013; Guan *et al.*, 2014).

The largest sources of air pollution in China are domestic and industrial combustion, and industrial processes (Cofala *et al.*, 2007; Schindell *et al.*, 2012). The emissions from the domestic sector in highly populated areas originate mainly from coal combustion, and in rural areas from the combustion of agricultural residues. Industrial emissions are mainly related to the production of bricks, cement, coke and pig iron. In addition to primary aerosol emissions, secondary aerosol formation is also important in determining overall aerosol mass and number concentrations. Thus, the emissions of volatile organic compounds (VOCs), as well as regional tropospheric ozone, play a role in regional air quality. In eastern China, natural aerosol sources such as dust emitted from deserts also play an important role.

Permafrost degradation and infrastructures

The degradation of permafrost (Figure 33) will cause serious damage to infrastructure, as well as to ecosystems and water systems in the Arctic and boreal regions. This damage includes, for example:

- Damage to pipe-lines and buildings
- Deformation of roads and railroads in Russia, Mongolia and China
- The variations in the ion distribution in soil water in young and ancient landslides.
- Cryogenic landslides, leading to spatial and temporal changes of grass and willow vegetation

- Saline water is accumulated in local depressions of the permafrost table, and forms highly saline lenses of ground water called 'salt traps'

Due to the large extent of permafrost-covered areas in the northern Eurasia (for ecosystem effects, see chapter 3.2.3: Risk areas of permafrost thawing), there are numerous infrastructural issues related to possible changes in the thickness and temperature of the frozen part of the subsurface, and thus its mechanical soil properties. Climate change -induced changes in the cryosphere are probably among the most dramatic issues affecting the infrastructure in the northern Eurasia, as the infrastructure is literally standing on permafrost. Moreover, an interesting coupling may be related to the decreasing ice-cover of the Arctic Ocean, which results in increased humidity and precipitation on the continent, and thus a further thickening and longer duration of the annual snow cover. Snow is a good thermal insulator, and influences the average ground surface temperature, thus playing a potentially important role in speeding up the thawing of permafrost.

The increased risk of damage to local infrastructure, such as buildings and roads, can cause significant social problems, and exerts pressure on the local economies. Thawing permafrost is structurally weak, and places a variety of infrastructure at risk. For example, the failure of buildings, roads, pipelines or railways can have dramatic environmental consequences, as seen in the 1994 breakdown of the pipeline to the Vozei oilfield in northern Russia, which resulted in a spill of 160,000 tons of oil - the world's largest terrestrial oil spill (UNEP, 2013). Maintenance and repair costs related to permafrost thaw and degradation of infrastructure in northern Eurasia have recently increased, and will most probably increase further in the future. This is an especially prominent problem in discontinuous permafrost regions, where even small changes in the permafrost temperature can cause significant damage to infrastructure. Most settlements in permafrost zones are located on the coast, where strong erosion places structures and roads at risk. After damage to the infrastructure, local residents and indigenous communities are often forced to relocate. This can cause changes in, or even disappearances of, local societies, cultures and traditions (UNEP, 2013).

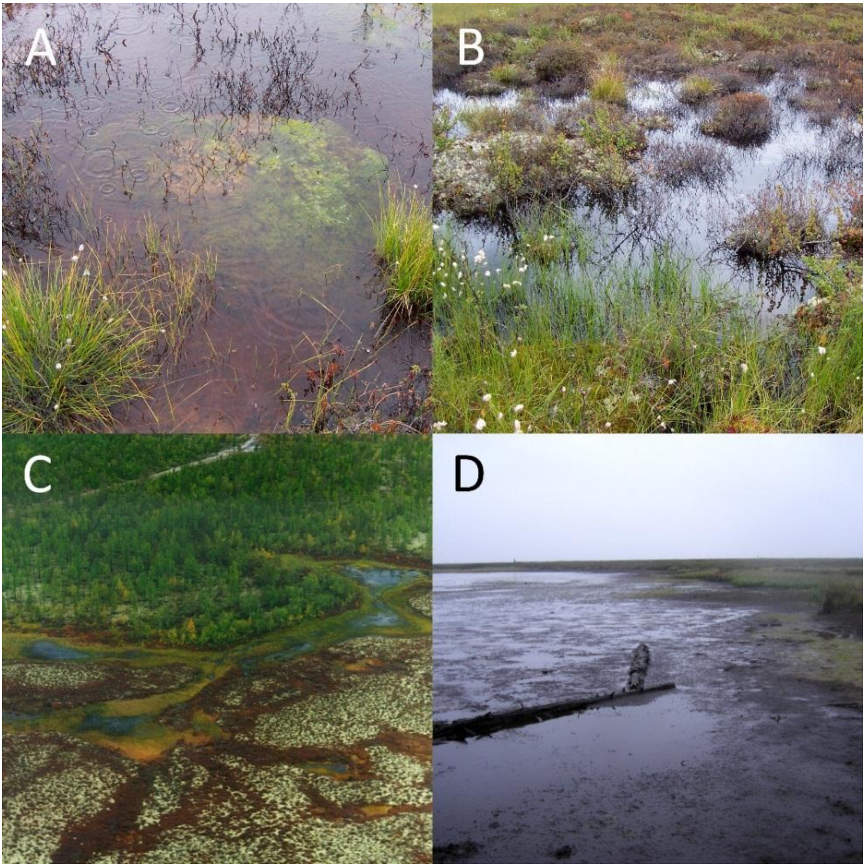


Figure 33 Permafrost degradation. (A-B) Fresh thermokarst subsidence - the dwarf shrubs have gone under water. (C) Melting permafrost edge of the bog in Northern West Siberia. (D) Shores of lakes in tundra zone are actively melting and their areas increased - large lake is shrinking. Photos from Sergej Kirpotin / TSU.

Changing sea environments and the risk of accidents in coastal regions

In northern Eurasia, from the eastern part of the Barents Sea to the Bering Sea, the permafrost is located directly on the sea coast. In many of these coastal permafrost areas, sea level rise and continuing permafrost degradation leads to significant coastal erosion, and to the possibility of collapse of coastal constructions such as lighthouses, ports, houses, *etc*. In this region, sea level rise is coupled to the permafrost degradation in a complex way, and should be focused on in future studies.

Understanding and measuring of artificial radionuclides in marine ecosystems components is needed to improve emergency preparedness capabilities, and develop risk assessments of potential nuclear accidents. The awareness of the general public and associated stakeholders across the region should also be raised concerning the challenges and risks associated with nuclear technologies, environmental radioactivity, as well as emergency preparedness.

The current state of radioactive contamination in terrestrial and marine ecosystems in the European Arctic region will be studied by examining environmental samples collected from Finnish Lapland, Finnmark and Troms in Norway, the Kola Peninsula, and the Barents Sea. The results will provide updated information on the present levels, occurrence and fate of radioactive substances in the Arctic environments and food chains. The results will also allow us to estimate where the radioactive substances originate from, and what risks they may pose in case of accidents.

Annual expeditions for sample collection (Figure 34) are needed for the development of models to predict the distribution of radionuclides in the northern marine environment, and for the assessment of the current state of radioactive contamination in marine ecosystems in the European Arctic region. In view of recent developments and increased interests in the European Arctic region for oil and gas extraction, special attention needs to be given to the analysis of norms (naturally occurring radioactive materials) in order to understand current levels. The work will focus on atmospheric modeling, and on the assessment of radionuclide distributions in the case of accidents leading to the release of radioactive substances to the environment in the European Arctic region. This includes the assessment of nuclear accident scenarios for dispersion modeling.

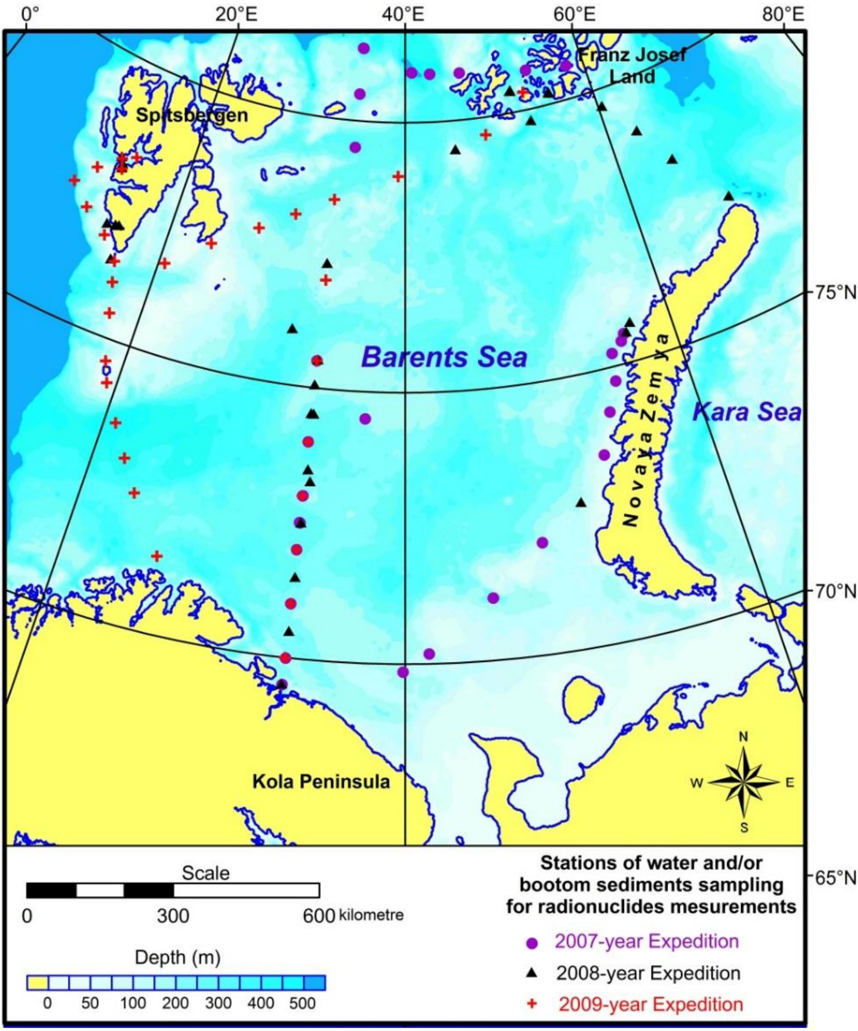


Figure 34 Stations for radioecological sampling expeditions. Figure from Gennady Matishov.

3.6.3 Social transformations

Figure 35 Ozone pollution in Nanjing during summer. Photo from Xie Yuning (Nanjing University).

SYNOPSIS Climate and weather strongly affect the living conditions of Pan-Eurasian societies, influencing people's health, the incidence of diseases, and the adaptive capacity. The vulnerability of societies, including their adaptive capacity, varies greatly, depending on both their physical environment, and on their demographic structure and economic activities. PEEX assesses the different ways in which societies are vulnerable to the impacts of climate change. PEEX will also help develop mitigation strategies that do not simultaneously increase the vulnerability of societies to climate change. More generally, PEEX analyzes the scientific background and robustness of the adaptation and mitigation strategies (AMS) of the region's societies, with special emphasis on the forest sector and agriculture.

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 changes?

Demography

Short-lived climate forcers (SLCF), such as black carbon, ozone (Figure 35) and aerosol particles, are important players in both air quality and Arctic climate change. Nevertheless, their impacts remain poorly quantified. The climate effects of SLCFs are tightly connected to cryospheric changes and associated human activities. Black carbon has a special role when designing future emission control strategies, since it is the only major aerosol component whose reduction is likely to be beneficial to both climate and human health. Health issues are also important in multidisciplinary studies of north Eurasia, as the living conditions of both humans and livestock are changing dramatically. These changes can be expressed through complex parameters combining the direct effects of *e.g.* temperature and wind speed with indirect effects of several climatic and non-climatic factors such as the atmospheric pressure variability, or the frequency of unfavorable weather events such as heat waves or strong winds. During the last decades, living conditions in Northern Eurasia have generally improved, but with significant regional and seasonal variation (Zolotokrylin *et al.*, 2012).

Both northern and eastern Russia have small and diminishing populations, mainly due to migration outflow in the 1990s due to of severe and unfavorable living conditions combined with an economic crisis. This reversed the previous long-standing pattern of migration inflow. The combination of outflow and natural population decrease (with some regional exceptions in several ethnic republics and autonomous regions (OKRUGS) with oil and gas industry) led to a steady population decline in most regions in northern and eastern Russia from 1990. In the post-soviet period, the population of eastern Russia decreased by 2.7 million, while the population of Russia's Arctic zone decreased by nearly by one third (500 000 people), in contrast to the majority of the world's Arctic territories (Glezer, 2007a; b). The population change in northeastern Russia was particularly remarkable: the Chukotka autonomous Okrug lost 68 % of its population, the Magadan Oblast 59 % and the Kamchatka Krai 33 %.

Geographical and ethnic factors influence the demography and settlement pattern in the region. Geographical factors include the environmental conditions and the mixture of urban and rural territories. Ethnically, two different local communities exists in northern and eastern Russia: indigenous, mainly nomadic people, and relatively newly arrived migrants, mainly Russians, Ukrainians and Tatars. The two communities are composed of quite different people, with specific physiological traits, ways of adaptation to natural conditions, and patterns of interactions with the environment. Therefore, the influence of climate and other natural changes on these two types of communities should be studied separately.

Areas with a large proportion of indigenous people employed in traditional nature management were exposed to relative small post-soviet transformations in the 1990's and 2000's. In contrast, the largest transformations occurred in areas with a larger proportion of Russian people and developed mining industries. The differences in the transformations between settlements with predominantly indigenous and predominantly Russian populations are evident. For example, in the Chukotka autonomous Okrug, the former remain mostly intact, with only small decreases in decreased population, while the latter have disappeared entirely, or been significantly depopulated (Litvinenko, 2012; 2013).

When assessing the impacts of climate change and other environmental changes on human societies, it should be taken into account that the urban environments in many Russian and Chinese cities and towns in the economically poorer regions are currently under-developed, and therefore incapable of mitigating unfavorable impacts. Different climate parameters, such as temperature (including seasonal, weekly and daily gradients, and extreme values), strong winds, snowfall, snowstorms, and precipitation should be investigated. Both the frequency and the duration of weather events should be considered. These climate parameters influence human health, the incidence of diseases, the adaptation potential, and economic development in general.

Integrating assessments for mitigation and adaptation with other research

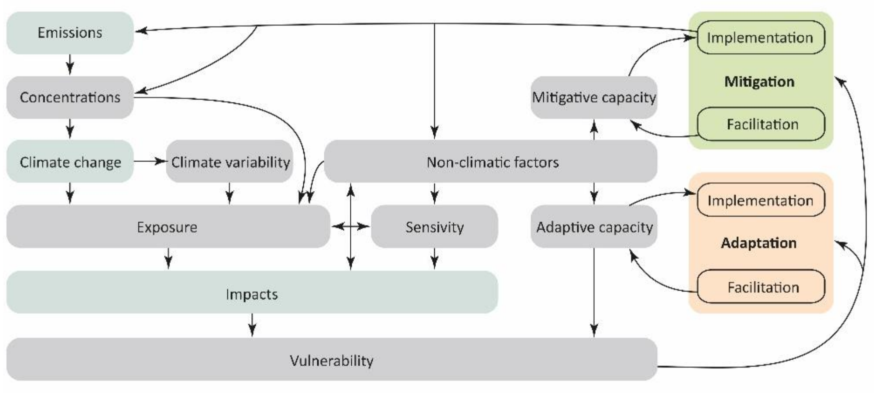


Figure 36 A framework for assessing climate change impacts, vulnerability and adaptation. Figure adapted from Füssel and Klein, 2006 and Klein and Juhola, 2014.

The development of adaptation and mitigation strategies (AMS) is a complicated task. PEEX will tackle this challenge using new methodologies of applied systems analysis. Adaptation and mitigation will be considered simultaneously, while accounting for the large uncertainties in both physical and social systems, and the different characteristics and needs of the heterogeneous regions of the PEEX domain. See Figure 36 for a schematic of the AMS development process.

Despite the importance of urban regions, they have been studied relatively little in the context of global environmental change (The Urbanization and Global Environmental Change (UGEC), 2012). The majority of research has focused on the effects of urban areas on global climate change (Rosenzweig *et al.*, 2010), whereas the impact of climate change on urban areas has been examined less. The latter is particularly important as the focus of climate research on climate change adaption, and the need for information related to climate-sensitive urban design and planning, are both increasing. Future Russian territorial and urban planning should be based on research, and on scenarios of natural change and hazards. Substantial amounts of relevant geographic data already exist, and should be incorporated into interdisciplinary studies. The PEEX program should become a source of reliable data for zoning and urban planning in the Arctic and boreal Pan-Eurasian areas based on 40-year forecasts. Some particular traits of urban areas (*e.g.* their location, structure and population density) may make their residents and assets especially vulnerable to climate change (Gasper *et al.*, 2011). Several cities have now begun to prepare climate change adaptation strategies (Ribeiro *et al.*, 2009; Hunt and Watkiss, 2011). These strategies have taken different kinds of forms, with most focusing on identifying local vulnerabilities, and designing adaptation measures to reduce those vulnerabilities (Sanchez-Rodriquez, 2009).

The PEEX large-scale science questions are focused on supporting the development of regional strategies for climate change adaptation and mitigation. Given the dramatic character of the expected climate changes and their impacts on the environment, living conditions, population health and ecosystem services, adaptation – reducing the vulnerability of societies and ecosystems to climate change – is one of the most important socio-economic challenges of the northern Eurasian region. Adaptation includes both the adaptive capacity of ecosystems, and the socio-economic preparedness to carry out planned adaptation measures. Adaptation and mitigation measures can be effective if they are part of a wide strategy involving all relevant sectors of the national economy, and if they are combined in a common political and institutional framework. The PEEX research agenda thus also examines the ongoing political and institutional arrangements for addressing climate change.

It is important to explore the interactions between environmental change and post-soviet transformations of natural resource utilization in northern Eurasia in order to assess the complexity of their socio-ecological consequences at regional and local levels (Litvinenko, 2012). The population dynamics of northern Russian regions in 1990-2012, and the linkage between intra-regional differences in population dynamics, spatial transformations of natural resources utilization, and ethnic composition of the populations, should be clarified. It would be desirable to develop an “early warning system” for the timely mitigation of the negative socio-ecological effects of both environmental changes, and changes in the availability of natural resources. Such systems would be useful for federal, regional and local authorities, as well as for local communities.

Environment and ethnodiversity

Ethnodiversity is defined as the variation of mankind in terms of a combination of biological, cultural and linguistic features called ethnic markers. Ethnic markers divide mankind into a limited number of ethnic groups, each of which represents a unique combination of ethnic markers. For various reasons, ethnic groups are in practice easiest to define in terms of linguistic features. In most cases, a group of people sharing a unique language also forms a unique and coherent ethnic group.

In the current global process of climate change and environmental deterioration, ethnodiversity is among the most threatened aspects of human heritage. There are currently still around 6000-7000 different languages and cultures in the world, but this number is decreasing by 1-2 every week. Depending on the method of calculation, 40 to 80 % of global ethnodiversity is already immediately endangered, and if nothing is done to enhance continuing diversity, only 10 % of the currently existing ethnic groups will outlive the 21st century.

The extent of endangerment and extinction among ethnic groups may be even greater than that of the parallel process observed in the biosphere. The impact of both types of endangerment is similar. In the short run, the loss of an ethnic group would seem to mean just as little as the loss of an individual biological species, but in the long run every loss is irreparable and irreplaceable. With each loss of a language, and the accompanying system of cultural heritage, we are losing an unknown potential that just might turn out to have been essential for the survival of mankind.

Behind the loss of ethnodiversity lie the same factors as behind environmental deterioration and climate change. The crucial underlying factor, and the most difficult to manage, is the massive overpopulation of the globe. In order to preserve both biodiversity and ethnic diversity, it is necessary to simultaneously reduce total consumption, and focus on sustainable sources of energy and food.

Since the majority of the world's ethnic groups are small, and also engaged in culturally specialized methods of subsistence, any change in their immediate environment may lead to their traditional way of life becoming unsustainable. These changes may be due to rising sea levels, warming sea water, melting ice cover, thawing permafrost, flooding rivers, changing rain patterns or moving vegetational zones. These are direct effects of climate change and environmental deterioration on ethnodiversity.

Even more threatening are the indirect effects. Since the overpopulated planet is dependent on a limited amount of natural resources, the immediate environment of small ethnic groups is vulnerable to the adverse impact of majority populations representing governments and nations. The effects of climate change may lead to rapid and massive transfers of majority populations to areas previously inhabited by small ethnic groups. Mines, pipelines, roads and new urban centers essentially only have negative impacts on ethnodiversity.

These problems are global, and can be observed on all continents except Antarctica. However, they are in some respects particularly acute in the trans-Eurasian geographical zone covered by PEEX, which comprises the Arctic and pacific sea coasts, the Eurasian permafrost area, and several large rivers of both Siberia and China. Ethnodiversity should therefore be among the parameters constantly monitored by PEEX.

EXAMPLES OF RESEARCH QUESTIONS

What are the most probable trajectories of shifting bioclimatic zones due to climate and other environmental changes? How will this impact the actual redistribution of major land cover classes?

Given the expected changes, what is the strategy for transition to sustainable land use?

What are the regional specifics of the expected acceleration of disturbance regimes (wildfire, outbreaks of insects and diseases)? How will this acceleration impact interactions between ecosystems and the environment?

What is the buffering capacity and adaptation potential of boreal forests? How will the expected climate and other environmental changes impact the functioning and vitality of boreal forests? How will it impact biodiversity?

What is the probability of non-linear changes in the functioning and vitality of ecosystems at high latitudes (in particular, what is the probability of boreal forests acting as a tipping element)?

What are the specific features needed for a transition to sustainable agriculture?

What is the capacity of societies to mitigate emissions and adapt to climate change?

What future pathways leading to social transformations can be identified for societies in the PEEX area?

How is ethnodiversity changing?

3.7 FEEDBACKS, INTERACTIONS AND BIOGEOCEMICAL CYCLES

SYNOPSIS 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). One of the first feedback loops to be quantified is related to the ambient temperature and gross primary production (Kulmala *et al.*, 2014). The northern Pan-Eurasian Arctic-boreal geographical region covers a wide range of interactions and feedback processes between humans and natural systems. Humans are acting both as the source of climate and environmental changes, and as recipient of their impacts. The effects of climate change on biogeochemical cycles are still inadequately understood, and there are many feedback mechanisms that are difficult to quantify. 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. Measurements of the changes in the hydrological and biogeochemical cycles are needed to construct and parameterize the next generation of Earth System Models.

Q-13 How will changing cryospheric conditions and the consequent changes in ecosystems feed back to the Arctic climate and weather systems, including the risk of natural hazards?

Q-14 What are the net effects of various feedback mechanisms in (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?

Feedbacks and interactions

The PEEX research approach emphasizes a holistic understanding of feedbacks in the climate and Earth system, and their impacts on the biogeochemical cycles in the Northern Pan-Eurasian region. The continental biosphere, including Northern Pan-Eurasia, plays an important role in the climate system via land-atmosphere processes of carbon dioxide and other greenhouse gases (Heimann and Reichstein, 2008; Ballantyne *et al.*, 2012). Furthermore, boreal forests are acting as a major source of natural aerosol particles and their precursors (Pöschl, 2005; Guenther *et al.*, 2012). Research in the PEEX domain is strongly focused on understanding links between temperature, CO_2 concentrations and aerosol formation processes, while keeping in mind that human activities are strongly affecting natural processes in the land-atmosphere continuum (see the PEEX large-scale research schematics in chapter 3.1)

Several holistic feedback loop hypotheses have been presented, for example the "CLAW" feedback between ocean ecosystems and the Earth's climate suggested by Charlson *et al.* (1987). The CLAW hypothesis connects ocean biochemistry and climate via a negative feedback loop involving cloud condensation nuclei production due to sulfur emissions from plankton (*e.g.* Quinn and Bates, 2011). Following this line of thought, one of the most interesting hypothesis in the PEEX domain is the so-called continental biosphere-aerosol-cloud-climate (COBACC) feedback (Kulmala *et al.*, 2004; 2014). The COBACC-hypothesis suggests two partly overlapping feedback loops (Figure 37) that connect the atmospheric carbon dioxide concentration, ambient temperature, gross primary production, biogenic secondary organic aerosol formation, clouds and radiative transfer.

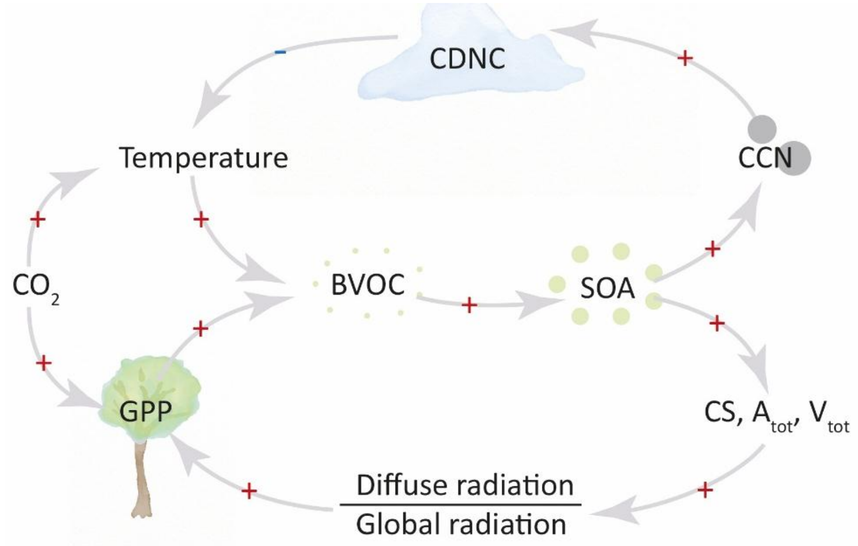


Figure 37 The two loops associated with the continental biosphere-aerosol-cloud-climate (COBACC) feedback. BVOC=biogenic volatile organic compounds, SOA=secondary organic aerosol, CS=the condensation sink (a measure of the aerosol particle population's ability to remove vapors from the air by condensation), A_{tot}=total aerosol surface area, V_{tot}=total aerosol volume, CCN=cloud condensation nuclei, CDNC=cloud droplet number concentration, and GPP=gross primary productivity, which is a measure of ecosystem-scale photosynthesis (Kulmala et al. 2014).

Biogeochemical cycles

The effects of climate change on biogeochemical cycles are still inadequately understood, and there are many feedback mechanisms which are difficult to quantify (Arneth *et al.*, 2010; Kulmala *et al.*, 2014). They are related to, for example, the coupling of carbon and nitrogen cycles, permafrost processes and ozone phytotoxicity (Arneth *et al.*, 2010), or to the emissions and atmospheric chemistry of biogenic volatile organic compounds (Grote and Niinemets, 2008; Mauldin *et al.*, 2012), subsequent aerosol formation processes (Tunved *et al.*, 2006; Kulmala *et al.*, 2011a) and aerosol-cloud interactions (McComiskey and Feingold 2012; Penner *et al.*, 2012). For a proper understanding of the dynamics of these processes, it is essential to quantify the range of emissions and fluxes from different types of ecosystems and environments, and their links to ecosystem productivity, and also to take into consideration that there may exist previously unknown sources and processes (Su *et al.*, 2011; Kulmala and Petäjä, 2011; Bäck *et al.*, 2010).

3.7.1. Hydrological cycle

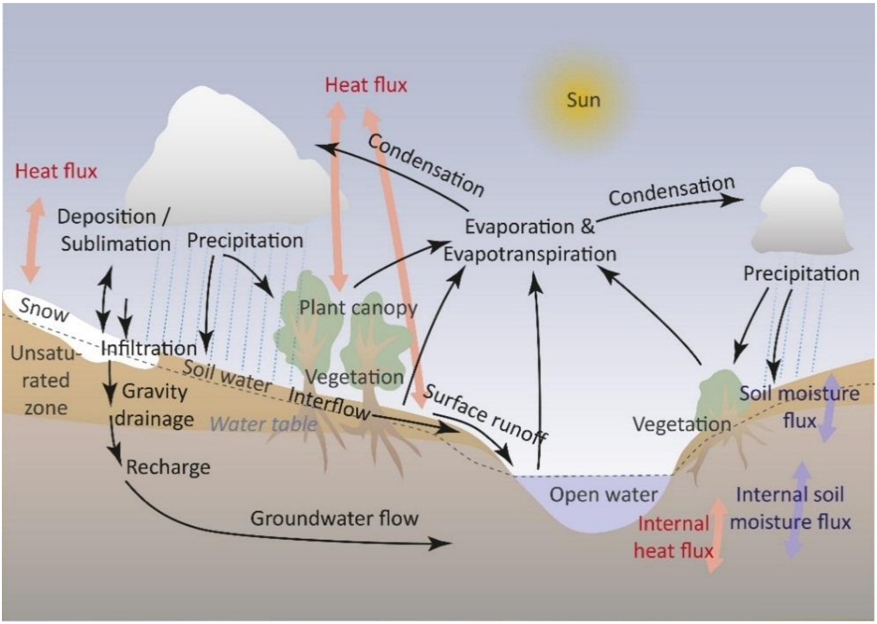


Figure 38 Schematic figure of the hydrological cycle.

SYNOPSIS The water, or hydrological, cycle (Figure 38) is composed of many different elements. These include evaporation of water from the surface of the ocean and bare soil, evapotranspiration from vegetation, transport of water vapor in the atmosphere, cloud droplet formation and cloud dynamics, liquid and solid precipitation, glaciers and snow cover dynamics, surface and river runoff, and subsurface processes such as root dynamics in vegetation and groundwater flow. Climate change may profoundly affect most elements of the hydrological cycle, giving rise to positive or negative feedbacks. While variations in the hydrological cycle often take place at regional or local scales (*e.g.* variations in ecosystem composition or runoff processes), they can also give rise to large-scale or even global changes.

The hydrological cycle is closely linked to other biogeochemical cycles. Climate change will alter the hydrological cycle, affecting all processes connected to the transport of water (*e.g.* evapotranspiration, atmospheric transport, phase transition and cloud formation, precipitation and its spatial distribution, melting and formation of sea ice, ocean currents and the general circulation of the atmosphere, permafrost thawing and dynamics). Since hydrology is also vital for biogeochemical cycles, and for the lateral fluxes of elements such as carbon, nitrogen, sulfur and phosphorus between terrestrial and aquatic ecosystems, changes in hydrology due to climate change are of crucial importance. In aquatic ecosystems, heat fluxes can also be impacted, which in turn affects *e.g.* transfer efficiencies of carbon-containing gases such as CO_2 or CH_4.

Precipitation is a critical component of the hydrological cycle and it has great spatial and temporal variability. The lack of understanding of some precipitation-related processes, combined with the lack of global measurements of sufficient detail and accuracy, limit the quantification of precipitation. This is especially true in the high-latitude regions, where observations and measurements are particularly sparse, and the processes poorly understood.

Recent retrievals of multiple satellite products for each component of the terrestrial water cycle provide an opportunity to estimate the water budget globally (Sahoo *et al.*, 2011). Global precipitation is retrieved at very high spatial and temporal resolution by combining microwave and infrared satellite measurements (Huffman *et al.* 2007, Joyce *et al.*, 2004; Kummerow *et al.*, 2001; Sorooshian *et al.*, 2000). Large-scale estimates of global precipitation have been derived by applying energy balance, process and empirical models to satellite derived surface radiation, meteorology and vegetation characteristics (*e.g.* Fisher *et al.*, 2008; Mu *et al.*, 2007; Sheffield *et al.*, 2010; Su *et al.*, 2007). The water storage change component can be obtained from satellite data, and the water level in lakes and large scale river systems can be estimated from satellite altimetry with special algorithms developed for terrestrial waters (Berry *et al.*, 2005; Troitskaya *et al.*, 2012; 2013; Velicogna *et al.*, 2012).

Examples of research questions − hydrological cycle

What are the future changes in the natural and perturbed hydrological cycles from semi-arid to Arctic zones in the Pan-Eurasian region?

Will climate change accelerate the hydrological cycle in the Pan-Eurasian region, and how will this affect precipitation patterns?

How is wetland hydrology affected by climate change?

How does ecosystem productivity change with changes in the hydrological cycle?

How are the large river systems changing due to temporal and spatial changes in precipitation patterns?

To what extent will the increases in winter precipitation (which will come partly as snow) affect the carbon flux in the PEEX domain?

How will the thawing of permafrost in the PEEX domain affect the hydrological cycle (runoff)?

How will variations of the Arctic sea-ice extent ocean affect the hydrological cycle?

What is the future role of the Arctic-boreal lakes and large river systems, including thermokarst lakes and running waters of all size, in the biogeochemical cycles, and how will these changes affect societies (livelihoods, agriculture, forestry, industry and processes in the Arctic shelf ecosystems)?

3.7.2 Carbon cycle

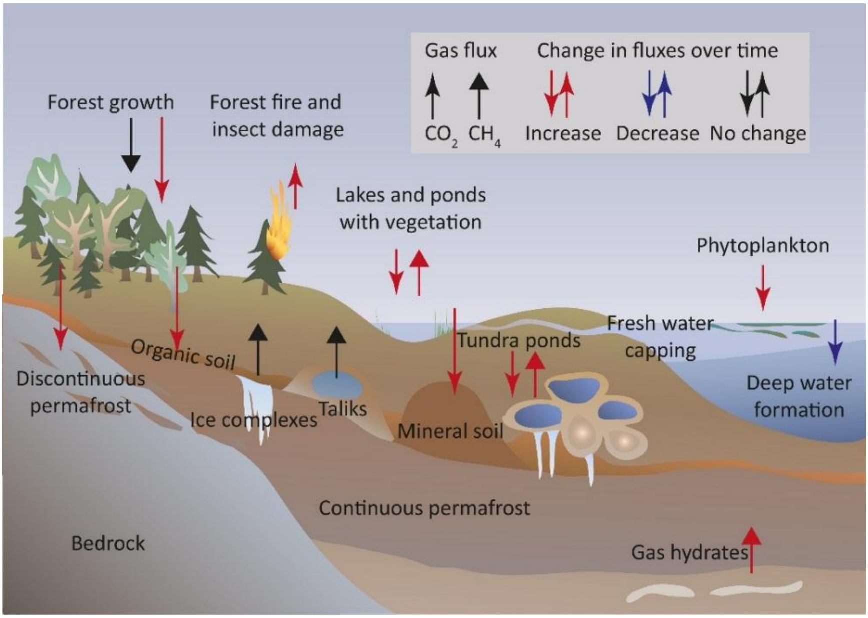


Figure 39 Carbon cycling in the Arctic will change as the climate warms. Figure after ACIA, 2004. (Impacts of a Warming Arctic: Arctic Climate Impact Assessment (ACIA) Overview Report).

SYNOPSIS Climate warming could change carbon cycling in the Arctic (Figure 39). Boreal forests may absorb more carbon dioxide from the atmosphere. However, there is little knowledge on the critical supply of recycled nutrients. Carbon dynamics may also change due to increased forest fires and insect damage, releasing more carbon to the atmosphere. The role of boreal and Arctic lakes and catchment areas in carbon storage is unclear.

The terrestrial biosphere is a key regulator of atmospheric chemistry and climate via its carbon uptake capacity (Arneth *et al.*, 2010; Heimann and Reichstein, 2008). The Eurasian area holds a large pool of organic carbon both within the above- and belowground living biota, in the soil, and in frozen ground, stored during the Holocene and the last ice age. The area also contains vast stores of fossil carbon. According to estimates of carbon fluxes and stocks in Russia made as part of a full carbon account of the land-ecosystem (Shvidenko *et al.*, 2010a; Schepaschenko *et al.*, 2011a; Dolman *et al.*, 2012), terrestrial ecosystems in Russia served as a net carbon sink of 0.5-0.7 Pg(C) per year during the last decade. Forests provided about 90 % of this sink. The spatial distribution of the carbon budget shows considerable variation, and substantial areas, particularly in permafrost regions and in disturbed forests, display both sink and source behavior. The already clearly observable greening of the Arctic is going to have large consequences on the carbon sink in coming decades (Myneni *et al.*, 1997; Zhou *et al.*, 2001). The net biome productivity is usually a sensitive balance between carbon uptake through forest growth, ecosystem heterotrophic respiration, and carbon release during and after disturbances such as fire, insect outbreaks or weather events such as exceptionally warm autumns (Piao *et al.*, 2008; Vesala *et al.*, 2010). This balance is delicate, and for example in the Canadian boreal forest, the estimated net carbon balance is close to carbon neutral due to fires, insects and harvesting cancelling the carbon uptake from forest net primary production (Kurz and Apps, 1995; Kurz *et al.*, 2008).

Although inland waters are especially important as lateral transporters of carbon, their direct carbon exchange with the atmosphere, so-called outgassing, has also been recognized to be a significant component in the global carbon budget (Bastviken *et al.*, 2011). In the boreal pristine regions, forested catchment lakes can vent *ca.* 10 % of the terrestrial nee (net ecosystem exchange), thus weakening the terrestrial carbon sink (Huotari *et al.*, 2011). There is a negative relationship between lake size and gas saturation, and especially small lakes are a relatively large source of CO_2 and CH_4 (*e.g.* Kortelainen *et al.*, 2006; Vesala, 2012). However, on a landscape level, large lakes can still dominate the GHG fluxes. Small lakes also store relatively larger amounts of carbon in their sediments than larger lakes. The role of lakes as long-term sinks of carbon, and simultaneously as clear emitters of carbon-containing gases, is strongly affected by the physics of the water column. In lakes with very stable water columns and anoxic hypolimnion sediments, carbon storage is especially efficient, but at the same time these types of lakes emit CH_4. In general, the closure of landscape-level carbon balances is virtually impossible without studying the lateral carbon transfer processes, and the role of lacustrine ecosystems as GHG sources/sinks. Besides lakes, these studies should include rivers and streams, which could be even more important than lakes as transport routes of terrestrial carbon, and as emitters of GHGs. Also the role of VOC emissions as a part of the carbon budget needs to be quantified.

Plant growth and carbon allocation in boreal forest ecosystems depend critically on the supply of recycled nutrients within the forest ecosystem. In the nitrogen-limited boreal and Arctic ecosystems, the biologically available nitrogen (NH_4 and NO_3) is in short supply, although the flux of assimilated carbon belowground may stimulate the decomposition of nitrogen-containing soil organic matter (SOM), and the nitrogen uptake of trees (Drake *et al.*, 2011; Phillips *et al.*, 2011). The changes in easily decomposable carbon could enhance the decomposition of old soil organic matter (Kuzyakov, 2010; Karhu *et al.*, 2014), and thus increase the turnover rates of nitrogen in the rhizosphere, with possible growth-enhancing feedbacks on vegetation (Phillips *et al.*, 2011).

Specific research questions: carbon cycle

What are the main sources and sinks of carbon in permafrost and non-permafrost regions?

How do the volatile organic carbon (VOC) emissions, the amount of secondary organic aerosols (SOA), and the structure of ecosystems change with changing climatic conditions?

How do different disturbances (fires, insects and harvests) differ in their effects on the greenhouse gas, VOC and pollutant balance in the PEEX domain?

How do elevated atmospheric ozone concentrations affect vegetation and the carbon cycle in boreal and Arctic areas?

3.7.3 Nitrogen cycle

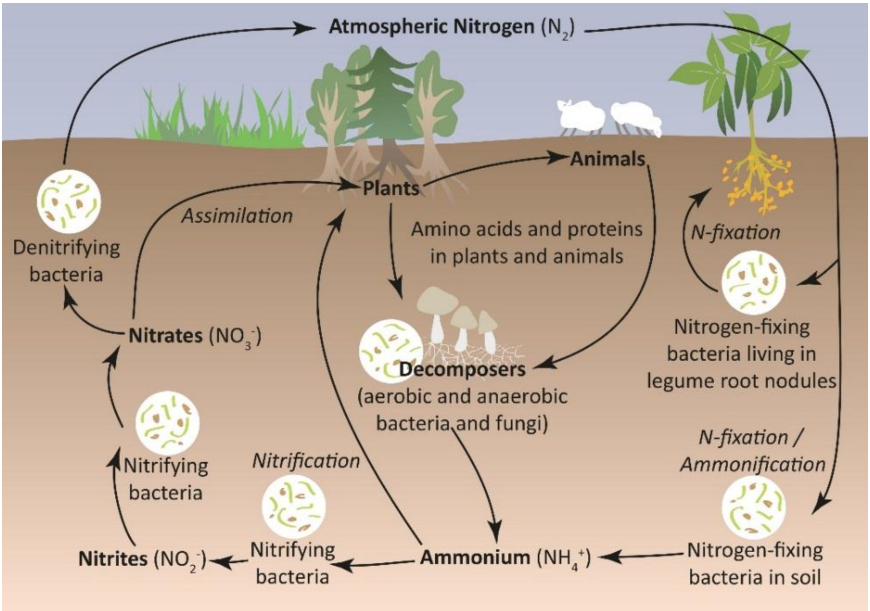


Figure 40 Schematic figure for nitrogen cycle.

SYNOPSIS Emission of reactive nitrogen (NO, NO_2, HONO, ammonia, amines) from soils, fossil fuel burning and other sources links the nitrogen cycle to atmospheric chemistry and secondary aerosol formation in the atmosphere. There are indications that emissions of N_2O from the melting permafrost regions in the Arctic may significantly influence the global N_2O budget and contribute to the positive radiative forcing by greenhouse gases.

Nitrogen is the most abundant element in the atmosphere. However, most of the atmospheric nitrogen is in the form of inert N_2, which is unavailable most for plants and microbes, and can only be assimilated into terrestrial ecosystems through biological N_2 fixation (Canfield *et al.*, 2010) (Figure 40). Only certain organisms living in symbiosis with plants are capable of nitrogen fixation, making nitrogen the main growth-limiting nutrient in terrestrial ecosystems. Human perturbations to the natural nitrogen cycle have, however, significantly increased the availability of nitrogen in the environment. These perturbations mainly stem from the use of fertilizers in order to increase crop production to meet the demands of the growing population (European Nitrogen Assessment, 2010), though atmospheric nitrogen deposition may also play a significant role in some areas. The increased use of fertilizer nitrogen, and consequent perturbations in nitrogen cycling, also cause severe environmental problems such as eutrophication of terrestrial and aquatic ecosystems, atmospheric pollution and ground water deterioration (European Nitrogen Assessment, 2010).

In natural terrestrial ecosystems, nitrogen availability limits ecosystem productivity, linking the carbon and nitrogen cycles together closely (Gruber and Galloway, 2008). The ongoing climate change raises temperatures, and therefore accelerates nitrogen mineralization in soils, leading to increased N availability and transport of N from terrestrial to aquatic ecosystems, and potentially to large net increases in the carbon uptake capacity of ecosystems. The large surface area of boreal and Arctic ecosystems implies that even small changes in nitrogen cycling or feedbacks to the carbon cycle may be important on the global scale (Erisman *et al.*, 2011). For instance, increased atmospheric nitrogen deposition has led to higher carbon sequestration in boreal forests (Magnani *et al.*, 2007). This increase can, however, largely be offset by the simultaneously increased soil N_2O emissions (Zaehle *et al.*, 2011). In the Arctic, there are indications that the high emissions of N_2O from the melting permafrost (Repo *et al.*, 2009; Elberling *et al.*, 2010) may significantly influence the global N_2O budget.

Emission of reactive nitrogen (NO, NO_2, HONO, ammonia, amines) from soils (Su *et al.*, 2011; Korhonen *et al.*, 2013), fossil fuel burning and other sources links the nitrogen cycle to atmospheric chemistry and secondary aerosol formation in the atmosphere. Understanding the processes within the nitrogen cycle, the interactions of reactive nitrogen with the carbon and phosphorus cycles, atmospheric chemistry and aerosols, as well as their links and feedback mechanisms, is therefore essential in order to fully understand how the biosphere affects the atmosphere and the global climate (Kulmala and Petäjä, 2011).

Specific research questions: nitrogen cycle

How sensitive are the boreal and Arctic ecosystems to accelerated nitrogen mineralization?

How will the changing climate influence nitrogen cycling and the emissions of reactive nitrogen into the atmosphere?

How will N_2O emissions from the Arctic respond to climate change?

3.7.4 Phosphorus cycle

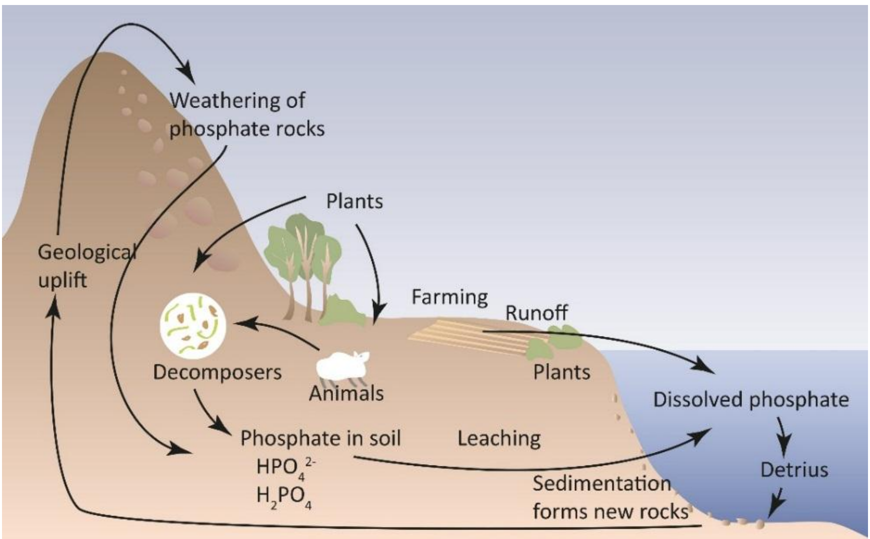


Figure 41 Schematic figure of the phosphorus cycle.

SYNOPSIS South-western Siberian soils have lately been reported to contain high concentrations of plant-available phosphorus (Achat *et al.*, 2013), which may enhance carbon sequestration of the ecosystems if they are not too limited in nitrogen. In freshwater and brackish water ecosystem, excess phosphorus leads to eutrophication, which has ecological consequences, such as the loss of biodiversity (Conley *et al.*, 2009). Due to the scarcity of studies focusing on ecosystem P cycling, the effects of climate change on physicochemical soil properties and p availability, and the interactions of P cycle with the cycles of carbon and nitrogen, are largely unknown.

Phosphorus (P) is together with nitrogen (N) one of the limiting nutrients for terrestrial ecosystem productivity and growth. In marine ecosystems, phosphorus is the main limiting nutrient for productivity (Whitehead and Crossmann, 2012). The role of P in nutrient limitation in natural terrestrial ecosystems has not been recognized as widely as that of N (Vitousek *et al.*, 2010).

In the global phosphorus biogeochemical cycle (Figure 41), the main reservoirs are in continental soils, where phosphorus in mineral form is bound to soil parent material, and in ocean sediments. Sedimentary phosphorus originates from riverine transported material eroded from continental soils. The atmosphere plays a minor role in the phosphorus cycle, and the phosphorus cycle does not have a significant atmospheric reservoir. Atmospheric phosphorus mainly originates from Aeolian dust, sea spray and combustion (Wang *et al.*, 2014). Gaseous forms of phosphorus are scarce, and their importance for atmospheric processes is unknown (Glindemann *et al.*, 2005).

In soils, phosphorus is found mainly in mineral form, bound to the soil parent material such as in apatite minerals. The amount of phosphorus in the parent material is a defining factor for phosphorus limitation, and the weathering rate determines the amount of phosphorus available for ecosystems. In ecosystems, most of the available phosphorus is in organic forms (Achat *et al.*, 2013; Vitousek *et al.*, 2010). In ecosystems growing on phosphorus-depleted soils, the productivity is more likely to be nitrogen-limited in early successional stages, and gradually shift towards phosphorus limitation as the age of the site increases

(Vitousek *et al.*, 2010). South-western Siberian soils have lately been reported to contain high concentrations of plant-available phosphorus (Achant *et al.*, 2013), which may enhance carbon sequestration of the ecosystems, if nitrogen is not too limited. In freshwater ecosystem, excess phosphorus leads to eutrophication, which has ecological consequences, such as the loss of biodiversity due to changes in physicochemical properties and in species composition (Conley *et al.*, 2009). Due to the scarcity of studies focusing on ecosystem phosphorus cycling, the effects of climate change on physicochemical soil properties and phosphorus availability, and the interactions of the phosphorus cycle with the cycles of carbon and nitrogen, are largely unknown.

Examples of research questions: phosphorus cycle

What are the links between phosphorus in the atmosphere, biosphere and hydrosphere?

How will phosphorus fluxes vary with climate change?

3.7.5 Sulfur cycle

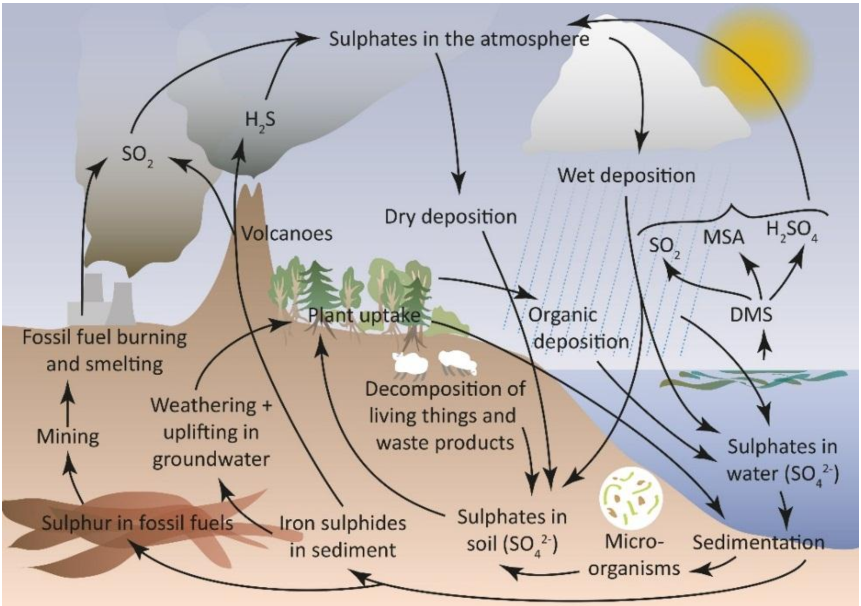


Figure 42 Schematic figure of the sulfur cycle.

SYNOPSIS Sulfur is released naturally through volcanic activity, as well as through weathering of the Earth's crust (Figure 42). The largest natural atmospheric sulfur source is the emission of dimethyl sulfide (DMS) from oceanic phytoplankton. DMS is converted to sulfur dioxide (SO_2), sulfuric acid (H_2SO_4) and methyl sulfonic acid (MSA) via gas-phase oxidation. However, human activities have a major effect on the global sulfur cycle via vast emissions of SO_2 from fossil fuel burning and smelting activities. The main sink of SO_2 is oxidation to sulfuric acid in both gas and liquid phases, and subsequent removal from the atmosphere via precipitation and dry deposition. Gas-phase H_2SO_4 triggers new aerosol particle formation in the atmosphere, affecting cloud cover and both regional and global climate.

Global anthropogenic SO_2 emissions are predicted to decrease significantly by the year 2100 (IPCC, special report on emissions scenarios, SRES, 2000). Emissions in Europe and North America started to decrease already in the 1970s, but this decrease is still overwhelmed on a global scale by increasing emissions in eastern Asia and other strongly developing regions of the world (Smith *et al.*, 2011). The current global anthropogenic SO_2 emissions are about 120 Tg per year, with Europe, the former Soviet Union and China together responsible for approximately 50 % (Smith *et al.*, 2011). Global natural emissions of sulfur, including DMS, are significantly smaller (a few tens of Tg per year; Smith *et al.* 2001). Anthropogenic emissions dominate especially over the continents. The main sources of SO_2 are coal and petroleum combustion, metal smelting and shipping, with minor contributions from biomass burning and other activities.

SO_2 emissions in Eurasia have a large spatial variability. Smelters in the Russian Arctic areas emit vast amounts of SO_2, significantly affecting the regional environment. Smelter complexes in Norilsk, with annual emission of 2 Tg (Black Smith Institute, 2007), are alone responsible for more than 1.5 % of global SO_2 emissions. However, the emissions from the smelters in Kola Peninsula, while still remarkably high, have decreased significantly during the past decades (Paatero *et al.*, 2008), thus altering the impact of human activities on the regional climate and environment. In general, existing anthropogenic activities are slowly becoming more sulfur-effective and less polluting. However, the emergence of new sulfur-emitting activities and infrastructures partially counteract this development.

The behavior of future changes in SO_2 emissions in the PEEX research area is uncertain. In northern Eurasia, natural resources like fossil fuels, metals, minerals and wood are vast, and their utilization is becoming more and more attractive due increasing demand. This will most likely lead to an increase in human activities (*e.g.* mining, oil drilling, shipping) in this area (*e.g.* Smith, 2010, and references therein). Sulfur emissions in China are rapidly increasing, while emissions in Europe have significantly decreased during the last decades.

Most of the natural and anthropogenic SO_2 is removed from the atmosphere by liquid-phase oxidation to H_2SO_4, and subsequent precipitation. In areas with high sulfur loadings, acid rain leads to acidification of soils and waters. The main final sink of sulfur is the oceans. A fraction of SO_2 is oxidized to H_2SO_4 in the gas phase in a reaction chain initiated by the reaction of SO_2 with the hydroxyl radical, OH. Especially in forested areas of Eurasia, reactions of SO_2 with a second important oxidant type, the stabilized Criegee intermediates originating from biogenic VOC emissions, also produces significant amounts of H_2SO_4 (Mauldin *et al.*, 2012). Gas-phase sulfuric acid plays a key role in the Earth's atmosphere by triggering secondary aerosol formation, thus connecting anthropogenic SO_2 emissions to global climate via aerosol-cloud interactions. Particle containing sulfuric acid, or sulfate, are also connected with air quality problems and human health deterioration. Understanding the spatial and temporal evolution of SO_2 emissions in northern Eurasia, along with atmospheric sulfur chemistry, is crucial for understanding and quantifying the impacts of anthropogenic activities and SO_2 emissions on air quality, acidification, as well as on regional and global climate.

Examples of research questions: sulfur cycle

What effect does sulfur deposition have on ecosystem resilience in boreal and Arctic conditions?

How does atmospheric nitrogen and sulfur deposition affect ecosystem vitality and productivity, and what are their links to the hydrological conditions?

Quantification of critical processes of the sulfur cycle in terms of new particle formation (NPF)

4. PEEX RESEARCH INFRASTRCTURE (F2)

4.1 CONCEPTUAL DESIGN AND GENERAL FRAMEWORK

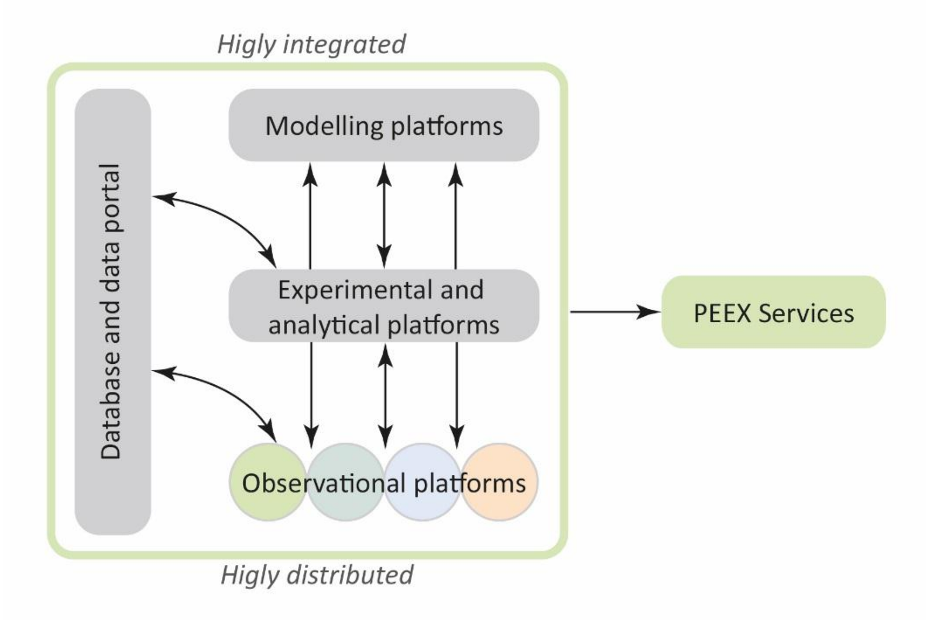


Figure 43 The conceptual design of the PEEX infrastructure is based on the service-oriented approach (Lappalainen et al., 2014) connecting and integrating data from highly distributed observational and modeling networks as well as from various experimental platforms. See also section 5.3.

Solutions to the interconnected global environmental problems can be provided only by a harmonized and holistic observational approach utilizing all available modeling tools representing different spatial and temporal scales. The PEEX approach uses research methods including both experimental and modeling tools, and ranging from nanometer and sub-millisecond observations and process studies to global and decadal scale measurement activities, datasets 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 (Figure 43).

The PEEX Focus-2 is to establish a sustainable, long-term Pan-Eurasian research infrastructure (RI), including measurement hardware and software, and validated and harmonized data products for implementation in models of appropriate spatial, temporal and topical focus (Kulmala *et al.*, 2011). The PEEX research infrastructures include comprehensive field observations of the atmosphere, biosphere, hydrology, cryosphere and oceans, as well as targeted laboratory experiments. The approach includes a hierarchical station network, as well as a suite of modeling tools (Hari *et al.*, manuscript in preparation; Lappalainen *et al.*, 2014). In the preliminary phase, the PEEX network is based on existing infrastructures, which are updated and harmonized where necessary and feasible. The most comprehensive stations, called flagships, act as testbeds, and operate as integrated research platforms. The PEEX Research Infrastructure (RI) will consist of a comprehensive field station network in the region covering Scandinavia, Finland, the Baltic countries, Siberia and China, complemented by satellite observations and corresponding integrated modeling tools. The ground component infrastructure development is made in concert with currently on-going European infrastructure projects. Outputs of the PEEX monitoring system will be used for appropriate modeling within the PEEX domain, and will be distributed to stakeholders and the public.

The PEEX toolbox includes a hierarchical station network consisting of super-sites for building a holistic *in-situ* understanding of the atmosphere-biosphere-cryosphere-anthroposphere continuum at the process level, and flux stations for targeted regional observations. Measurements at standard stations will provide data on the spatial *in-situ* variability of selected parameters at the ground level. A suite of satellites extends the observations to global scales, and provides data on the vertical structure and distribution of the measured atmospheric parameters, as well as on the biosphere, land-use and the hydrological cycle.

The methods for solving large-scale research questions and investigating complex feedbacks in the PEEX research agenda are adopted from the EU-FP6 "Integrated project on aerosol, cloud, climate, and air quality interactions" (EUCAARI), (Kulmala *et al.*, 2009; Kulmala *et al.*, 2011). The idea of the multi-scale modeling approach is based on the integration of scientific knowledge from nano- to global scales with a multidisciplinary scientific approach (see also Figure 65). A suite of models covers the processes leading to *e.g.* changes in atmospheric composition, biosphere functions and cloud formation. Boundary layer modeling is utilized in analyzing vertical structures and atmospheric stability, whereas regional chemical transport models integrate the chemistry and physics of the atmosphere for specific tasks such as trans-boundary pollution transport. The results of smaller-scale modeling, together with observational data, are fully utilized in global Earth System Models, which provide tools to assess the overall effects of feedback mechanisms, and the anthropogenic influences on environmental changes.

The PEEX observation network preliminary phase program, targeted for the years 2015-2020, will include the following actions and objectives:

- To identify the on-going measurement routines of the PEEX preliminary phase ground stations,
- To analyze the end-user requirements of the global and regional-scale climate and air quality modeling communities in the PEEX domain,
- To provide an outline for the standards of the PEEX-labeled network, including measurement and data product archiving, and delivery requirements for each station category,
- To identify the key gaps in the initial phase observational network, including long-term observational activities within the PEEX domain, in Europe, in China and globally,
- To initialize harmonization of the observations in the PEEX network following *e.g.* accepted practices from GAW or European observation networks,
- To carry out inter-platform inter-comparisons between ground-based and satellite observations.
- To establish a PEEX education program of measurement techniques and data-analysis for young scientists and technical experts.

4.2 THE ENVISIONED PEEX HIERARCHICAL STATION NETWORK

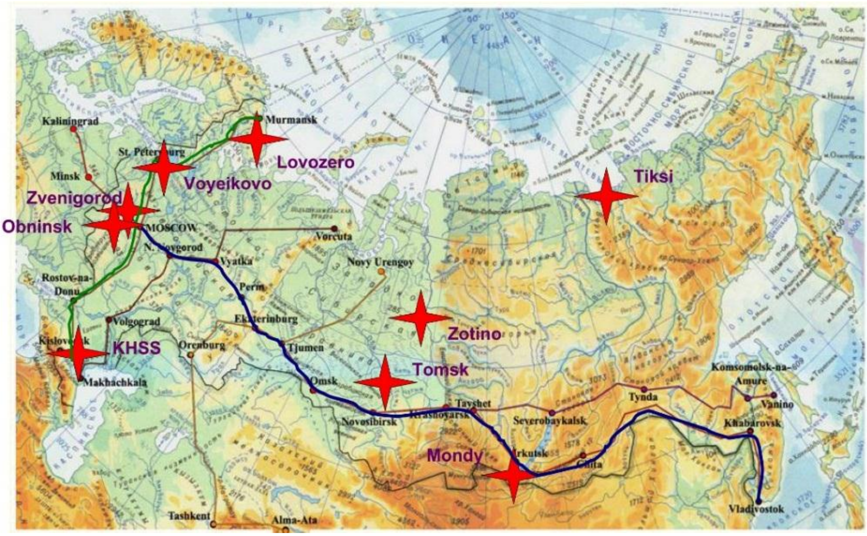


Figure 44 An example of existing research infrastructures and activities: the Obukhov Institute of Atmospheric Physics Measurements (Elansky, 2012).

The hierarchical observation network envisioned here is based on ideas and concepts introduced, developed and refined in Hari *et al.*, 2009 and Hari *et al.*, 2015.

The Arctic-boreal regions currently lack coordinated, coherent *in-situ* observations despite their critical role in the climate system. The first step towards coherent atmosphere-ecosystem measurements is the establishment of a preliminary-phase observation network based on already existing activities. There are already several state-of-the-art field stations, which provide a pilot approach (Figure 44). In the full PEEX network, there will be one station for every 2000−3000 km of the Siberian region, representing all major ecosystems.

The PEEX-labelled network of field stations forms a hierarchical station network from Scandinavia to China, and has a continuous, comprehensive science program (Hari *et al.*, 2009; Lappalainen *et al.*, 2014; Hari *et al.*, 2015, in preparation). The concept of a hierarchical station network is based on the need to set up comprehensive measurements of fluxes, storages, and processes, providing quantitative process understanding of the Earth system (Hari and Kulmala, 2005). Anthropogenic emissions have changed the chemical composition of the atmosphere, as well as the structure of the atmosphere itself, and forests, peatlands, tundra and aquatic systems are responding. This global change is insufficiently understood, and the future development of the climate, the biosphere and the oceans is at present quite uncertain. In order to make proper decisions, we need an improved understanding of the expected future climate, and of the responses of the living components of the Earth system.

The PEEX area is large: it extends thousands of kilometers in the east-west direction, and slightly less in the north-south direction. The relevant time span is also long, about 100 years. On one hand, the fundamental metabolic and physical phenomena occur at the atomic, molecular or cellular spatial level, and their timescales span from picoseconds to seconds. On the other hand, the responses of the biosphere to altered anthropogenic forcing can take decades or longer. The PEEX research focuses on ensuring an efficient knowledge flow from microscopic time and space scales to large domains and prolonged periods.

Climate change, and its effects on biological systems, involves several very different phenomena, such as the transport of radiation in the atmosphere, the growth of forests, CO_2 fluxes between the atmosphere and the oceans and emissions of reactive trace gases from the biosphere to the atmosphere A research system that combines the information dealing with different phenomena, obtained at different spatial and temporal scales, is needed in order to find solutions to grand challenges, and provide reliable early warning systems. The proper combination of knowledge of versatile phenomena on different scales requires coherent common concepts and ideas, enabling knowledge flow between disciplines.

The fundamental phenomena in the PEEX domain take place on an elemental level in space and time. Metabolic, physical and chemical processes convert matter and energy into other forms. These processes generate concentration, temperature and pressure differences, which in turn give rise to material and energy flows. These flows combine to produce metabolic, physical and chemical phenomena covering large temporal and spatial scales. The common features of these biological, physical and chemical phenomena enable the construction of sets of coherent theories to describe the behavior of matter and energy in the vast PEEX domain, and provide the theoretical basis for the construction of a network of coherent measuring stations.

The northern research area is characterized by a mixture of forests, peatlands, tundra, fresh waters, oceans and urban areas. These land cover types have clear and distinct features, acting as rather independent functional units. These functional units exchange material and energy, especially with the atmosphere, but also with each other. These material and energy fluxes convey the interactions in the PEEX domain. The water flux between the vegetation and the atmosphere is the largest single flux. The fluxes of carbon, nitrogen and several atmospheric trace gases are quite small by mass, but their relevance to the global change are important.

The PEEX toolbox includes a hierarchical station network consisting of super-sites (Flagship stations) for a holistic *in-situ* understanding of the atmosphere-biosphere-anthroposphere continuum at the process level and, flux stations for targeted regional aspects and observations. The standard stations in turn would provide the spatial *in-situ* variability of the selected parameters at the ground level. A suite of satellites extends the observations to global scales and provides also the vertical structure of the atmosphere as well as data on biosphere, land-use and hydrological cycle. The network includes components covering both the atmosphere and the ecosystem functions.

4.2.1 Atmospheric component

The general description of the hierarchical station network for the atmosphere is introduced in Hari *et al.* (2009) and Hari *et al.* (2015, in preparation). The system consists of the following building blocks:

The standard station

The standard stations provide measurements of such properties that act as key drivers for the most important processes in land-atmosphere interactions. The observations are made at the ground level with a dense geographical grid to provide a good spatial coverage. The measurements include the following:

i. Standard meteorological quantities in the atmosphere (temperature, relative humidity, wind direction, wind speed, precipitation, solar radiation)
ii. One additional measurement, user selectable, such as:
    a. Solar radiation in different wavelength regimes (PAR, global, net)
    b. Measurements on the properties of the soil and ground: temperature profiles, soil water content and tension, snow depth and water content
    c. Concentrations of some trace gases (*e.g.* SO_2, O_3, NO_X, CO)
    d. Number concentration of aerosol particles

The flux station

The flux stations in the atmospheric component are advanced versions of standard stations, with the following capacity:

i. All measurements made at the standard stations, including the user-selectable components
ii. Aerosol particle number concentrations and size distributions
iii. Upward and downward longwave radiation, sensible heat, and latent heat/water vapor fluxes
iv. Flux measurements of a user-selectable set of trace gases, such as CO_2, O_3, SO_2, O_3, NO, NO_2, N_2O, CH_4, CO and volatile organic compounds (VOC)

The flux stations host focused campaigns, the purpose of which is to determine connections between the fluxes and environmental and ecosystem factors.

The flagship station

The flagship stations in the PEEX atmospheric component provide state-of-the-art observations of atmospheric concentrations and material and energy fluxes in the atmosphere-biosphere continuum.

General principles for the flagship stations:

i. The foundation is the observation of material and energy fluxes.
ii. The observations need to be performed continuously, day and night, winter and summer.
iii. The time resolution depends on the processes that are studied, varying from 100 Hz to years / decades.
iv. The detection limits of the instruments in all locations need to be low enough to capture the temporal variation of the measured gas and aerosol concentrations.
v. Data quality procedures, distribution and storage format need to be harmonized within the network.

The atmospheric flagship station provides a comprehensive monitoring of processes and contributing factors at high spatial and temporal resolution, such as:

i. All observations conducted in standard and flux stations
ii. Aerosol chemical composition
iii. Characterization of aerosol vertical profile and boundary layer structure (lidar)
iv. Atmospheric ion and cluster size distribution
v. Comprehensive characterization of reactive trace gas (such as VOC, ELVOC, sulfuric acid, ammonia, methane) and atmospheric oxidant concentrations

In addition the flagship station can provide additional data, such as:

vi. Advanced characterization of atmospheric turbulence and trace gas and aerosol fluxes in multiple heights incl. below canopy
vii. Cloud characterization (cloud radar)
viii. Advanced characterization of solar radiation (spectral dependency)
ix. Reflected and absorbed radiation (PRI, chlorophyll fluorescence)

The flagship station is involved in development of novel instrumentation and provides benchmarking and in-depth comparison of the novel instruments with the existing data. The flagship station regularly hosts intensive and comprehensive field studies and performs inter-platform calibrations and verifications (*in-situ*, satellite, airborne). In the infrastructure point of view, the flagship stations consists of a tall mast (>100 m in height) and its instrumentation. The instrumentation measures temperature profiles, 3-dimensional wind velocities, aerosol size distributions, concentrations and fluxes of trace gases, down and upward radiation spectra, and energy fluxes.

The flagship stations simultaneously measure meteorological factors and atmospheric composition (including both greenhouse gases and short-lived climate forcers; gases and aerosols), together with several processes and phenomena in the ecosystem they are situated in. This enables comprehensive understanding of feedbacks and connections, combining the ecosystem compartments and the surrounding atmosphere, lithosphere, cryosphere and hydrosphere in a dynamic manner. These SMEAR (Station for Measuring Ecosystem – Atmosphere Relations, Hari and Kulmala, 2005) -type flag ship stations include (i) carbon and nitrogen fluxes (photosynthesis, respiration, growth), (ii) trace gas exchange (reactive carbon compounds, nitrogen compounds, ozone), and (iii) hydrological fluxes. Supporting measurement points can be set up around the main stations with the aim to observe *e.g.* vegetation characteristics and soil microbial processes, or soil-atmosphere interactions (such as CO_2 and other greenhouse gas fluxes, Pumpanen *et al.*, 2013). It is crucial to have one supersite in all major ecosystem areas (Figure 44), which in practice would mean a station for every 2000−3000 km in the PEEX domain.

During the PEEX preliminary phase, several targeted field experiments are performed to investigate key processes and feedback mechanisms in more details. The *in-situ* field experiments are performed at the existing ground-based stations, together with the observations on board aircraft and ships, also utilizing existing datasets and archives. In the second phase of PEEX, several new Pan-Eurasian field stations are planned to be built in order to provide improved spatial coverage. In practice, at least one supersite with comprehensive water-soil-atmosphere-cryosphere measurements is needed for every representative biome.

4.2.2 Ecosystem component

Within the PEEX station network, different ecosystem types need to be characterized and here we provide an example of the hierarchical station network for forest environment.

Forest ecosystem standard station

Forest standard station measures the basic features and phenomena in forests. They include the following measurements:

i. Standard stand measurements at a forest site (tree species, diameter, height and volume)
ii. Standard soil measurements (amount of soil organic matter, size distribution of mineral soil particles and concentration of main nutrients)

Forest ecosystem advanced station

When we expand the standard station measurements to the development and fluxes of the stand we obtain the advanced station. They include the following measurements:

i. The measurements conducted at standard forest stations
ii. Measurement of CO_2, water and heat fluxes between the ecosystem and atmosphere
iii. Retrospective measurements of the stand development

Forest ecosystem flagship station

When we expand the advanced station measurements to cover the detailed structure and processes in the stand we obtain the flagship station: They include the following measurements:

i. The measurements conducted at advanced forest stations
ii. Masses as well as protein, cellulose, lignin, starch and lipid concentrations of the components of trees and ground vegetation
iii. Protein, cellulose, lignin, starch and lipid concentrations of soil layers
iv. Isotopic composition of vegetation and soil layers
v. Measurements of CO_2 exchange, transpiration and VOC emissions at shoot level and from soil
vi. Water storage in soil, rainfall above and under the canopy, run off of water and of DOC and DIC
vii. Inventories of animals in the surrounding (mammals, birds and insects)

4.2.3 Cryospheric component

Figure 45 Cryospheric observations within the DEFROST (Impact of a changing cryosphere - Depicting ecosystem-climate feedbacks from permafrost, snow and ice) network.

The cryosphere in the Arctic is changing rapidly. Measurements of the current and past conditions of the cryosphere are made at deep boreholes, permafrost sites, buoy/floating stations in the Arctic Ocean, on-board ships, and through geophysical observations on-board aircraft. These activities are already ongoing.

A good example is the Nordic Center of Excellence "DEFROST", which operates sites in Russia, Finland, Sweden, Iceland and Norway (Figure 45).

Crucial tasks for the ground-based network are to develop instrumentation and infrastructures for the observation of fundamental cryospheric processes, to improve methods for the geocryologic and geoecological monitoring of natural and anthropogenic environments, and to train specialists for obtaining objective information about the current state of the Arctic processes. These are necessary preconditions for the development of methods and tools for maintaining the stable functionality of the northern infrastructure, which in turn supports the living standards of native populations and newcomers.

Improving environmental geocryological forecasting is important, as it has far-reaching implications both for geopolitics and for environmental security. Because of the vulnerability of Arctic and subarctic regions to natural and anthropogenic influences, it is especially important to forecast destructive and potentially disastrous processes in these natural systems. The interactions between the cryosphere and other geospheres, affected by dynamics as well as by thermal and geological processes, are the most dramatic in the Arctic region.

Changes in the permafrost will be monitored using the existing subsurface temperature observatories in Eurasia. As a special addition to surface and meteorological data, borehole temperatures, which can be used for forward and inverse modeling of ground surface and subsurface temperature development, will be compiled from previous historical data sets and new observations. Selected shallow (<100 m) and deep (>1 km) boreholes will be instrumented for the long-term observation of temperatures. A set of "borehole observatories" will be established, extending from Europe to Siberia and China. This will require an organized international collaboration for efficiently initiating and running the subsurface monitoring program as part of the PEEX infrastructure.

From a resource point of view, a relatively low geothermal gradient may allow the temperature-depth behavior to be within the stability field of methane hydrates. One of the essential objectives of the PEEX program is to improve understanding of the potential release of methane (and other greenhouse gases) from the thawing permafrost. Prediction and modeling of the methane gas release requires well-coordinated observation systems, including a suite of shallow and deep boreholes with thermal instrumentation, estimation of the amount of gas-hydrates *in-situ*, and application of indirect geophysical proxies for monitoring time-dependent changes in the permafrost layers. One of the most interesting techniques would be the use of ground-based and airborne geophysical measurements utilizing the electrical conductivity contrast between frozen and thawed soil. Combining the results of such surveys, repeated at regular intervals (*e.g.* 1-5 years), with the long-term borehole and laboratory data allow for coverage of the large areas surrounding the PEEX stations.

4.2.4 Inland waters component

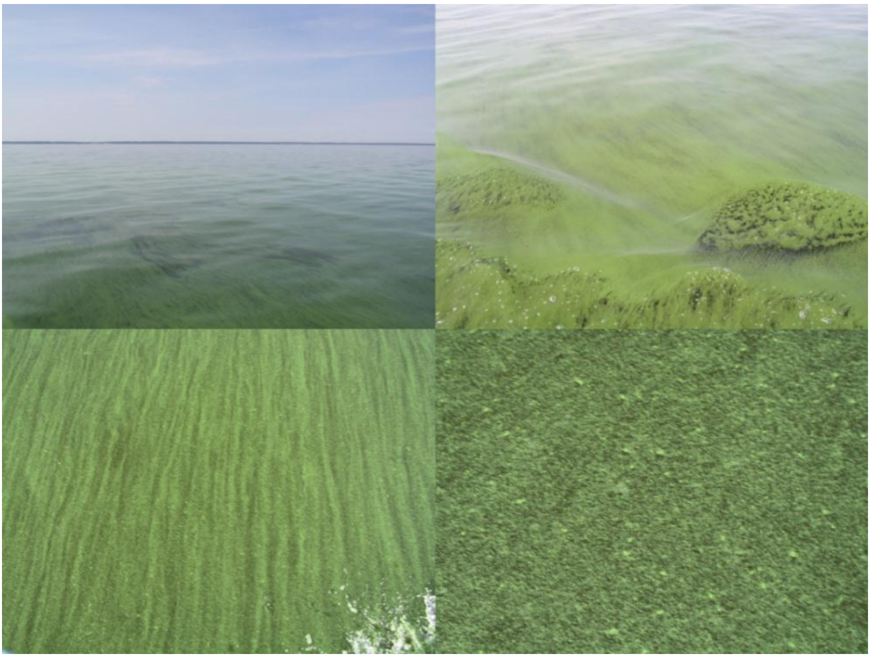


Figure 46 Algae bloom 29.07.2009 in the northern part of Gorky reservoir at Volga River. Photos by Yulia Troitskaya.

A comprehensive investigation of the hydrophysical, hydrochemical and hydrobiological parameters of inland waters is required for understanding the water cycle in the changing PEEX domain. The large river systems discharging into the Arctic Ocean are of particular importance. The activities include the development of a measurement system for a series of representative water bodies in different geographical conditions, and under the influence of climatic changes of varying intensity.

A comprehensive system for the monitoring of the physical, chemical and biological state of inland water bodies based on *in-situ* and remote sensing methods is required. The necessary observations include parameters describing the atmosphere (temperature, pressure, humidity, wind) and the water bodies (temperature, velocity, turbidity, chemical composition, surfactant concentrations, 3-dimensional spectra of surface waves, biomass) as well as the relevant exchange processes (evapotranspiration, evaporation) and geographically representative parameters (water body area and depth, runoff and soil moisture). The *in-situ* observations need to be complemented with satellite remote sensing.

Tools and techniques for real-time monitoring of toxic water blooms should be developed in order to effectively prevent the negative effects of toxic blooms. This will help improve both water quality and normalization processes in the regulation of natural biological communities of blooming water bodies (Figure 46).

Objectives related to the monitoring of inland water bodies include:

- Selection of a series of representative water bodies in different geographical conditions, and under the influence of climatic changes of varying intensity
- Simultaneous ground-based measurements of atmospheric, hydrophysical, hydrochemical and hydrobiological parameters of the environment for calibration of aerospace methods
- Assessing the effect of climate change on the extent of toxic water blooms

4.2.5 Marine component

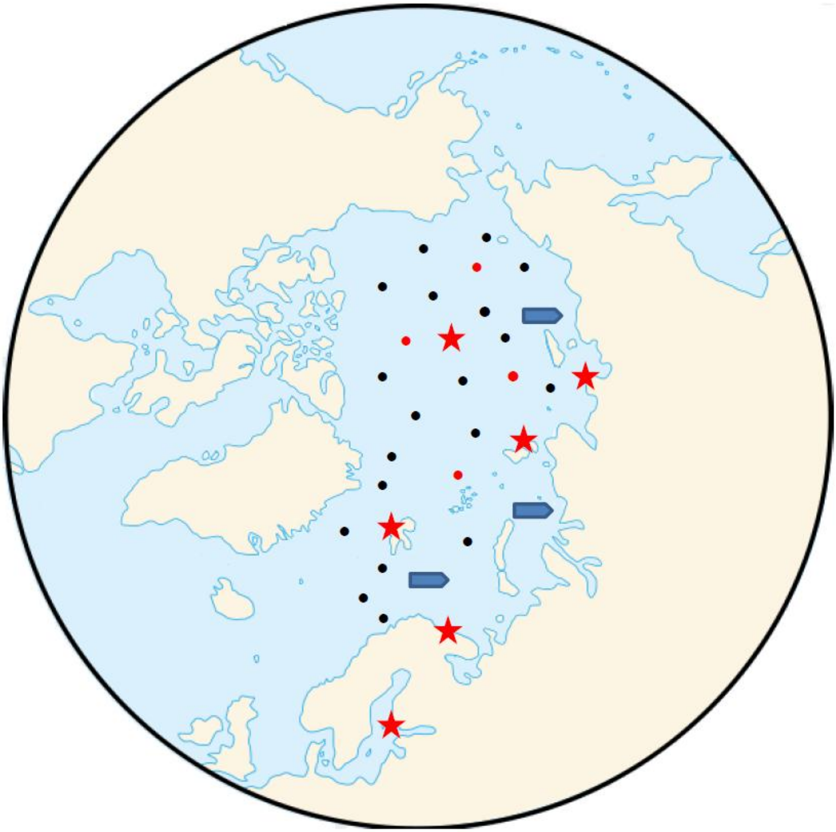


Figure 47 Schematic illustration on the potential station network in the Arctic Ocean. There are presently several simple buoys (black dots) and sophisticated buoys (red dots), and (mostly in summer) also some research vessels (blue boxes), but their locations are continuously changing. Also, each individual station has a limited operational time. For flagship stations (red stars), the figure only provides a vision for the future: the number and locations of the stations are open, except that the station in the Baltic Sea is already in operation. Figure from Lappalainen et al., 2014.

The role of oceans in the climate system is related, among others, to (i) transport of heat from lower latitudes towards the poles, (ii) supply of water for evaporation and further to precipitation and, (iii) via the large heat capacity, dampening of diurnal, seasonal, and inter-annual variations in the air temperature. Compared with terrestrial regions, much less climatological data are available from the oceans, sea ice, and the atmosphere above them. This example presents a conceptual plan for measurement stations in high-latitude oceans (Figure 49), where sea ice occurs for at least part of the year. While the standard and flux stations will yield essential information on the state and change of the marine climate system, Flagship stations are needed for better understanding and parameterization of small-scale physical processes in the system (Vihma *et al.*, 2014).

Standard station

The standard stations provide measurements of properties that are essential for ocean-sea ice-atmosphere interaction. The stations are buoys deployed on ice floes or in the open ocean. Depending on the location and ice conditions, the buys can be either drifting or moored ones. Due to buoy drift, the geographical grid does not keep constant, and a typical lifetime of a drifting station is of the order of one year. In coastal regions, moored stations have, however, much longer lifetimes. The measurements include atmospheric pressure and temperature profiles from the sea water through ice and snow to the air, with a 2-cm vertical resolution. The profile measurements also yield information on the temporal evolution of ice and snow thickness. In the case of drifting buoys, the GPS-based location data yield the ice drift or ocean current vector (a drogue is needed for the open ocean buoys). The data are transmitted via a satellite link.

Flux station

The flux station, either moored or drifting, is an advanced version of the standard station, where the capacity includes:

i. The measurements made at the standard stations
ii. Temperature and wind profiles in the lowermost meters of the atmosphere
iii. Temperature, salinity and current profiles in the uppermost tens or hundreds of meters of sea water.

iv. Surface sensible heat flux (the measurements of vertical gradients in ii-iv are essential in the case that the direct heat flux measurements will not be accurate enough due to various problems met at unmanned ocean stations, such as waves, spray droplets, and ice/snow accretion on the instruments)
v. Upward and downward components of the solar shortwave and thermal long wave radiation (in most cases, good data will require sufficient electrical power for heating and ventilation of the sensor domes)
vi. If the climate at the station is not too harsh and necessary electrical power can be provided, also other measurements may be carried out, such as the water vapor and trace gas fluxes.
vii. CO_2 and DMS concentrations in the water and air

Flagship stations

The Flagship stations provide the state-of-the art observations on the ocean and sea ice, as well as their interaction with the atmosphere. The stations are (i) either moored or drifting ice stations, capable in operating over a winter or even throughout the year, and (ii) permanent coastal/archipelago stations. Accordingly, electrical power is provided, and the instruments and supporting structures are monitored and maintained. The measurements include

i. All the measurements made at flux stations (including v and vi)
ii. Snow and ice properties: including density, grain size and shape distributions, surface roughness, sastrugi, ice rafting and ridging, and portions of columnar and granular ice.
iii. CO_2, CH_4, VOC and DMS profiles in water and in the air
iv. Temperature, light intensity and ion concentration profiles
v. Phytoplankton mass profiles
vi. Fluxes of CO_2, CH_4, VOC and DMS
vii. Profiles of key enzymes of photosynthesis

The continuous measurements at Flagship stations can be strongly supplemented by frequent missions by autonomous under-ice gliders, yielding data on *e.g.* ocean temperature, salinity and dissolved gases. Also, within the limits of aviation regulations, Unmanned Aerial Systems can be operated from Flagship stations.

These will yield data on the atmosphere as well as ocean and sea ice and ocean surface properties.

We stress that it will be challenging to establish Flagship stations in the open ocean, whereas the coastal ones will be easier. A year-round drifting station corresponding to our vision for a Flagship station is planned for the Arctic Ocean for 2018-2019 (see http://www.mosaicobservatory.org). For periods with no marine Flagship stations, we have to rely on data collected by standard and flux stations, as well as during research vessel cruises, which sometimes allow measurements comparable to those planned for the Flagship stations, but for a shorter duration.

4.2.6 Coastal component

The PEEX standard station measurements in the marine area are conducted with drifting stations, buoys and by satellite remote sensing, as described above. The marine area measurement activities are complemented by scientific expeditions onboard research ships. The land-based measurement network provides a link between the marine observations and the coastal environments in key areas, such as Tiksi. In the Arctic, another connecting point is the Svalbard Integrated Arctic Earth Observing System, SIOS. As part of PEEX, the standard buoys used in the studies of oceans are modified to measure also water and air co2 concentrations, temperature and photosynthetically active radiation.

Utö in the Northern Baltic Sea is an example of a marine station. The Utö station is a member of the HELCOM (Baltic Marine Environment Protection Commission) marine monitoring network, and a founding member of the European ICOS network. The station has long records of physical observations (water salinity and temperature measurements since 1900), and is currently under further developments for greenhouse gas (concentrations and air-sea fluxes of CO_2 and CH_4) and marine biogeochemistry observations, the latter including chlorophyll, nutrient, and fluorescence. Another flagship station at coastal site is envisioned in Severnaya Zemlya.

4.2.7 Remote sensing observations

The ground-based observations should be complemented by remote sensing observations of atmospheric-land-aquatic systems. One of the key PEEX objectives is to address climate change in the Pan-Eurasian region using a combination of three approaches: remote sensing data from both airborne and satellite observations, ground-based *in-situ* and remote sensing data, and model simulations of the physical aspects of the Earth system (Lappalainen *et al.*, 2014).

The main advantages of airborne and satellite observations are:

- The same type of instruments and techniques are used across the globe for extended periods of time (spanning several decades), providing consistent data sets. (A necessary condition for this is that successive instruments provide consistent data sets for calibration and intercomparison. It should be noted that inconsistencies may exist between similar data sets, even those obtained from similar instruments.)
- Up-to-date information on atmospheric composition, land surface properties and the water environment.
- The ability to acquire environmental properties data on various spatial and temporal scales, and both horizontally and vertically
- High spatial resolution allows the study of processes and phenomena on local, regional and global scales
- High data reliability (especially when combined with ground-based measurements)
- Wide range of measured environmental parameters, including pollutant concentrations and spatial distributions

Remote sensing data, together with ground-based measurements and numerical modeling, provides information on land, atmosphere and water system properties, as well as on spatial and temporal changes of their components. Remote sensing enables the accumulation of statistical data for modeling dynamic processes of different environments. This helps develop precise guidelines for ecology departments and agencies, and for other consumers (Lappalainen *et al.*, manuscript).

Satellite observations (Figure 48) provide information complementary to local *in-situ* observations. Satellites can provide information of the spatial distribution of key variables relate to:

- Atmospheric composition (Burrows *et al.*, 2011):
  - Aerosols, Trace gases, Greenhouse gases, Clouds
- Land surface properties:
  - surface albedo
  - land cover: vegetation, phenology, tree line, burned area
  - Fire detection, Soil moisture
- Ocean surface properties
  - Ocean color: chlorophyll, algae blooms, waves
  - Sea surface temperature, salinity, sea ice mapping,
  - Snow properties: snow cover, albedo, snow water equivalent
- Lake properties
  - Area, Biomass, Water quality.

Correspondingly, the PEEX infrastructure has an important role in the validation, integration and full exploitation of satellite data for Earth system studies.

<u>Examples of topics relevant to remote sensing</u>

Arctic greening and treeline: an advance of the treeline in the Kola Peninsula region has already been observed.

Toxic water blooms: satellite remote sensing data can be used to assess the extent of toxic water blooms, and changes in this extent due to climate change. Satellite data on the water cycle of the cross-border river basin in Pan-Eurasia is needed to develop hydrological models which can be utilized in water budget estimates for the entire PEEX domain.

Hydrological system: recent studies show substantial changes in the Arctic terrestrial hydrological system, including changes in precipitation, evapotranspiration, river discharge and terrestrial water storage. Data from the gravity recovery and climate experiment (grace) satellite mission show long-term changes in the hydrological budgets of the large Siberian watersheds. A new application of satellite altimetry, originally designed for measurements of sea level, is the monitoring of inland waters.

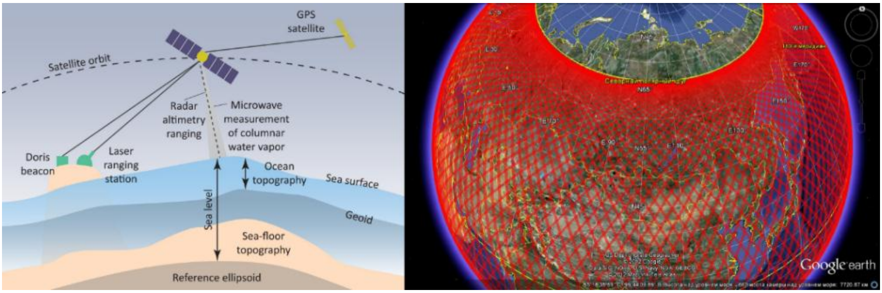


Figure 48 The basic principles of satellite altimetry (left, figure adapted from CNES), and the positions of the ground tracks of the Jason-2 altimetry satellite (right, figure courtesy of Yulia Troitskaya).

4.2.8 System analysis

Global change science is in need of a full and verified greenhouse gas account for terrestrial ecosystems. The nucleus of this account is the full carbon account (FCA). The uncertainties in previously reported estimates of the role of terrestrial ecosystems in global biogeochemistry are large (Shvidenko and Nilsson, 2003), hindering scientific understanding of the problem (Schulze *et al.* 2002), and hampering political and economic decision-making (Janssens *et al.*, 2005). However, an assessment of the uncertainties of the FCA is not trivial, and requires new approaches. FCAs, particularly for large territories such as the PEEX domain, are typical fuzzy (underspecified) dynamic systems (also described as fully complex or wicked problem). This means that all of the existing methods of assessment for terrestrial ecosystem carbon cycling (i.e., the landscape-ecosystem approach, process-based models, eddy-covariance and inverse modeling), when applied individually, are able to produce only an "uncertainty within an approach" value, which may have a little in common with the "real uncertainty" (Shvidenko *et al.*, 2010). PEEX will provide a systems analysis and future elaboration of this problem as a whole. One possible approach is the further improvement of the methodology for FCA developed by IIASA. This methodology is based on system integration of different methods, followed by harmonization, yielding mutual constraints for the intermediate and final results obtained by independent methods (Shvidenko *et al.*, 2010; 2013).

4.3 EXISTING ACTIVITIES AS A BASIS FOR THE PEEX RESEARCH INFRASTRUCTURE

Figure 49 Exemplary set of existing field stations and field expeditions within the PEEX domain in different type of environments. From the left: Zotino tower (ZOTTO) and TROICA expedition onboard a train. Photos from Nikolay Elansky.

Many different topical infrastructures exist within the PEEX domain (Figure 49). As an example, a short summary of the selected infrastructures is presented below, along with an illustration of their potential contribution to the PEEX science topics. The infrastructures include both national and distributed multi-national infrastructures.

4.3.1 Scandinavia

An example of an existing extensive network of atmospheric and ecosystem sites can be found in Finland. The SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) network forms the foundation for the PEEX *in-situ* network. The SMEAR network covers all boreal forest conditions in the Scandinavian part of the global band of northern latitude taiga (Figure 14). The SMEAR consists of super-site stations in boreal environments. The measurements from the SMEAR station network are descriptive of conditions ranging from remote boreal environments north of the polar circle to more temperate boreal environments in Southern Finland. The measurements in Helsinki also provide information on the effects of urban emissions in a boreal context. The wide spatial range of the SMEAR network also provides, for example, the possibility to study the aging and transport of plumes from large-scale forest fires and large-scale biomass burning in Russia (Figure 50, Table 1).

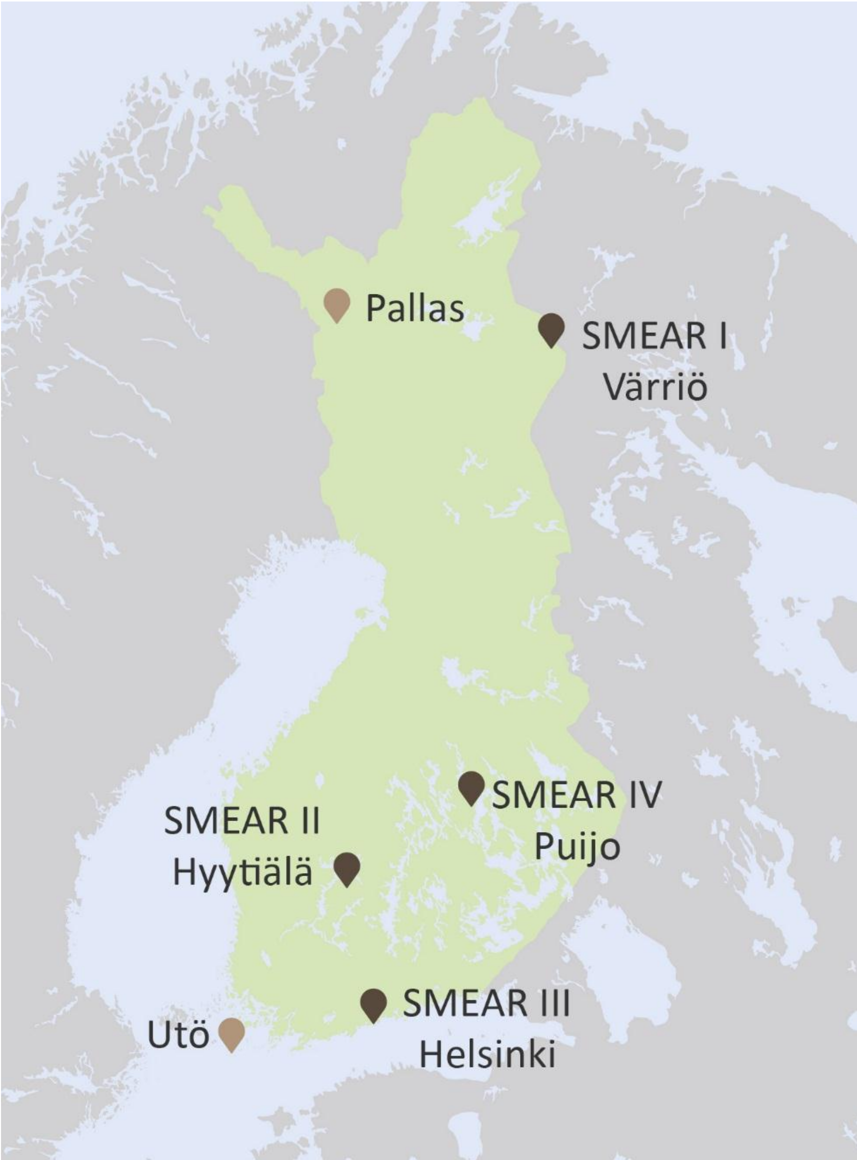


Figure 50 The SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) atmospheric observation network. The station descriptions are presented in Table 1.

Table 1 An overview of SMEAR network stations and Pallas-Sodankylä GAW and Utö stations. SMEAR network data can be visualized and downloaded from smart-SMEAR portal: http://avaa.tdata.fi/web/smart (Junninen et al., 2009).

<table>
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<td>
Hyytiälä. The SMEAR II station in Hyytiälä (N 61°51', E 24°17', 181 m above sea level, ASL). (Photo from Juho Aalto.)</td>
<td>

- Extensive facilities for measuring forest-atmosphere interactions
- Operational since 1996 (Hari and Kulmala, 2005).
- Sub-micron aerosol size distribution measurements since January 1996.
- Surrounded by scots pine forest, with the managed stand established in 1962 by sowing after the area had been treated by controlled burning and light soil preparation.
- Forest ecosystem and tree physiological measurements
- Measurements conducted on a raft in Kuivajärvi Lake (Heiskanen *et al.*, 2014) and in Siikaneva fen (Riutta *et al.*, 2007).
- The nearest urban pollution sites are Tampere (ca. 50 km to the southwest) and Jyväskylä (ca. 100 km to the northeast).
- Site for the ICOS, ACTRIS, INGOS, EXPEER, ANAEE and LIFEWATCH networks; also for WMO, EMEP, CarboEurope, NitroEurope, EUCAARI AND PEGASOS

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<td>
Värriö. The SMEAR I station in Värriö (N 67°46', E 29°35', 400 m ASL). (Photo from Ella-Maria Kyrö).</td>
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- Situated in Lapland, in a remote rural area.
- Surrounded by a Scots pine (*Pinus Sylvestris* L.) Forest, which is over 40 years old in the station's immediate vicinity. The measurements are performed on a hilltop (Hari *et al.*, 1994).
- No pollution sources are nearby, but emissions from industrial activities (*e.g.*, smelters) from the Kola Peninsula area may be advected over the station (Kyrö *et al.*, 2014). New mining activities are planned in nearby Sokli area.

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	• Sub-micron aerosol size distribution measurements started in 12/1997 in the 8-460 nm size range. In 04/2003, a twin-DMPS system was added for measuring the 3-1000 nm size range. Sampling is done at 2 m above ground, inside the forest canopy. • A range of atmospheric parameters, incl. trace gas concentrations along with temperature, relative humidity, solar radiation and wind speed.
 **Helsinki**. The SMEAR III station in Helsinki (N 60°12’n, E 24°57’, 26 m ASL). (Photo from Antti-Jussi Kieloaho.)	• Started operations in Helsinki in autumn 2004. • Instrumentation covers aerosol dynamics and atmospheric chemistry, micrometeorology, weather monitoring and the ecophysiology of trees growing in the urban environment. • Situated at two different locations, Kumpula and Viikki. The Kumpula site is located about 4 kilometres from downtown Helsinki. • Atmospheric observations at a 31 m high tower equipped with meteorological instrumentation at several heights (Järvi *et al.*, 2009).
 **Puijo**. The SMEAR IV station in Kuopio (N 62°55', E 27°40', 224 m ASL). (Photo from Pekka Ahponen.)	• Located on the top of an observation tower. • Continuous measurements of aerosols, cloud droplets, weather parameters and trace gases (Leskinen *et al.*, 2009; Portin *et al.*, 2009) since 06/2005. • Station frequently located within a cloud, *e.g.* more than 40 % of days in October. • Two sampling inlets for aerosol sampling: an interstitial inlet equipped with a PM1 impactor, and a total air inlet with a heater for drying the cloud droplets.

	• Aerosol size distributions are measured from both inlets with the same DMPS by using a synchronized valve system in two 6-minute cycles, giving a 12-minute time resolution for the whole measured size range. • The difference in particle size distributions provides information on the partitioning of particles between cloud droplets and interstitial particles in the cloud.
 **Pallas**. The Sammaltunturi Global Atmospheric Watch station (N 67°58’, E 24°07’, 565 m ASL). (Photo from Juha Hatakka.)	• Operated by the Finnish Meteorological Institute. • Situated on top of a hill in Western Lapland in the subarctic region near the northern limit of the boreal forest zone. • Vegetation in the immediate vicinity is mixed pine, spruce and birch forest. • The station is located above the tree line sampling from 7 m above ground. • No significant local or regional pollution sources, 20 km to the nearest town (Muonio with 2500 inhabitants). • DMPS system operational since 04/2000, measures aerosol particles in the size range 7-500 nm.
 **Utö**. Atmospheric and Marine Research Station (N 59° 46'50, E 21° 22'23, 1 m ASL). (Photo from Minna Aurela.)	• Operated by the Finnish Meteorological Institute in collaboration with Finnish Environment Institute. • Meteorological observations since 1881, marine salinity and temperature measurements since 1900, and atmospheric trace gas and aerosol measurements since 2003 (Engler *et al.*, 2007) • Part of ICOS (since 2014), EMEP (since 1980) and HELCOM marine monitoring networks.

Expanding beyond Finland, the scope of a Scandinavian observation network ranges from Scandinavian itself to the Arctic environment. A suitable connection point is the "CRyosphere-Atmosphere Interactions in the Changing Arctic, "CRAICC" network. The CRAICC observation sites provide atmospheric and ecosystem observations in different locales, from the High Arctic to the hemiboreal environment in Denmark (Figure 51).

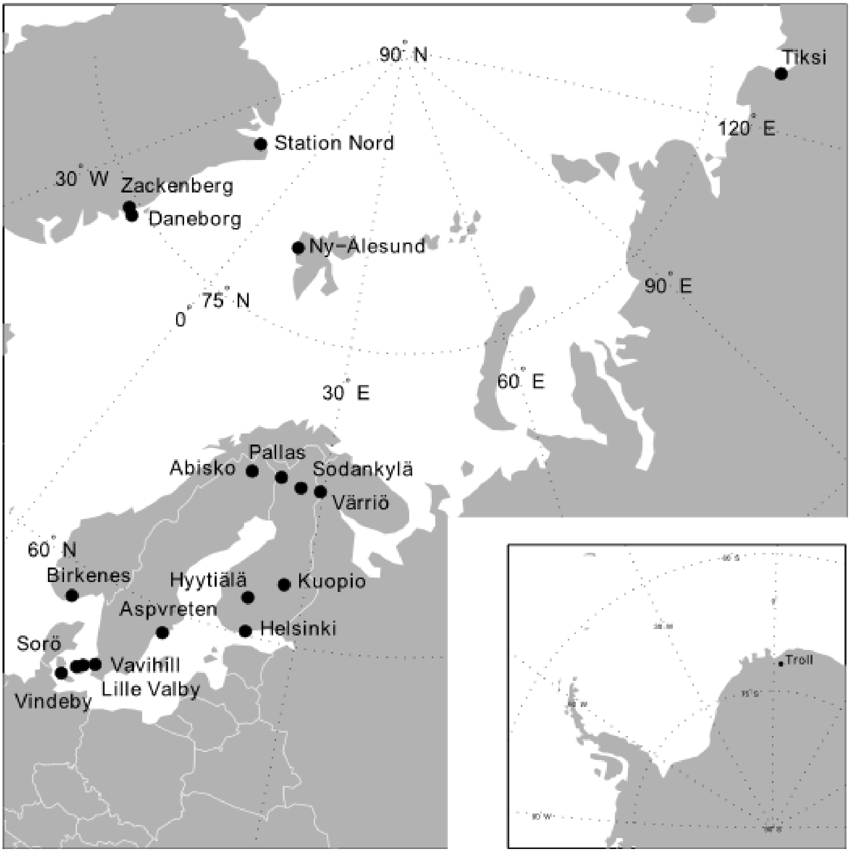

Figure 51 The in-situ station network for the Nordforsk-funded Center of Excellence on "Cryosphere-Atmosphere Interactions in the Changing Arctic Climate" (CRAICC).

4.3.2 Europe

Within Europe, there are many suitable environmental research infrastructures that contribute to the science relevant to PEEX. There are already harmonized structures in place both for greenhouse gases (integrated carbon observation system, ICOS; integrated non-CO_2 greenhouse gas observation system, INGOS) and for short-lived climate forcers (aerosols, clouds, and trace gases research infrastructure network, ACTRIS, Figure 52). A global perspective is provided by the global atmospheric watch network, GAW, which is operated by the world meteorological organization. This infrastructure offers atmospheric observations with a global perspective, but is lacking coverage in the high Arctic and in Russia.

In terms of ecosystem observations, relevant infrastructures are the "experimentation in ecosystem research" network, ExpeER, and the "analysis and experimentation on ecosystems" network, ANAEE. These structures increase our understanding of the ecosystem behavior of the terrestrial and aquatic biomes in the PEEX domain.

The SMEAR flagship site(s), and in particularly SMEAR II in Hyytiälä, are part of all of the above research infrastructures. This underlines the strength of the supersite concept and the hierarchical station network approach utilized in PEEX. The adaptive PEEX network of stations, and in particularly the PEEX supersite network, can contribute to the thematic and topical research questions in the PEEX domain, and contribute to an increased understanding of the Earth system behavior on a global scale.

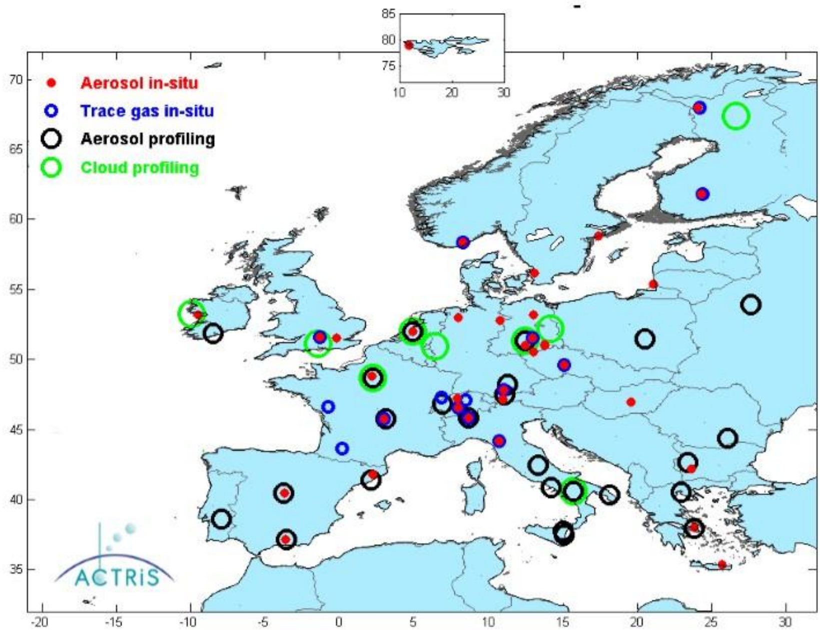

Figure 52 The aerosols, clouds, and trace gases research infrastructure network ACTRIS provides harmonized observational in-situ and remote sensing data on aerosol particles, cloud profiling and concentrations of volatile organic compounds and nitrogen oxides.

4.3.3 Russia and particularly Siberia

The spatial coverage of the station network and other research infrastructure in the pan Eurasian region is currently unevenly distributed. There are several long-term measurement stations, towers and masts (Figure 53), equipped with diverse instrumentation providing data on multiple gas and particle parameters. Intensive campaign-based measurements have also been carried out.

The main problems for atmospheric monitoring in Siberia are deterioration of the instruments, insufficient development of maintenance capabilities for the upkeep and quality control of measurements, the lack of continuous observations in a large fraction of the territory, insufficient equipment for data processing and transmission, and the incompatibility of the Siberian measurement network with the existing international observation networks. Reconstruction of the Russian System of Atmospheric Monitoring (RSAM) is currently on the way. This includes both the modernization of research equipment, and a broader use of remote sensing methods. One objective is that RSAM will be a part of the integrated global Earth observing system in the future.

In the first phase of PEEX, its observation network consists of the existing stations and their measurement programs, and the quality analysis and data dissemination procedures developed in other projects. In order to ensure long-term sustainability and comparability, these measurements need to be connected to international networks wherever possible. The existing stations should be equipped with the instruments they are currently missing, so that they can contribute to the PEEX science mission efficiently. The minimum setup should consist of tools for the measurement of fluxes and concentrations of aerosols and trace gases, including greenhouse gases and short lived climate forcers, snow/ice cover, surface radiation budget components, and, finally, supporting meteorological quantities. Continuous data obtained from satellites need to be complemented with *in-situ* measurement data from the trans-Siberian railway, as well as from purpose-built research vessels and aircraft.

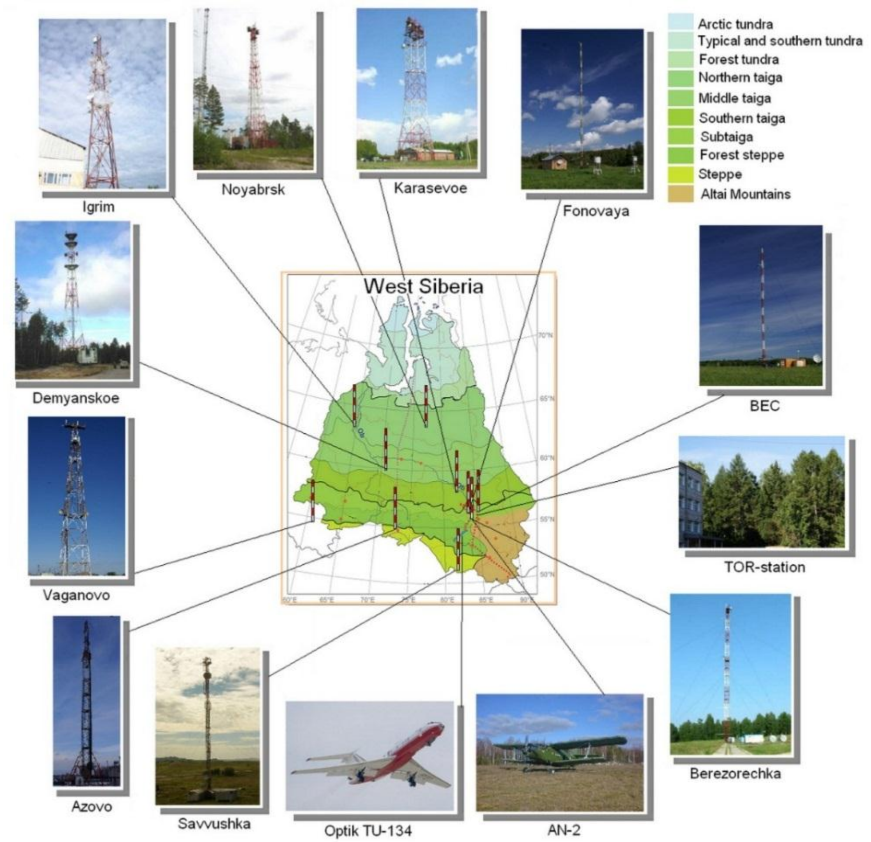

Figure 53 The joint Japanese-Russian Siberian tall tower inland observation network (JR-Station, NIES&IAO SB RAS) for greenhouse gas monitoring.

4.3.4 China

An example of the on-going activities in China is the measurement and research platform station for observing regional processes of the Earth system (Sorpes-NJU), developed by the Institute for Climate and Global Change Research (ICGRCi) and Nanjing University. The station went operational in 2009. The overall objective of this platform is to characterize the temporal variation of key quantities related to climate change, and to understand the interactions of different regional processes of the earth system in east China – a region strongly influenced by monsoon weather, and by intensive human activities (Ding *et al.*, 2013a; b). In Figure 54, the footprint areas, calculated by 20-day backward trajectory analysis, contributing to the data observed at Sorpes-NJU and Hyytiälä are presented. The entire PEEX domain is located within these footprint areas.

Sorpes-NJU is in the process of being developed into a SMEAR-type (station for measuring ecosystem-atmosphere relations) measurement station. It focuses mainly on the impact of human activities on the climate and on the environment in the rapidly urbanized and industrialized Yangtze River Delta region. Based on the geography, climate, and environmental characteristics of east China, Sorpes-NJU focuses on four major processes: land-surface processes, the air pollution-climate interaction, the ecosystem-atmosphere interaction, and hydrology and the water cycle. The entire platform will be developed into an integrated observation network with a "flagship" central site, a few “satellite” sites, and mobile platforms in the vicinity. Other potential PEEX stations in China are the Changbai mountain research station for forest ecosystems 42°4' - 42°36'N, 126°55' - 129°8'E and the Beihai ecosystem station, CERN Network Station 37°37'N, 101°19'E) (Lappalainen *et al.*, 2014).

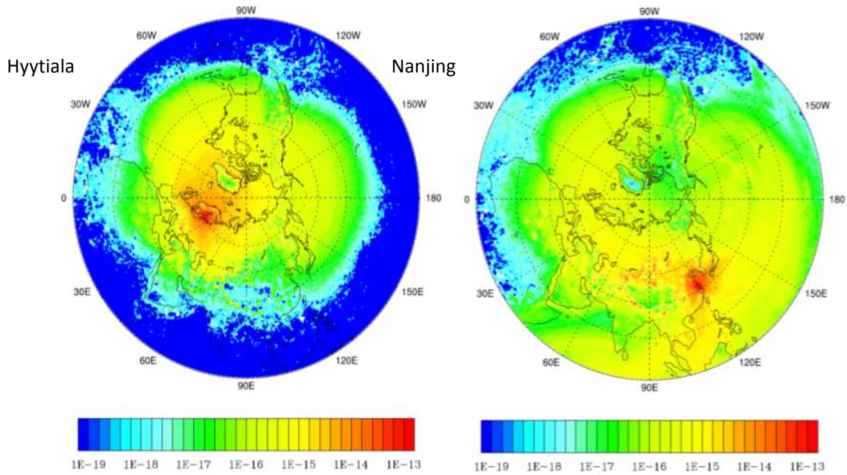

Figure 54 Annual mean "footprint" retroplume plots for the Hyytiälä and Sorpes-NJU sites, based on 20-day backward Lagrangian dispersion simulations for the year 2012, using the Hysplit trajectory model. The methodology is presented in Ding et al., 2013c.

4.3.5 Satellite monitoring

Figure 55 Areas of space information reception by AEROCOSMOS ground stations (left) and Chinese satellite-receiving stations (right, figure from RADI, CAS).

Satellite remote sensing (Figure 55Figure 54) provides data on atmospheric composition, land and sea surface properties, snow, ice, vegetation, and other parameters, as described in section 4.2.7.

The principal parameter measured by remote sensing instruments is electromagnetic radiation. Radiation measured at wavelengths in the UV, visible and infrared spectral bands provides information on atmospheric composition:

i. Aerosol properties: primary aerosol optical depth (AOD) at several wavelengths, Ångström exponents (AE) and the absorbing aerosol index (AAI). Information on aerosol physical and optical properties is used in AOD retrievals. In principle, the AOD defines aerosol properties such as the fine mode fraction, aerosol composition, single scattering albedo, *etc*. (Kokhanovsky and de Leeuw, 2009; de Leeuw *et al.*, 2011; Holzer-Popp *et al.*, 2013; de Leeuw *et al.*, 2014)
ii. Cloud properties: cloud fraction, cloud optical thickness, cloud top height, cloud droplet effective radius, liquid water path, *etc*. (Kokhanovsky *et al.*, 2011)
iii. Concentrations of trace gases (*e.g.* O_3, NO_2, CO, NH_3, H_2O, VOCs, halogens) (Burrows *et al.*, 2011)
iv. Concentrations of greenhouse gases (*e.g.* CO_2, CH_4) (Buchwitz *et al.*, 2014).
v. Ecosystems

Satellites also measure land surface, ocean and lake properties as described in section 4.2.7.

All this information is available on a global scale, with a frequency and spatial resolution depending on the instrument and the platform (satellite). In some cases, the data are available for a period of over three decades. In other cases, such as aerosols and clouds over polar regions, the retrieval is in its initial state of development due to problems arising in discrimination between snow/ice, the reflectance of which overwhelms that of aerosols or clouds.

<u>On-going satellite monitoring activities in Russia and China</u>

Russia:

AEROCOSMOS: near real-time fire monitoring, assessment of carbon monoxide emission, global ocean surface temperature distributions, monitoring of terrestrial ecosystems, forestry, forest pathology, forest resources, revealing and estimation of wildfire damage, forest certification, lumbering monitoring, reforestation estimation, detecting areas with intensive anthropogenic load.

Moscow State University geoportal (http://www.geogr.msu.ru:8082/api/index.html). Over 20 of such Russian centers have now joined in the consortium of university geoportals (UNIGEO).

Institute of space research RAS (http://smiswww.iki.rssi.ru/): reception of open remote sensing data, such as TERRA/AQUA MODIS, and thematic processing of this and other imagery, own receiving station for MODIS.

China:

RADI: comparison study of remote sensing for global environmental change from four countries (Australia, Brazil, Canada and China), covering a large fraction of the total land area of the world on four continents.

RADI: drought, fires, flood monitoring and assessment in the different Asian regions, i.e., East Asia, Middle Asia, southern Asia, West Asia and South-East Asia, under the CAS-TWAS projects.

RADI: Pan-Eurasian and Arctic aerosol satellite retrieval and dynamics; Pan-Eurasian snow/ice and permafrost satellite retrieval and dynamics.

RADI: aerosol-cloud atmosphere-hydrosphere processes of the Earth system, and characteristics of extreme precipitation events. Simulation on spatial and temporal scales supported by the Chinese academy of sciences.

RADI: Pan-Eurasian spatial and temporal land use/ land cover change and phenology detection using multi-satellite data.

RADI: Pan-Eurasian forest/grassland/wetland carbon dynamics under extreme climate events based on integrated remotely sensed data and ecological modeling.

RADI: satellite-based water cycle measurements of the cross-border river basin in Eurasia.

Satellite-based marine observations

Satellites provide valuable data on parameters of the Arctic sea ice. Sea ice types can be determined from synthetic aperture radar (SAR) images (ASAR/ENVISAT, SAR/RADARSAT-2, up-coming SAR on Sentinel-1 and others) using automatic classification algorithms (Zakhvatkina *et al.*, 2013). The concentration, extent and area of Arctic sea ice have been continuously measured by satellite microwave radiometers (SMMR/NIMBUS-77, SSMI/DMSP, AMSR-E/AQUA, AMSR 2/GCOM-W1) since 1979 (Parkinson and Cavalieri, 2008). A new era of regular monitoring of the Arctic sea ice thickness began in February 2010, with the launch of the European satellite CRYOSAT with a Synthetic aperture Interferometric Radar ALtimeter (SIRAL) onboard (Laxon *et al.*, 2013). Sea ice drift can be also retrieved using various satellite sensors, such as radars, scatterometers (SEAWINDS/QUIKSCAT, ASCAT/METOP), radar altimeters and microwave radiometers (http://cersat.ifremer.fr/data/discovery/by-parameter/sea-ice).

4.3.6 Ground-based remote sensing

To complement *in-situ* observations, especially the *in-situ* observations at the flagship stations, and satellite based remote sensing capabilities, the ground-based measurement sites need have equipment for active remote sensing from the ground. In Europe, ground-based active remote sensing is performed as part of the ACTRIS infrastructure project. A suite of lidars is well equipped to derive profiles of aerosol properties. Depending on the instruments, different sets of aerosol products can be obtained.

The ideal aerosol profile instrument setup consists of a three-wavelength Raman lidar with depolarization measurement capability (3 elastic backscatter channels, 2 N2 Raman channels, depolarization at one wavelength), and an AERONET sun photometer (Heese *et al.*, 2010), both running continuously every day of the year, together with a ceilometer (*e.g.* Vaisala CL51), and *in-situ* instrumentation. This configuration provides spectrally resolved aerosol extinction and backscatter profiles, together with the particle depolarization ratio. Aerosol typing and the retrieval of microphysical particle properties are also possible with this setup.

Lidars which cannot measure a pure molecular return signal (Raman or Rayleigh) need an assumption of the extinction-to-backscatter ratio (lidar ratio) for aerosol retrievals (Binietoglou *et al.*, 2011). Accurate extinction profiling is not possible with such instruments. When operated in the UV or visible spectral range, calibration is possible in aerosol-free regions of the atmosphere. Reliable backscatter profiles are obtained when these lidars are combined with a sun photometer to constrain the aerosol optical depth of the atmosphere. Ceilometers can be regarded as low-power backscatter lidars, and operate at 905 or 1064 nm. Because of the low signal-to-noise ratio, only layers with high aerosol loads (PBL, pollution or dust plumes) can be observed.

Hierarchy of potential aerosol products

The hierarchy of products is coupled to the instrument capabilities (from simple ceilometer to advanced multi-wavelength Raman lidars). Products i-iv can be measured with simple backscatter lidars. Products v-viii can only be measured using the ideal instrument setup (Böckmann *et al.*, 2004).

i. Attenuated backscatter profile: range-corrected and calibrated atmospheric backscatter profile (O'Connor *et al.*, 2004).
ii. Aerosol mask: atmospheric regions with enhanced aerosol loads (Binietoglou *et al.*, 2011).
iii. Planetary boundary layer height, aerosol layer boundaries: upper boundary of the aerosol layer that is in touch with the surface, and top and bottom heights of lofted aerosol layers
iv. Particle backscatter-coefficient profile (at one or several wavelengths): quantitative (calibrated and attenuation-corrected) description of 180° volume backscattering caused by aerosol particles (in $m^{-1} sr^{-1}$) (Böckmann *et al.*, 2004; Pappalardo *et al.*, 2004).

v. Particle linear depolarization-ratio profile (at one or several wavelengths): quantitative (calibrated) description of the depolarization of linear-polarized laser light caused by (non-spherical) aerosol particles

vi. Particle extinction-coefficient profile (at one or several wavelengths): quantitative description of atmospheric extinction caused by aerosol particles (in m^{-1}, derived from a pure molecular return signal, i.e. with a self-calibrating method) (Böckmann *et al.*, 2004; Pappalardo *et al.*, 2004).

vii. Aerosol type/target classification: discrimination of major aerosol types (such as dust, maritime aerosol, smoke, pollution, volcanic ash) from the depolarization ratio, lidar ratio, and/or Ångström exponent (color ratio) (Pappalardo *et al.*, 2004).

viii. Particle microphysical properties (*e.g.*, effective radius, volume size distribution, refractive index) derived from spectral extinction and backscatter coefficients.

Observing cloud and precipitation processes

Figure 56 Ground-based remote sensing of aerosols and cloud properties. Photos by Dmitri Moisseev.

Advances in understanding of the role of cloud processes are critical for reducing the uncertainty in predictions of precipitation and the water cycle. Precipitation is a key component of the global climate system, as well as of aerosol-cloud interactions. A number of cloud and precipitation profiling stations in the PEEX domain are needed to understand and map the continuum of climatically important cloud regimes, from heavy rain to light drizzle and snowfall. These stations should document cloud regimes that are representative of the region, i.e. deep convection, shallow cloud systems, frontal systems and orographic precipitation enhancement.

To record cloud and precipitation processes, comprehensive measurements of cloud and precipitation microphysical properties are needed (Figure 56). A combination of cloud radars, microwave radiometers and lidars are required to achieve this (Illingworth *et al.*, 2007)

Hierarchy of cloud and precipitation profiling station products

Raw products:

i. Radar reflectivity factor and Doppler velocity (cloud radar)
ii. Lidar-attenuated backscatter coefficient (lidar)
iii. Microwave radiometer brightness temperatures and liquid water paths

From these observations, a number of meteorological products can be derived, such as:

i. Liquid water content
ii. Ice water content
iii. Drizzle flux and drizzle drop size from radar and lidar
iv. Ice effective radius from radar and lidar
v. Turbulence kinetic energy (TKE) dissipation rate from radar Doppler velocity
vi. Precipitation rate and type

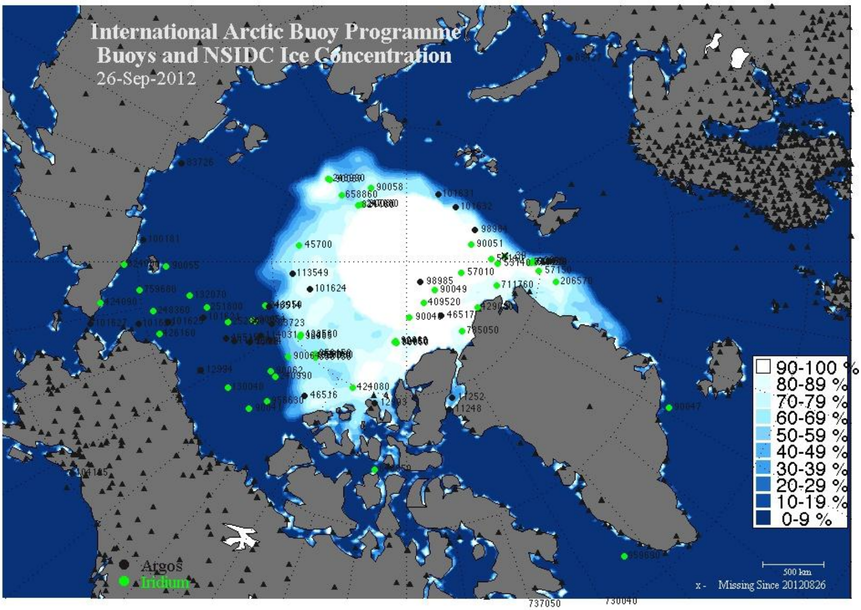

Figure 57 A map of IABP buoy locations (black and green circles) on 26 September 2012. The triangles denote terrestrial weather stations. The sea ice concentration is shown on a color scale. Figure source, http://iabp.apl.washington.edu/maps_monthly_nsidcice.html, courtesy of the University of Washington.

Data on the temperature, salinity, and current profiles of the upper ocean are obtained from buoys equipped with chains of instruments at various depths. In addition to drifting buoys, also buoys moored to the sea floor are used (Figure 57). The network of upper ocean observations is, however, far less dense than that of sea ice observations. Satellite observations provide much of the information on the upper ocean. The contemporary fleet of satellite remote sensors offers a fairly wide spectrum of parameters characterizing the state and properties of open oceans. For example past and current data on sea surface temperatures for the Arctic are available from infrared measurements by MODIS/AQUA, AVHRR/NOAA and AATSR/ENVISAT, as well as from microwave observations with SSMI/DMSP, AMSR-E/AQUA and AMSR 2/GCOM-W1. Sea Surface Salinity (SSS) has been measured regularly since 2009 by the microwave radiometer MIRAS aboard the European satellite SMOS, providing synthesized

SSS maps with high accuracy. Since 2011, SSS data are available also from the microwave radiometer AQUARIUS (NASA) aboard the Argentinian SAC-D satellite (Klemas, 2011). Current profiles are retrievable from altimeters (data available at the archiving, validation and interpretation of satellite oceanographic service, AVISO; see http://www.aviso.oceanobs.com), as well as from infrared and microwave sensors (Dohan and Maximenko, 2010). Together, this community of satellite sensors provides not only the trajectories of currents, but also their velocities and profiles (with the application of numerical simulations). Surface wind fields, wave characteristics, biogenic films and oil spills can be retrieved from SAR and optical data. The clear sky albedo is generated from data measured by the CERES instruments aboard the TERRA, AQUA and NASA-NOAA's SUOMI NPP satellites. Phytoplankton chlorophyll, dissolved organic and suspended inorganic carbon as well as primary productivity rates are retrieved from data measured by MODIS/AQUA, MODIS/TERRA, ALI/HYPERION, VIIRS/SUOMI NPP and the SENTINEL-3 satellite to be launched next year (Petrenko *et al.*, 2013).

4.3.7 *In-situ* marine observations

Figure 58 On field expeditions in the Arctic Ocean. Figures from Ella-Maria Kyrö (left) and Gennady Matishov (right).

The marine observations to be utilized in PEEX include both *in-situ* and remote sensing observations. *In-situ* measurements are made, among others, of the ocean temperature, salinity, chemical components and organic matter; of sea ice and snow thickness, temperature, structure, and composition; as well as of the marine atmosphere (temperature, humidity, winds, clouds, aerosols, chemical composition). The remote sensing observations will address the ocean surface temperature, color, and wave field, as well as sea ice properties, including the ice type, concentration, extent, thickness, and albedo, and also biological activity (plankton biomass) parameters. Research based on these observations will be supported by reanalysis and experiments applying process models, operational models, as well as regional and global climate models. Observations are made at drifting ice stations and research cruises, as well as by autonomous drifting stations/buoys and moorings and (manned and unmanned) research aircraft.

Many *in-situ* observations are collected during measurements campaigns (Figure 58) based on ships and ice stations. These have strongly contributed to improved understanding of the physical processes in the Arctic sea ice, ocean, and atmosphere, but most of the campaign data represent point measurements from the spring and summer seasons. The Russian drifting ice stations are among the few campaigns that have yielded year-round data. PEEX will also closely collaborate with the mosaic (multidisciplinary drifting observatory for the study of Arctic climate, http://www.mosaicobservatory.org) initiative for a year-round drifting station, which is planned for construction around 2018. A challenge for the PEEX marine observations is to obtain regular observations throughout the year with a reasonably good spatial and temporal resolution. These require automatic *in-situ* or remote sensing observations, and the technical capabilities available for such observations strongly depend on the variable to be measured.

Considering sea ice, the most essential *in-situ* observations include the ice drift vector, which is detected on the basis of GPS buoys deployed on sea ice. Since 1979, a network of buoys has been maintained by the International Arctic Buoy Programme (IABP, http://iabp.apl.washington.edu). At present, there are typically 50-100 buoys simultaneously in the Arctic Ocean and its marginal seas (Figure 57). Some of the buoys, so-called ice mass balance buoys, also measure the sea ice and snow thickness, as well as the temperature profiles through the ice and snow. In a few locations, such as the Fram Strait, the sea ice thickness is also measured by applying bottom-based sonars. Major challenges remain in obtaining regular observations on sea ice structure, chemistry and biology.

4.3.8 Airborne observations

The PEEX airborne observations are based on ongoing measurement activities as well as new initiatives. One of the main advantages of airborne research platforms is that aircraft enable *in-situ* measurements to be carried out in the atmosphere over vast areas. Furthermore, airborne observations can track the studied atmospheric phenomena at long ranges. If the aircraft is well-equipped, complex measurements of the atmosphere and the underlying surface can be performed simultaneously. The main disadvantage is the high cost of the flights. Nevertheless, airborne methods are very useful for exploring the Arctic, where it is difficult to establish a dense surface observational network. Furthermore, the aircraft measurements provide a link between the different PEEX ground-based supersites, by providing data between the stations.

Examples of airborne activities

Europe

Figure 59 Examples of airborne measurements in Europe. Cessna flight measurements by University of Helsinki (left) and PEGASOS zeppelin measurements (middle and right). Photos by Ella-Maria Kyrö.

Russia

Figure 60 Airborne measurements in the Tomsk area. Photos from IAO SB RAS.

Figure 61 Optik TU-134 aircraft laboratory. Photo from IAO SB RAS.

CNRS, FR & IAO SB RAS: “airborne extensive regional observations in Siberia-Yak-Aerosib”

NIES, JP & IAO SB RAS: “measurements of greenhouse gases affected by Siberian ecosystems”

Belan B.D., Arshinov M. YU., Panchenko M.V., Institute of Atmospheric Optics SB RAS, Russia, Tomsk

CAO (Central Aerological Observatory (CAO) of Roshydromet): opportunities in ground-based and airborne investigations of atmospheric composition (Borisov YU. A)

Dyukarev E.A., Krutikov V.A., Kabanov M.V., Institute of Monitoring of Climatic and Ecological Systems SB RAS, Russian federation, Tomsk

Optik TU-134 aircraft laboratory (Figure 60, Figure 61). Research capabilities: *in-situ* measurements of CO_2, CH_4, CO, O_3, black carbon, aerosol scattering coefficient, aerosol size distribution, ambient temperature and humidity, navigation parameters, as well as filter sampling and lidar sensing of aerosols. A more detailed description can be found in Antokhin *et al.* (2012), where the scientific complex deployed on the previous airborne platform is described, except for the recently installed Picarro G2301-m analyzer, and the new generation eye safe Cimel lidar to be installed in 2014.

China

Figure 62 Airborne observations in China. Photo RADI, CAS.

The airborne remote sensing center of RADI operates two Cessna citation S/II airplanes, and two new advanced ARI 21-700er airplanes with 10 new sensors (Figure 62).

The two new remote sensing aircraft are equipped with 10 state-of-the-art remote sensors in the visible, infrared, and microwave bands, a high-performance data processing system, an airborne atmospheric laser radar, a digital CCD camera, an airborne whiskbroom imaging spectrometer (0.45 µm - 12.5 µm), an airborne 3-D light detection and ranging instrument, an airborne x-band interferometrer (SAR), and an airborne pushbroom imaging spectrometer (0.45 µm - 2.5 µm).

Airborne marine observations

Many of the IABP buoys are equipped with pressure and temperature sensors for measurements of the atmosphere over the Arctic Ocean. Assimilation of these data into models has a clear positive impact on the quality of atmospheric reanalyzes (Inoue *et al.*, 2009). The sea ice decline tends, however, to generate data gaps over the open ocean. During onshore winds, also coastal/archipelago radiosounding and surface weather station observations yield valuable information on the state of the atmosphere over the Arctic Ocean. The surface station data, as well as ship observations, are collected *e.g.* in the GIStemp archive (Hansen *et al.*, 2010). Unmanned Aerial Systems (UAS) have a great potential for atmospheric observations over the Arctic Ocean (Starkweather *et al.*, 2013). Various types of UAS are presently available, ranging from small ones (less than 1 kg) applicable for vertical profiling of the lowermost 1-3 km, to large ones with an operation time of tens of hours, and capable of reaching the lower stratosphere. Many UAS can simultaneously make meteorological observations and remote sensing measurements of ice and ocean properties, such as the surface temperature and albedo, as well as the ice concentration and freeboard.

4.3.9 Laboratory studies

Figure 63 CLOUD chamber in CERN. Photo by Jonathan Duplissy.

Research within PEEX involves not only comprehensive field observations, but also laboratory experiments. Experimental work is conducted in various laboratories in Europe, Russia and China. As an example, aerosol emissions from Siberian boreal forest and forest fires are crucial for the understanding of environmental and climate change impacts in subarctic regions and the Arctic. The ability of biogenic and biomass burning aerosol to absorb or scatter incoming radiation, as well as act as cloud condensation nuclei, strongly depends on their optical, microphysical, chemical and hygroscopic characteristics. The regional database for these properties is sparse, and laboratory investigations are needed to produce the required data.

Laboratory experiments important for the PEEX domain are conducted *e.g.* in the CLOUD-chamber in CERN (Kirkby *et al.*, 2011; Figure 63), and in the Jülich Plant

Atmosphere Chamber (JPAC) hosted by the Leibniz Institute for Tropospheric Research (TROPOS). These experiments shed light on the initial steps of secondary aerosol formation (Schobesberger *et al.*, 2014), which is an important regional phenomenon in the boreal environment (Kulmala *et al.*, 2004). The work conducted at the Paul Scherrer Institute chamber has also underlined the importance of organic vapors to the initial clustering process (Riccobono *et al.*, 2012). Laboratory experiments relevant to PEEX are conducted also in various laboratory facilities in Russia and China.

The comprehensive investigations of biomass burning aerosols are currently performed under controlled conditions in a large (1800 m^3) aerosol chamber at the IAO (institute of atmospheric optics of the Siberian branch of the Russian academy of sciences). The chamber is equipped with modern devices for the measurement and definition of radiative-relevant optical-microphysical characteristics, such as the aerosol scattering coefficients, mass concentrations of aerosol and black carbon (BC), BC fraction, single scattering albedo (SSA) in the visible region and particle size distributions. The chamber is also equipped for the sampling of aerosol particles on filters and metallic substrates for subsequent gravimetric definition of PM10/PM2.5, and for chemical analysis of the biomass burning aerosols.

Size distributions of smoke particles, and their complex indexes of refraction, Ångstrom parameters of scattering and absorption, single scattering albedo, and emission factors of size-selected aerosols, are studied using polarization spectronephelometry of scattered radiation, aethalometers, photoelectrical particle counters and gravimetry. Comprehensive characterization of the physico-chemical properties of combustion aerosols is performed, including morphology, elemental composition, surface chemistry, carbon and ion content, organic carbon / elemental carbon content, and the concentration measurements of organic/inorganic and selected organic compounds (levoglucosan, mannosan and dycarboxylic acids). Scanning electron microscopy coupled with energy-dispersive x-ray spectroscopy, Fourier transform infra-red spectroscopy, capillary electrophoresis, thermo-optical techniques and chromatography are proposed for further characterization.

The main processes of biomass burning in Siberian boreal forests are smoldering and open fires. In simulations of the different properties of aerosol emissions, and their dependence on the fuel type (pine, debris and others), the mixing states of the aerosols originating from the two fire types, the combustion conditions, and aging in the atmosphere all need to be modeled. Special attention is needed for the identification of microphysical, morphological and chemical micro-markers of combustion aerosols assigned to Siberian boreal wildfires. Individual particle characterization, supported by cluster analysis, allows the quantification of smoke structures and major types of particles. This helps us discriminate between different types of biomass burning, and identify their morphological and chemical micromarkers.

The black carbon (BC) fraction, single scattering albedo, emission factors, organic to elemental carbon ratio (OC/EC) ionic composition, and molecular markers (anhydrosugars) of aerosol produced by combustion all depend significantly on the combustion phase. The largest emissions of organics and levoglucosan occur during the smoldering phase. The optical and chemical profiles for the dominant components in particulate matter need to be obtained in order to assess the contribution of Siberian biomass burning to atmospheric pollution and to the aerosol/climate system in general.

4.4 HARMONIZED DATA PRODUCTS

Figure 64 The multi-platform PEEX measurements provide crucial data on Earth system behavior.

The PEEX program will produce an extensive amount of observational measurement data, scientific publications, method descriptions and modeling results (Figure 64). 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 communities. The PEEX data will be harmonized with international measurement systems and data formats, in collaboration with existing Arctic and boreal infrastructure projects. A coherent and coordinated observation program of the Arctic-boreal regions needs to be built in co-operation with existing Arctic and boreal stations and networks.

4.4.1 Common data products and formats

The organization of databases, data products and formats will be made in collaboration with ongoing, joint European, Chinese, Russian and American activities. The development of instrumented sites is not trivial, and will require not only technical expertise on best measurement practices, but also the parallel development of data management capacities in order to utilize the full scientific potential of the collected data. Data management capacities embrace all issues that facilitate the use of data by external users, from data storage to the access to both raw and processed data, and data products. In this framework, the need for standardized data products is demanded by the user communities. PEEX should therefore implement data portals, (near) real-time automatic data processing workflow tools, data retrieval algorithms and user interfaces to facilitate use of data and, on the longer term, increase the number of users. The most relevant projects in the years 2013-2020 are linked to on-going EU-FP7 and H2020 projects, either through the single research infrastructures already mentioned, through the FP7-ENVRI-project "Common operations of environmental research infrastructures" in Europe, a collaboration effort of the ESFRI environment cluster to develop common e-science components and services for their facilities, or through the FP7-COOPEUS-project "Transatlantic Cooperation in the field of Environmental Research Infrastructures" between Europe and the USA. The aim of these research infrastructure projects is the identification of next-generation user-friendly data structures and formats, which will facilitate the inter-domain and multi-disciplinary approach relevant to PEEX. The key institutes in Europe are those with relevant data centers such as the Norwegian Institute for Air Research, NILU (Norway), where a major part of the atmospherically relevant datasets/products are currently stored and distributed, and the different components of the world data centers of the WMO-GAW program (WMO-GAW 2014).

The PEEX network will utilize the existing knowledge of WMO-GAW recommendations and guidelines for establishing long-term, highly standardized data formats and network systems. The Global Earth Observation System (GEOSS) connects PEEX to the Intergovernmental Group on Earth Observations (GEO) cold regions activities. GEOSS has already listen PEEX among several other international programs and global research infrastructures enhancing Arctic data - information coordination for cold regions. These include ACTRIS2, ICOS, SAON, SIOS, INTERACT, ABDS-ABA/CAFF, and CRYOCLIM. Furthermore, the Future Earth initiative will enhance the international visibility of PEEX network, and opens up opportunities for the PEEX office to act as a regional node for Future Earth in the Arctic and boreal zone.

The following is a list of examples of *in-situ* observational data provided by the PEEX *in-situ* infrastructures and in connection with satellite observations:

Short-lived pollutant concentrations and greenhouse gas concentrations in the air and biosphere, and their deposition on vegetation, snow and ice surfaces.

Seasonal evolution of terrestrial and oceanic snow and ice cover.

Surface shortwave and longwave radiation and heat fluxes between the compartments.

Surface albedo

Cloud properties with active remote sensing from the ground, complemented with satellite observations.

Boundary layer structures and vertical profiles of gases, aerosols and clouds.

Spatial variability of relevant meteorological variables.

Ecosystem functioning, *e.g.* primary productivity, transpiration and water use efficiency, soil respiration, nutrient cycling.

Production, exchange and fluxes of *e.g.* volatile organic compounds, methane and nitrous oxide between the ecosystems and the atmosphere.

Vegetation phenology, length of growth period, greening.

Chronosequences of different disturbances like forest fires.

Population migration (birds, insects, mammals, plants), species extinction, invasive species occurrence.

Transitions from woodlands to grasslands/tundra or *vice versa*, treeline advancement towards higher and northern latitudes.

4.5 Modeling and analysis infrastructures

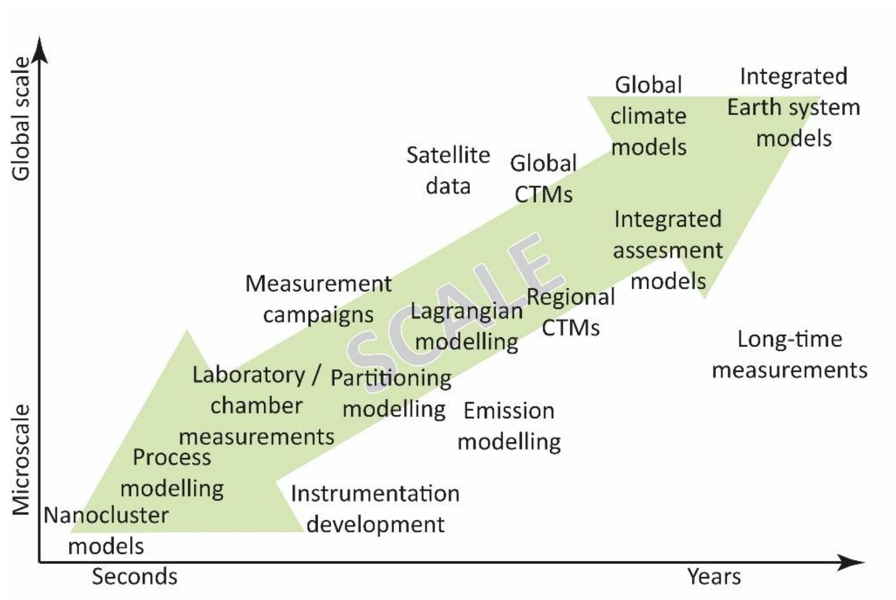

Figure 65 The temporal and spatial scales of modeling and observations within the PEEX domain.

The PEEX Modeling Platform (MP) is characterized by a complex integrated Earth System Modeling (ESM) approach, in combination with specific models of different processes and elements of the system, acting on different temporal and spatial scales. 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: scenario analysis, inverse modeling, and modeling based on measurement needs and processes (Figure 65). The models are 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.

As the part of the PEEX initiative, a hierarchy/framework of modern multi-scale models for different elements of the Earth system, integrated with the observation system, is needed. This will both support the PEEX observational system, and help answer the PEEX scientific questions.

Earth system modeling is one of the key topics in the international debate on land-atmosphere interactions in relation to global change. The question is, whether or not the ESM components actually represent how the Earth is functioning. The ESMs consist of equations describing processes in the atmosphere, ocean, and cryosphere, and in the terrestrial and marine biospheres. ESMs are the best tools available for analyzing the effect of different environmental changes on future climate, or 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 the recent decades.

The processes, and hence the parameterizations, included in ESMs are still based on insufficient knowledge of the physical, chemical and biological mechanisms involved in the climate system. Also, the spatial or temporal resolution of known processes in the models is often insufficient. Global-scale modeling of land-atmosphere-ocean interactions using ESMs provides a way to explore the influence of spatial and temporal variations in the activities of land systems, and on the climate. However, there is a lack of methods for forwarding improvements in process understanding effectively to ESMs, and for linking all this to the decision-making process. The Arctic-boreal geographical domain plays a significant role as a source of both natural and anthropogenic greenhouse gases, aerosols and other emissions in the Earth system.

A network of monitoring stations, with the capacity to quantify the interactions between neighboring areas (ranging from the Arctic and the Mediterranean to the Chinese industrial areas and the Asian steppes) is needed. For example, in addition to the development of Russian stations in the PEEX area, strong co-operation with surrounding research infrastructures needs to be established, along the lines of the ICOS and ACTRIS networks. This allows PEEX to obtain a global perspective on emissions transport, and on the transformation and ageing of pollutants entering and exiting the PEEX area.

To meet challenges related to the growing volumes of global and PEEX-domain environmental data, the creation of Virtual Research Environment (VRE) archives is required. This enables researchers to process structured and qualitative data in virtual workspaces. VREs should integrate data, networks and computing resources, providing the interdisciplinary climatic research community with the opportunity to obtain a profound understanding of ongoing and possible future climatic changes, and their consequences for the targeted region.

4.5.1 Earth System Models

There has been criticism that the processes, and hence parameterizations, in the 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. We lack ways to forward the necessary process understanding effectively to the ESMs. Within PEEX we will tackle this issue.

The PEEX modeling platform aims to simulate and predict the behavior of the physical aspects of the Earth system, and to improve understanding of the bio-geochemical cycles in the PEEX domain and beyond. The environmental changes observed in this region imply that, from the point-of-view of atmospheric flows, the lower boundary conditions are changing. This is important for applications with immediate relevance for society, such as numerical weather prediction. The PEEX infrastructure will provide a unique view of the physical properties of the Earth's surface. This can be used to improve assessment and prediction models. It will also directly benefit citizens of the north through, for instance, better early warnings of hazardous events. On longer time-scales, models of the bio-geochemical cycles in the PEEX domain absolutely need support from the new monitoring infra-structure in order to better measure and quantify soil and vegetation properties.

In the most basic setup, the atmospheric and oceanic Global Circulation Models (GCMs) are connected to each other, sharing *e.g.* fluxes of momentum, water vapor and CO_2. Traditionally, the land compartment has been an integral part of the atmospheric model, but in most modern ESMs, the land model has been clearly separated. In most cases, the GCMs are complemented by other additional sub-models, covering, for example, atmospheric chemistry and aerosols, biogeochemistry, or dynamic vegetation. Although the models can communicate directly with each other, a separate coupler is usually used as an interface between different sub-models.

Evaluation of process-models to improve GCM parameterizations

One of the main PEEX modeling activities is to evaluate process models of biosphere-cryosphere-atmosphere interactions in the Pan-Eurasian region, and to improve GCM parameterizations. The PEEX scientific plan is designed to serve as a research chain that aims to advance our understanding of climate and air quality. It can be visualized as a series of connected activities, starting at the molecular scale, and extending to the regional and global scales. The temporal scale of the research chain extends from nanoseconds to centuries, or even to geological timescales via firn and ice cores in glaciers and ice sheets. Firn and ice cores reveal past variations in climate in the Pan-Eurasian region, and can help identify the corresponding forcing agents.

A combination of direct and inverse modeling will be applied to the diagnosing, monitoring and forecasting of air pollution in Siberia and Eurasia (Penenko *et al.*, 2012). Regional models, coupled with global models by means of orthogonal decomposition methods, allow the correct introduction of data on global processes onto the regional level, where environmental quality control strategies are typically implemented (Baklanov *et al.*, 2008).

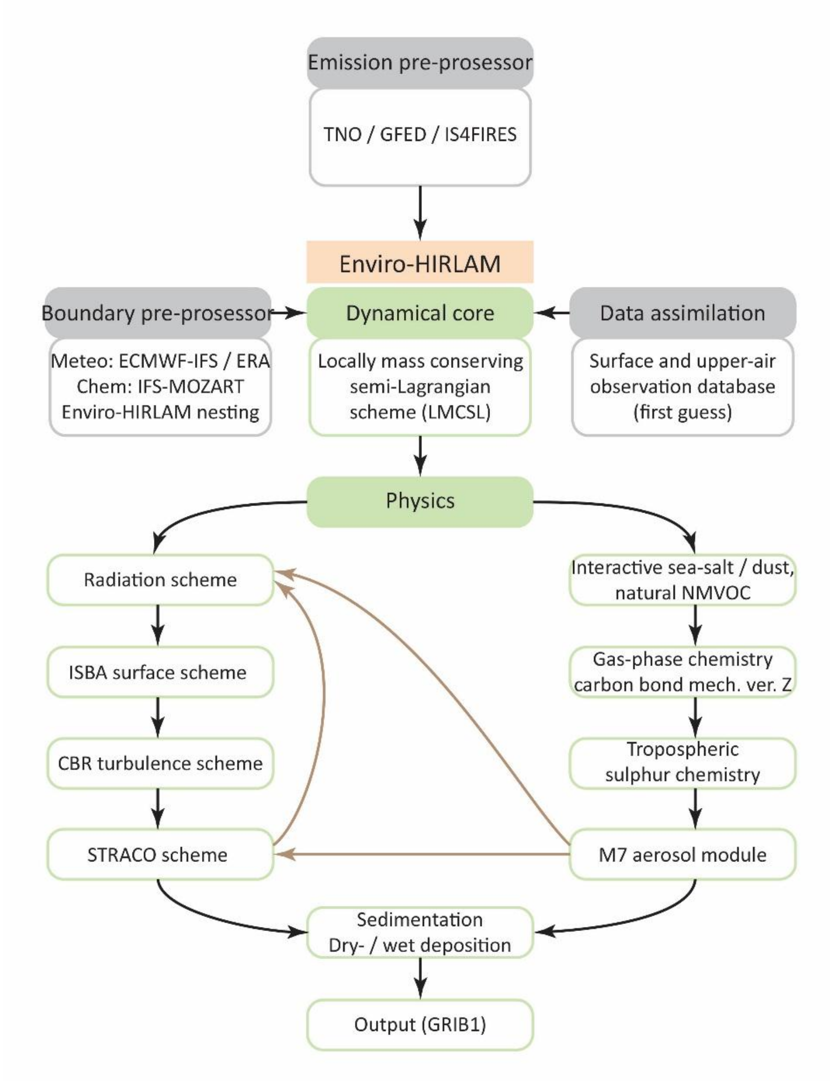

Figure 66 The "one-atmosphere" concept visualized as the two-way interaction of meteorological and chemical processes. This also illustrates the PEEX strategy for a new generation of integrated chemistry-climate modeling systems for predicting atmospheric composition, meteorology and climate change. Figure adapted from Nuterman et al., 2013.

Recently, a new concept and methodology for atmospheric modeling called the "one-atmosphere" approach has been developed (Figure 66). In the one-atmosphere approach, atmospheric modeling is carried out using two-way interactions between meteorological and chemical processes (Baklanov *et al.*, 2011; Zhang *et al.*, 2012). Atmospheric chemistry transport models should thus include not only health-affecting pollutants (air quality components), but also greenhouse gases (GHG) and aerosols, which affect climate, meteorological processes, *etc*. This approach should be used in the development of a new generation of integrated chemistry-climate modeling systems for predicting atmospheric composition, meteorology and climate change. The on-line integration of meteorological/climate models and atmospheric aerosol and chemical transport models allows the utilization of all meteorological 3-D fields at each time step, and the modeling of feedbacks of air pollution (*e.g.* aerosols) on meteorological processes and climate forcings, and further on the atmospheric chemical composition (Figure 66). This promising approach for future atmospheric simulation systems (as a part of, and a step toward, better ESMs) will be considered in PEEX. It will lead to a new generation of models for climatic, meteorological, environmental and chemical weather forecasting (EUMETCHEM, 2012: http://www.eumetchem.info), and also provide tools for environmental risk assessments and strategy optimization.

Science questions, the integrated ESM approach

How can we describe the response of BVOC emission to changes in atmospheric chemistry, and the related impacts on vegetation (CO_2 impact, ozone induction, nitrogen dependency), taking into account the phenological and physiological states of the plants as well as immediate climatic conditions?

How can we quantify the deposition of air pollutants (*e.g.* ozone) onto vegetation, and how can we distinguish explicitly between stomatal- and non-stomatal deposition (including chemical deposition by BVOC emissions, ozone impact on stomata)?

4.5.2 Socio-economic models

The socio-economic development of the Pan-Eurasian region depends on a number of global and macro-economic processes such as future development of the world's energy production and consumption, the national and global demand for natural resources, specifics of the national policies for the development of northern territories, and policies with respect to small ethnic communities. Climate change will play a substantial role in the overall socio-economic predictions and assessments, as will existing climate policies which already influence economic development. The regional dynamics of the post-soviet period were characterized by many negative social tendencies and processes, such as the substantial migration of populations away from the northern regions, the decline of thousands of taiga settlements due to the collapse of the soviet forest industry, the destruction of transport connections and the substantial deterioration of social services, including medicine, education and the supply of indispensable goods, particularly in remote territories.

A crucial prerequisite for the socio-economic development of the region, particularly in high latitudes, is the transition to sustainable development patterns aiming at the creation of acceptable standards of human life, and the maintenance of the environment and the regional stability of the biosphere. In Russia, this transition is declared as a starting point for national and regional policies of natural resources management. However, the reality is far from such declarations. The ecological and environmental situation in large regions of northern Eurasia can be described as an ongoing severe ecological crisis, initiated by the unregulated anthropogenic pressure on nature, and the explosive increase in the production and transport of natural resources, mostly fossil fuels. Altogether, this has resulted in decreases in the quality of all major components of environment – air, water, soil and vegetation – and has generated many risks. The Pan-Eurasian region is one of the most vulnerable areas of the globe.

Given the complexity and uncertain character of predictions of socio-economic development in the region, PEEX will employ integrated modeling as a major modeling tool (Figure 67). Integrated modeling combines the consideration of problems of different nature – economic, ecological and social. One of the planned approaches is the use of integrated clusters such as IIASA's ESM integrated modeling cluster (http://www.iiasa.ac.at/web/home/research/researchprograms/ecosystemsservicesandmanagement/integrated-model-approach.en.html). This cluster integrates different models: the economic model GLOBIOM (Havlik *et al.*, 2011), the forest specialized model G4M (Rametsteiner *et al.*, 2007), the agricultural model epic (Izaurradle *et al.*, 2006) and others. These are then combined in a common modeling framework. The ESM cluster could be modified and adapted for the region's conditions and problems.

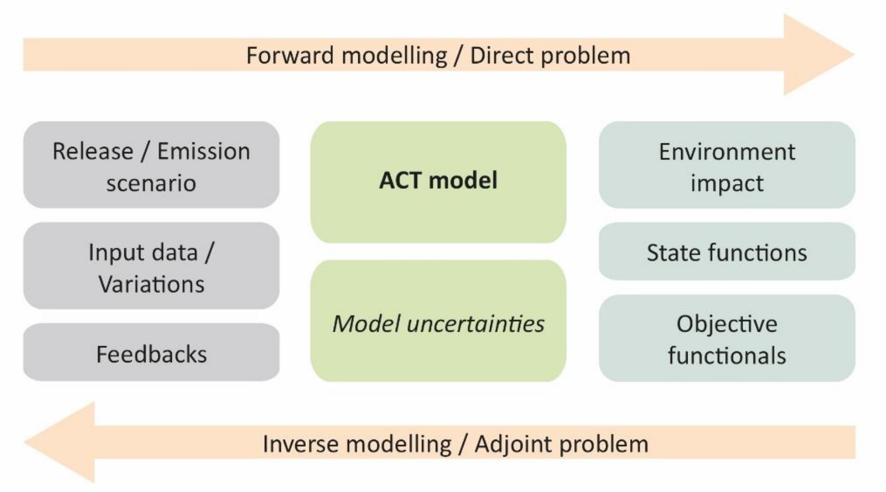

Figure 67 *A scheme for environmental risk assessment and mitigation strategy optimization based on forward/inverse modeling. ACT models = atmospheric chemical transport models Figure after Baklanov et al., 2012.*

Another promising modeling approach is the combination of agent-based and stock-flow modeling in a participative analysis of the integrated land system. In essence, an agent-based model considers a collection of individual, heterogeneous decision-makers, referred to as agents, who consider their options in their respective environments and make decisions on the basis of a pre-defined set of rules. The agents are influenced by different internal and external factors, and several different scenarios can be explored. Real options modeling will be used to investigate the impacts of uncertainty emerging from a lack of information. In questions related to adaptation and mitigation strategies and development, a variety of social science methods will be employed in order to gain a better understanding of how these political processes take place, and how they can best be supported. This includes a variety of participatory methods for including relevant stakeholders.

4.5.3 Virtual research environments for supporting regional climate and ecological studies

The volumes of environmental data archives are growing immensely due to recent developments in modeling, high performance computing and sensors. This makes their comprehensive analysis using conventional in-house computing facilities, data storage and processing software impossible. One of possible answers to this challenge is the creation of virtual research environments (VRE), which provide researchers with an integrated access to huge data resources, tools and services across disciplines and user communities. VREs enable researchers to process structured and qualitative data in virtual workspaces (de Roore and Goble, 2007). Thematic VREs can integrate data, network and computing resources, providing the interdisciplinary climate research community with the opportunity to obtain a profound understanding of ongoing and possible future climate changes and their consequences.

The first steps in the development of PEEX domain VRE elements, aimed at regional climatic and ecological monitoring and modeling, as well as at continuous education and training support, were done as part of the FP6 EC ENVIRO-RISKS project (Baklanov and Gordov, 2007). An interactive web-system for regional climate assessments, based on standard meteorological data archives, was developed and launched (http://climate.risks.scert.ru) (Figure 68). The experimental software and hardware platform "climate" was recently developed on this basis. "Climate" is intended for an integrated analysis of heterogeneous georeferenced data (http://climate.scert.ru; Gordov *et al.*, 2013;

Shulgina *et al.*, 2013; Pkladnikov *et al.*, 2013). It can be used as a PEEX VRE element prototype, and as a test bench for the VRE approach. Currently, this VRE element is accessible via a geoportal from the same link (http://climate.scert.ru). The VRE integrates the WRG and "planet simulator" models with basic reanalysis and instrumental measurement data, and supports the advanced statistical analysis of stored and modeled-on-demand data. Using the VRE, one can run the integrated models, preprocess the modeling results using dedicated modules for numerical processing, perform data analysis, and visualize the obtained results. New functionalities have recently been added to the statistical analysis toolset. These are intended for the detailed studies of climate extremes occurring in northern Asia. The VRE element also supports thematic educational courses for students and post-graduate students, including the relevant training (Gordova *et al.*, 2013). The VRE element "climate" provides specialists in multidisciplinary research projects with reliable and practical instruments for integrated research on climate and ecosystem changes on global and regional scales. With the help of "climate", even a user without programming skills can process and visualize multidimensional observational and model data through a unified web-interface, simply by using a normal web browser.

The PEEX VRE to be developed should integrate different distributed data storage, processing and analysis systems, and a set of models of complex climatic and environmental processes run on supercomputers. VRE-specific tools should be aimed at high-resolution rendering of on-going climatic processes occurring in northern Eurasia, and reliable prognoses of their future dynamics in selected sets scenarios of human activities.

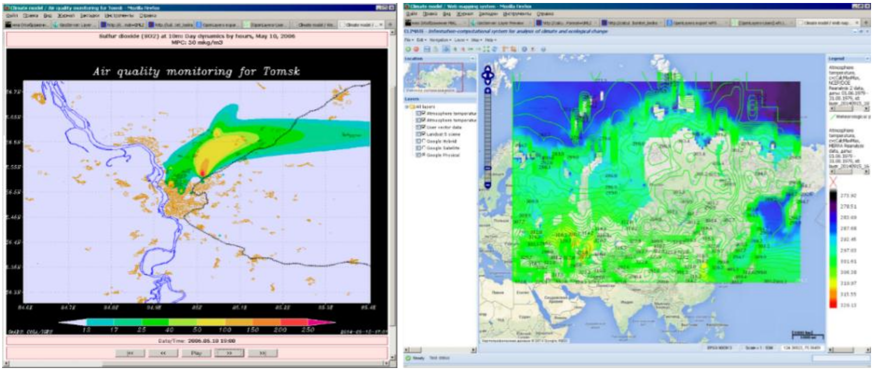

Figure 68 The ENVIRO-RISKS web portal climate site (http://climate.risks.scert.ru/) provides access to an interactive system for regional climate and environment assessments based on meteorological and air quality data (in this case, the sulfur dioxide concentration in Tomsk, Russia) (left). Right, an example of a user interface of the "climate" platform, supporting multidisciplinary Earth/environmental sciences regional studies.. Figures from Evgeny Gordov SCERT/IMCES SB RAS.

Taking into account the diversity and integrated character of research to be done by PEEX, it is important for the program to have a solid georeferenced basis dataset which contains all the accumulated information about, for example, landscapes, terrestrial ecosystems, water bodies, or the biological productivity of the biosphere and its interaction with the lower troposphere. This basis will be realized in the form of an integrated land information system (ILIS) for northern Eurasia (Schepachenko *et al.*, 2010). The ILIS used in PEEX will be a multi-layer geographic information system (GIS) with corresponding attributive databases. The georeferenced background of the ILIS is represented by a hybrid land cover database, which is developed using multi-sensor remote sensing and all available ground-based information (forest and land state accounts, monitoring of disturbances, verified data of official statistics, *in-situ* measurements, *etc*.). The basic resolution of the ILIS is 1 km^2. Finer resolution could be used for regions undergoing rapid changes of land cover. The initial version of the ILIS will developed based on data for the year 2011. The ILIS is planned to be used for the following purposes: (i) introduction of a unified system of classification and quantification of ecosystems and landscapes; (ii) as a benchmark for tracing the dynamics of land-use land cover; (iii) for empirical assessment of fluxes of interest

(NO_2, CH_4, VOC, NOx, aerosols, *etc*.); (iv) for use in different models and for model validation; (v) to obtain gradients needed for the up-scaling of "point" data.

The methodology for multidisciplinary probabilistic environmental risk and vulnerability assessments elaborated in the Arcticrisk-Narp and FP6 ENVIRO-RISKS projects (Baklanov *et al.*, 2006a-c; Mahura *et al.*, 2005; 2008) can be refined, and applied as a web-based tool for the evaluation of potential impacts of environmental changes and hazards on the ecosystems and populations in the PEEX region. The GIS and Google Earth components of such a tool can be used to further improve visualization and analysis of the results. Using this online web tool, short- and long-term (ranging from a day up to a year) simulations with trajectory and dispersion modeling approaches can be used to construct various indicators for potential impacts of, for example, continuous emissions, accidental releases, or planned constructions and operations, at selected geographical locations. The simulations include factors such as atmospheric transport pathways, airflow probabilities, maximum reaching distances, fast transport, precipitation factors, time integrated air concentrations, dry, wet, and total deposition patterns, as well as other indicators. The results of the simulations can be used as input for the further evaluation of doses, impacts, risks and short- and long-term consequences for populations and the environment from potential emission sources. Risk evaluations and mappings will be important for decision-making processes, and for the analysis of environmental, social, and economic consequences for different geographical areas and various population groups. This analysis needs to take into account all relevant social-geophysical factors and probabilities, and make use of demographic and administrative databases. All these can be provided through the web portal to be developed under PEEX.

5. PEEX IMPACT ON SOCIETY (F3)

There are a number of ways to advance the society dimension and societal impact within PEEX. These will be developed in collaboration with the PEEX research agenda (F1) and the PEEX infrastructure (F2) plans, as well as the education and knowledge transfer aspects (F4). The strategy is two-fold. First attention is paid to the societal needs of the PEEX region when formulating the research questions within the research agenda. This has already been done in this Science Plan. Further investigations of this issue are carried out when more detailed research projects are launched as part of PEEX. This is particularly relevant to the research questions addressing the anthropogenic system. Second, the society dimension is taken into account when addressing the future needs of the research infrastructure, and the role of societal actors in it. A number of interactive methods can be employed here, ranging from stakeholder workshops to participatory research. Accordingly PEEX will act as a test laboratory for co-design. These will be further explored and developed as needed when the PEEX science plan is implemented.

5.1 CLIMATE: MITIGATION AND ADAPTATION

Mitigation of greenhouse gas emissions and adaptation to the impacts of climate change are the two main societal responses to climate change. Mitigation activities include changes in the ways that energy is produced and consumed in societies, while adaptation measures are taken to ensure that risks and vulnerabilities arising from the impacts of climate change are avoided as much as possible. Both include changes in energy systems, agriculture, the built environment and forestry. These are thus the main sectors within which mitigation and adaptation need to be taken into account. In addition, it is important to recognize and analyze the inter-relationship between adaptation and mitigation. Some of the key questions addressed in the IPPC 2007 report are: How much adaptation and mitigation activities would be optimal? When should they be performed, and how should the two be combined? Are adaptation and mitigation substitutes, or are they complementary to one another? What is the potential for creating synergies between the two responses? How do their costs and effectiveness vary over time? The Fifth Assessment Report of the IPCC notes that in the coming years, there is a need to avoid trade-offs and identify synergies between mitigation and adaptation. It is also necessary develop institutional links and mainstream mitigation and adaptation concerns into broader sustainable development policy (Denton *et al.*, 2014).

5.1.1 Mitigation and societal impact

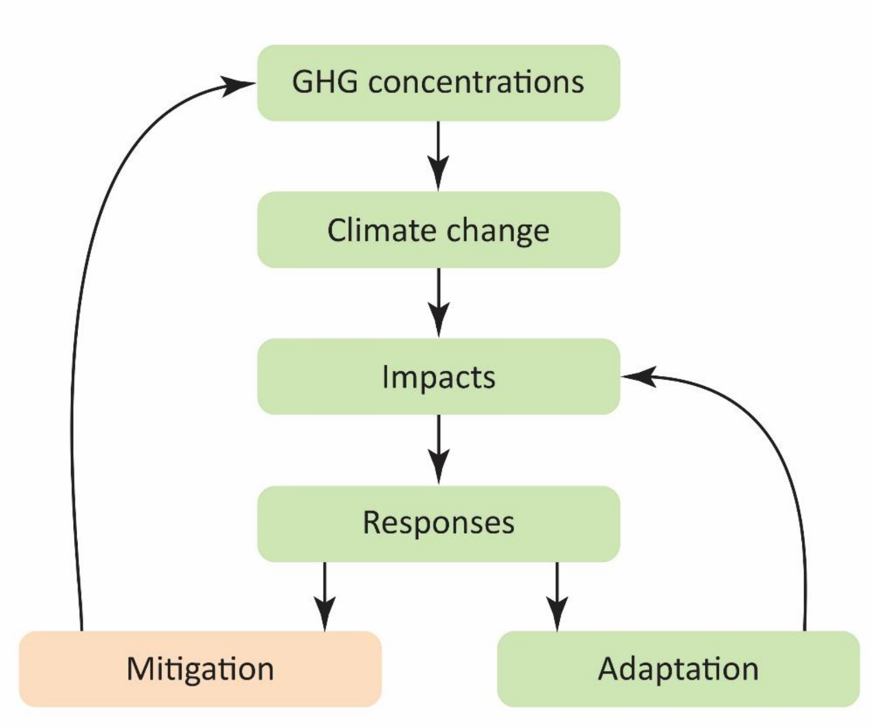

Figure 69 Mitigation is understood as activities to protect nature from society (Stehr et al., 2005).

SYNOPSIS The primary aim of mitigation plans/strategies is a move towards low-carbon societies in the Arctic-boreal region. Future actions are needed first stabilize and then reduce greenhouse gas emissions from agriculture and forestry, energy production and manufacturing. For this GHG stabilization, we need to develop new technologies as well as management and urban planning practices, and increase the use of renewable energy (such as wind). Furthermore, conservation activities and changes in land use patterns in agriculture and forestry, as well as protection of ocean ecosystems, are needed to protect the natural carbon sinks.

PEEX addresses the following main topics of mitigation

Energy production, energy efficiency and manufacturing

Industrial activities such as energy production and manufacturing are some of the key anthropogenic activities contributing to environmental changes. The main environmental consequences of these activities are pollution, land transformations and the intense use of natural resources. On the other hand, industrial activity is a vital part of the economy of all contemporary societies. One of the challenges in the forthcoming decades is to optimize industrial activities in order to minimize their impacts on the environment, without reducing their productivity. PEEX will contribute to solving this problem by examining the feedbacks between anthropogenic activities and the environment. PEEX will conduct local case studies of the interactions between ecosystems and industrial infrastructure, and use these to build an efficient model of such interactions. This is a necessary step for optimizing the human footprint in the environment. Improving energy efficiency and increasing the use of renewable energy imply saving scarce energy resources, reducing the pressure on the environment, supporting technology transfer, and promoting technological innovations. The implementation platform may employ modified versions that take into account policy changes (refer to IIASA used procedures).

Both Russia’s North and East possess abundant mineral resource potential. The resource orientation of the economy in northern and eastern Russia increased in the post-Soviet period, and was influenced primarily by the product market. The natural resource development sector of the economy (mining and forestry) will remain dominant in the majority of these territories for the next decades. However, serious socio-ecological problems remain. In the post-Soviet period, profitability has become the dominant criteria in the decision-making of enterprises and federal/regional governments, while socially responsible and ecological criteria have not yet been implemented. Consequently, the local population is now faced with grave ecological problems in areas where natural resource are exploited industrially. There are also social and ecological conflicts between the industrial exploitation of natural resources, and the traditional forms of nature management (*e.g.* reindeer breeding). Processes aimed at mitigating the negative impacts of resource utilization are weak, because the federal government takes a too large share of the tax revenues collected in areas where the resources are exploited. Consequently, local authorities cannot fund adequate social and environmental protection measures.

Coordination in management of water resources and ecosystem services

A great deal of control and co-ordination is needed in order to optimize the interactions between the industrial infrastructure and the environment. Coordinating the management of water resources and ecosystem services is highly important both for maintaining economic growth, and for preventing the destabilization of the environment. Northern Eurasia accumulates tremendous water resources and ecosystem services (particularly in the largest ecosystem of the globe: the boreal forests including the Siberian taiga), which operate as important components of the global biotic regulation mechanism. In the future, they will very likely be subject to substantial risks. Northern Siberia alone contains to 900 Pg of carbon in the frozen ground. The warming and thawing of permafrost may have destructive impacts on the Earth System, the survival of boreal forests, and the life of indigenous people, and may have grave consequences for national and global economies. Understanding the interactions between Earth system components under both current and future hydrological regimes, as well as the dynamics of permafrost and the functioning of the Arctic and boreal ecosystems, are necessary preconditions for ensuring the satisfactory socio-economic development of these huge territories. Working out balanced recommendations for the transition toward a sustainable management of water resources and ecosystems in Eurasia is crucial for strategic planning, and will be a challenging research task of systems analysis.

Urban planning and design

Urban areas are among the major contributors to climate change through the emissions of greenhouse gases and aerosol particles. The potential for reducing emissions in urban areas is great, and many cities have already taken advantage of this by pursuing low-carbon initiatives. Within PEEX, the research agenda in the urban context focuses on identifying the best possible strategies for a reduction of greenhouse gases, while keeping in mind the interactions between land use and the atmosphere. On the other hand also air pollution-climate interactions are considered.

For example, present-day Russian territorial and urban planning does not usually take into account the results of research work on, and forecasts of, possible future climate changes and natural hazards. There is no master plan for regional development in Russia. At the same time, there exist significant amounts of geographic information that could be incorporated into interdisciplinary studies to contribute to urban planning. The PEEX program should become a source of reliable data for zoning and urban planning in the Arctic and boreal Pan-Eurasian region, based on 40-year forecasts.

Eurasian transport corridors

The development of new Eurasian transport corridors (both across land and via the Northern Sea Route) can initiate a rapid growth in commodity circulation in the region, raise employment, promote the implementation of technological innovations in the transport and infrastructure sectors, and lead to economic and social development. An important research task will be the assessment of the energy efficiency and socio-ecological consequences of the new transport corridors, and the optimization of the future transport flows at both the Eurasian and sub-regional scales (Buixadé Farré *et al.*, 2014).

Protecting the natural carbon sinks

Protecting natural carbon sinks includes natural resources management, implementing ecological safety measures and new ecological standards of living, protecting biodiversity, and sustainably managing the resources of the Russian coastal zones. Key tasks here include the identification of sustainable forest management practices, and assessing their effects on the ecosystems.

Geoengineering

Geoengineering and remediation are methods for the artificial transformation of the environment, such as the technical removal of contaminants, isolation of hazardous wastes, and solar radiation management. Generally, geoengineering is often proposed as a separate option for ameliorating the effects of climate change, but it is also perceived as an additional technique for adaptation and mitigation strategies (Wigley, 2006). The main critique of geoengineering methods is that they lack control and predictability. Due to uncertainties in the feedbacks between different components of the Earth systems, science cannot yet predict with certainty the long-term effects of geoengineering methods. Furthermore, it has been pointed out that we cannot seriously propose to conduct any geoengineering efforts regarding climate change until we will fully understand our earlier contributions to this change (Matthews *et al.*, 2009). In this sense, PEEX contributes to exploring geoengineering technologies by providing the necessary information on diverse interactions in the climate system.

In the coming decades, certain geoengineering technologies may be developed and used to counteract climate change. Before conducting any large-scale field experiments, it is important to quantify and analyze the impact of their implementation on sensitive Arctic ecosystems by modeling and scenario studies. Within the PEEX research domain, future research will encompass issues such as soft geoengineering namely different feedback loops, albedo changes *etc*.

5.1.2 Adaptation – key aspects

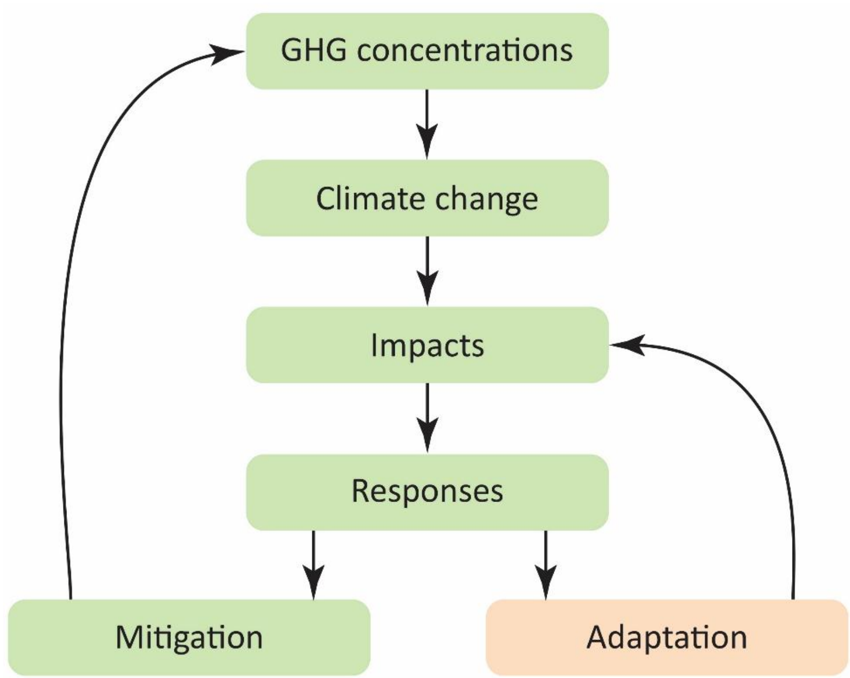

Figure 70 Adaptation represents activities understood as protecting society from nature (Stehr et al., 2005).

SYNOPSIS The PEEX research agenda supports the planning for adaptation through the provision of scientific knowledge of natural and climatic processes in order to assess the extent of climate risks in the future. PEEX will accumulate scientific knowledge of how societies in the PEEX area are able to adapt to climate change, and what issues can hamper the adaptation process.

PEEX addresses the following topics of adaptation

The development of adaptation strategies is a political process, and requires decisions on what kinds of measures can be taken to reduce the risks and vulnerabilities to climate change. The Fifth Assessment Report considers climate risks arise from the interplay of hazards, exposure and vulnerability, see Figure 71. Anthropogenic climate change and natural variability drive hazards, whilst exposure is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. Vulnerability is defined as the propensity or predisposition to be adversely affected, according to the IPCC and it includes both sensitivity and adaptive capacity. Within the PEEX program, the overall aim is to understand how the area is affected by climate risks and what can be done to adapt to them.

Climate risk assessments

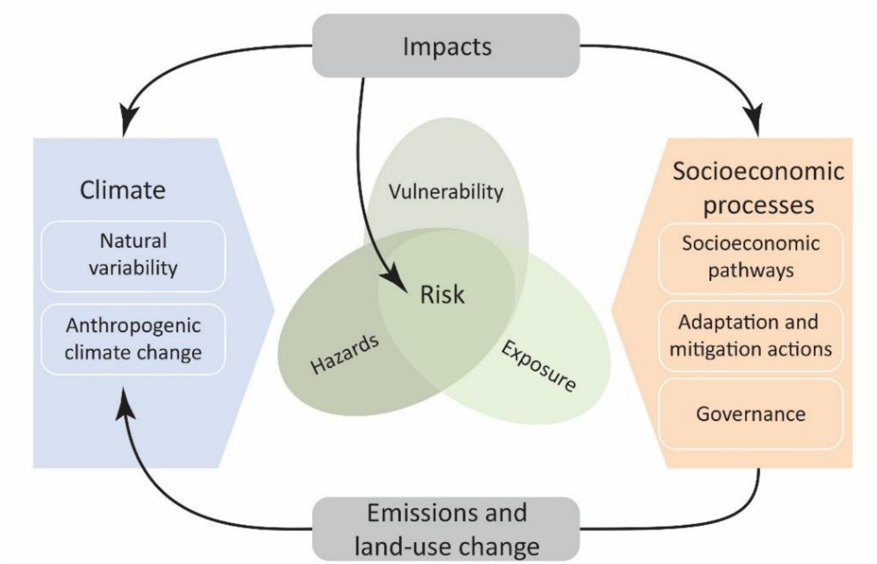

Figure 71 Conceptualization of climate risk. Figure adapted from IPCC, 2014.

Climate change will have different kinds of effects throughout the PEEX region, but the ways in which how different hazards vary across the PEEX region, and how populations and assets are exposed to these changes and this depends on the local characteristics and capacities. Given the wide variation of these conditions in the PEEX region, it is necessary to develop methodologies to assess the climate risks within the region. For example, European wide assessments of climate change vulnerability exist that cover the EU Member States at the regional level (Schmidt-Thome and Greiving *et al.*, 2011; Holsten and Kropp, 2012). For the PEEX region, the focus will be two-fold: first, an emphasis on identifying ways to assess wider variation within the entire region and secondly, to identify key sectors or geographical areas where more detailed studies can be undertaken.

Exposure to extreme weather events

There is also a need to assess to what extent extreme weather events are likely to increase within the PEEX area and what kinds of adaptation measures are needed for these. Whilst there are methodologies to assess these (Greiving *et al.*, 2006), there is a need to investigate how these can be improved. Extreme events in the region vary from storm surge, landslides to heavy precipitation that place people and assets at risk. The key research needs here include linking methods to estimate extreme weather events and linking them to the development of Early Warning Systems (see section 5.3.2.)

Sustainable agriculture and forestry

The major part of the territory used for extensive agriculture in Northern Eurasia is in sub-regions of Russia, Ukraine and Kazakhstan. The intensification of agriculture, and the implementation of efficient agricultural technologies, can multiply the productivity of the agriculture sector in the region. In combination with the development of new Eurasian transport infrastructures, this will significantly improve food security in Eurasia. Important topics of study within the forestry sector include the institutional shifts in Russian forestry in the 1990-2000s, and their impact on forest management and adaptation to climate change (Kuzminov, 2011); forecast of the frequency of forest fires due to climate change, and accounting for the way in which forestry policy impacts the sector and its ability to adapt to the changing climate.

Adaptation policies and implementation

Adaptation can take place both through long-term structural changes in society, as well as through shorter-term changes resulting from unexpected shocks (IPCC, 2014). For the former, longer-term political strategies are necessary, while the latter requires measures such as early warning systems, through which information of climate impacts can be fed into the shorter term management of natural and economic resources, as well as societal activities. Hence, adaptation can be divided into planned adaptation, which consists of measures taken by the state to reduce climate change vulnerabilities through political processes, and autonomous adaptation, in which different actors, such as private companies or individuals, change their practices in order to reduce the risks from climate change (IPCC, 2007). Planned adaptation processes have normally taken place at the national level, with different ministries engaging in planning for adaptation. In the context of this research program, adaptation, as well as mitigation strategies should be developed out for federal, regional and local authorities across different economic sectors. Furthermore, the possibilities for integrated adaptation and mitigation solutions should also be investigated, as discussed earlier.

Livelihoods of the northern people

Northern reindeer husbandry, together with sea and river fishery, is one of the main branches of the traditional northern economy, and the main occupation of the nomadic northern people. This is a source of sustainability for the northern indigenous societies. The number of wild and domestic reindeer in Siberia has dramatically declined in the post-soviet period (Gray, 2000; Hiyama and Inoue, 2010; Litvinenko, 2013). Field studies in North Yakutiya revealed that the availability of drinking water (stored as ice in winter), the availability of bio-fuels (mainly wood), pasture and land productivity, and patterns of animal reproduction and hunting, are all changing (Hiyama and Inoue, 2010). The migration routes of wild reindeer are changing in response to new environmental conditions. MODIS satellite data showed that reindeer move along rivers and through zones of better vegetation, while avoiding increasingly common forest fires. Interviews with indigenous people, keepers of domestic reindeer, revealed that while climate change has so far not severely damaged their operations, and they have been able to successfully adapt to changes in climate, they were severely impacted by social changes following the collapse of the Soviet Union (http://www.chikyu.ac.jp/rihn_e/project/C-07.html).

5.2 CLIMATE POLICY MAKING

SYNOPSIS PEEX will work closely with influential organizations such as the Intergovernmental Panel for Climate Change (IPCC), the emerging international global sustainability initiative Future Earth, and Digital Earth. Future Earth is a new 10-year research initiative developed by the International Council for Science (ICSU), the United Nations, the International Social Science Council (ISSC), and the Belmont Forum. Future Earth will move the focus of ICSU-led global environmental change research from basic science to solution-oriented, cross-disciplinary research that is co-designed together with end-users (policy-makers, private sector, non-governmental organizations, citizens, media). Digital Earth is a global initiative aimed at harnessing the world's data and information resources to develop a virtual 3-D model of the Earth in order to monitor, measure, and forecast natural and human activity on the planet.

One of the main goals of PEEX is to provide tools for scientists to produce results that can diminish the uncertainties in scientific knowledge that policy makers are utilizing in the PEEX region. Reducing these uncertainties requires multidisciplinary research with advanced measurement and modeling methods. However, an equally important aspect is mapping the needs of the end-users of PEEX scientific results, and involving the end-users (governments, parliaments, funders, municipalities and cities, private sector, citizens, non-governmental organizations, media) in planning research that will address these needs. Different policy sectors and scientific disciplines will be invited to join the PEEX program in order to be able to respond to the challenges that require a multidisciplinary approach.

PEEX will contribute to solving major global challenges, and contribute significantly to solving socioeconomic challenges related to global sustainability and ecosystem-atmosphere-society interactions. Examples include the interactions between climate change and the terrestrial, coastal, and marine environment and agriculture, forestry, energy consumption, urban planning, and extreme events. PEEX will answer the needs of policy-makers in the region by producing assessments and policy briefs on relevant topics and by maintaining an open dialogue with stakeholders and policy-makers. PEEX will also create communication channels internationally, and within each individual country, to ensure that new scientific understanding is available and ready to use at the policy level

PEEX will work closely with influential organizations such as the Intergovernmental Panel for Climate Change (IPCC), the International Council for Science (ICSU), the emerging international global sustainability initiative Future Earth, and Digital Earth. Future Earth is a new 10-year research initiative developed by ICSU, the United Nations, the International Social Science Council (ISSC), and the Belmont Forum. Future Earth will move the focus of ICSU-led global environmental change research from basic science toward solution-oriented, cross-disciplinary research that is co-designed together with end-users (policy-makers, private sector, NGOs, citizens, media). The key concept in Future Earth science is the co-designing of research together with stakeholders, scientists, and funders in order to produce knowledge necessary for societies to cope with global change, and to transition to sustainable economies and practices.

PEEX is endorsed by the IGBP (International Geosphere-Biosphere Program) core project iLEAPS (Integrated Land Ecosystem-Atmosphere Processes Study), which is presently a Future Earth's core project. iLEAPS will bring visibility especially to the ecosystem-atmosphere-society interactions research within PEEX. Also, as part of the Future Earth, iLEAPS can act as a channel for the PEEX results to reach the policy level in different PEEX countries. Via iLEAPS, PEEX is linked to the Future Earth initiative, which will reorganize ICSU's Global Environmental Change programs toward integrated global sustainability research. This requires the integration of social science and economics with natural sciences at all levels of research, from planning to implementation, and the interpretation of results. Finding the best ways to get these different communities to work together is challenging, but PEEX is well equipped to take the first steps in the Pan-Eurasian region on the road to solving the equation of one Earth and a growing human population.

In each country, scientists have their own channels through which they can reach out to policy-makers. PEEX engages the local scientific leaders and, using their experience, creates the multiple pathways necessary for an effective science-policy dialogue. *E.g.* in Finland, PEEX has direct links to the National Climate Panel, to the Forum of Environmental Information (http://www.ymparistotiedonfoorumi.fi) that produces scientific information for policy-making, to Future Earth, the international initiative on global sustainability led by ICSU, ISSC, and UN (http://www.ICSU.org/future-earth), and to the Digital Earth forum.

5.3 SERVICES TO SOCIETY

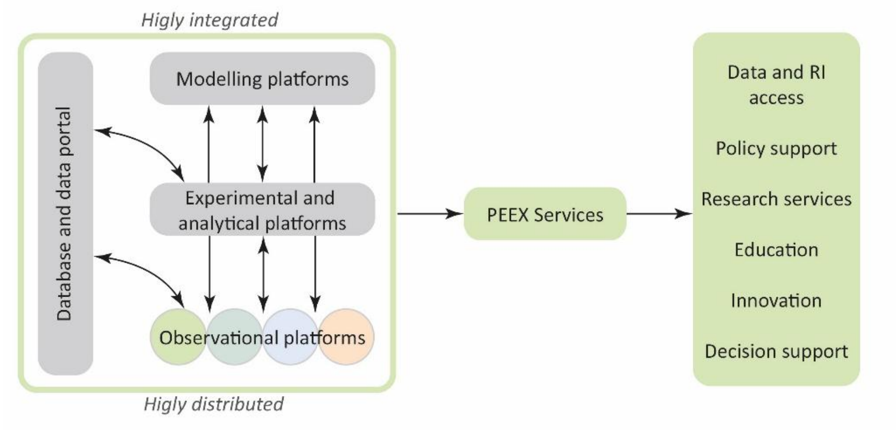

Figure 72 The conceptual design of the PEEX infrastructure is based on the service-oriented approach (Lappalainen et al., 2014).

5.3.1 Quality checked data distribution

Coherent and coordinated *in-situ*-data on land-atmosphere-aquatic systems, together with satellite observations, form the cornerstone for novel science result together with new Earth system models and scenario building and early warning service systems. One of the main outcomes of the PEEX Preliminary Phase is the PEEX observation network, which will fill the current observational gap in the Northern Pan-Eurasian region. This is especially the case for the northernmost regions of the Arctic coastline and Siberia. The aim is to bring the observational setup into an international context with standardized or comparable procedures.

The European union ESFRI process, together with the EU-infrastructure projects (For example EU-FP-7 ACTRIS, ANAEE, ENVRI, COOPEUS projects, and the upcoming RI project within the Horizon 2020 framework), provide a framework for harmonized data product development, and for the calibration of network measurements with international standards. Wide collaboration in a circumpolar context is also an essential part of the harmonized data product approach. For example, the atmospheric, terrestrial and marine components of the PEEX observation program will fulfill the quality objectives of other international networks, such as the USA AErosol RObotic NETwork (AERONE), Network For The Detection Of Atmospheric Composition Change (NDACC) and the Global Atmospheric Watch (GAW) network, hosted by the World Meteorological Organization (WMO).

5.3.2 Early-warning systems

Anthropogenic activities directly interfere with natural environments and systems, and indirectly accelerate the processes responsible for climate change. Furthermore, the Northern societies affect the biological-chemical-physical processes of the sensitive environments and ecosystems in the taiga and Arctic regions. In the worst case, this type of two-fold development may further accelerate other negative trends. For example, 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. The thawing permafrost and extreme weather events both accelerate the risk of natural disasters such as forest fires, floods and landslides, as well as the destruction of infrastructure such as buildings, roads and energy distribution systems. The extreme events that already occur (storms, floods, forest fires, landslides, air pollution episodes in megacities *etc*.), and their impacts on human well-being and infrastructures, gives us an insight into the possible short-term future hazards, and emphasizes the increasing need for reliable early warning systems. The coherent and coordinated PEEX observation network together with the PEEX modeling approach form the backbone for the next generation early warning systems across the PEEX geographical domain.

5.3.3 Innovations and new technology

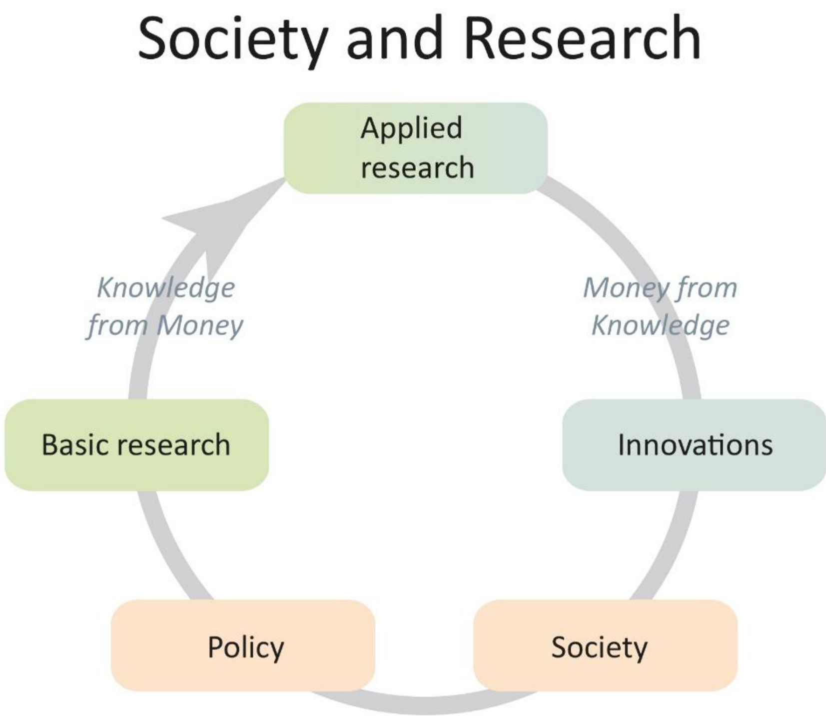

Figure 73 Society and basic research are tightly connected with each other.

Society and basic research are tightly connected with each other. Using the resources provided by society (or policymakers), basic research generates new knowledge, which is then used in applied research. Through applied research, and in particularly via innovations, new money is produced from this new knowledge. It is crucial to ensure that this cycle remains healthy and is not broken in any place. Technological development can answer some of the questions arising in F1. However, the whole society, including economic and cultural aspects, must be considered in the search for sustainable answers to grand challenges.

5.4 AIR QUALITY IN MEGACITIES

China is an example of an environmental hot spot region with rapidly changing socio-economic conditions. Currently, the bad air quality in Beijing and other megacities of China threatens the health of hundreds of millions of people, and causes major problems to the environment, thus severely decreasing the productivity of the land and of the entire nation. China is pro-actively searching for new ways of environmental protection that cost less, produce more benefits, lead to reduced emissions, and contribute to sustainability. China intends to speed up the construction of a resource-conserving and environmentally friendly society, and strives to improve the level of ecological conservation and quality of life. In particular, China aims to decrease the annual mortality due to bad air quality (Internation Eurasian Academy of Sciences, 2012). The emissions of different pollutants are interlinked, and their health and environmental effects depend on a large number of different factors, involving all processes from the initial emissions to the final degradation or deposition reactions.

PEEX will use a holistic approach in contributing to solving the air quality problem. The holistic approach takes into consideration all relevant pollutants and their sources, transportation and transformation in atmosphere, as well as the effects of the pollutants on society and on policymaking. Using this approach, the most practical solutions can be implemented stepwise. The goal is to achieve clear improvements in air quality in as short time as is economically and socially feasible. For a problem as complicated and multi-faceted as the air quality situation in the Beijing region and in Eastern China, solutions can be achieved only via a holistic approach.

It is essential to address simultaneously the various different air pollutants in order to reach the targeted air quality improvements decided by the National People's Congress. This is because of several feedback mechanisms and interactions between the different pollutants. Therefore, we have provided a roadmap from understanding to solutions:

i. Establish a comprehensive and continuous measurement network to collect socially and economically the most crucial air quality and meteorology data. This will include pilot and reference systems.
ii. Make a comprehensive source sector analysis for the emissions of different air pollutants. This will provide detailed information on the most effective regional ways to reduce emissions.
iii. Conduct comprehensive indoor air quality measurements in a representative selection of residential and office buildings, and apply outdoor-indoor modeling to identify and understand the critical points for indoor air quality in China.
iv. Carry out an integrative analysis of the data from the measurement network, emission analysis and indoor air quality modeling, in order to evaluate population exposures to air pollutants, and identify the societally, economically and environmentally most useful solutions.
v. Apply the results to make structural and infrastructural changes, and to develop engineering solutions together with industrial partners.

6. KNOWLEDGE TRANSFER (F4)

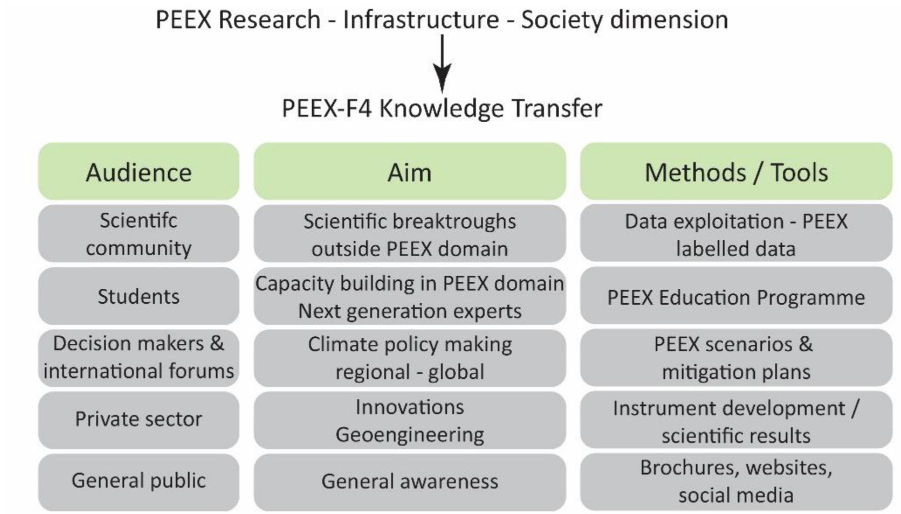

Figure 74 PEEX Knowledge transfer main audiences, aims and methods.

6.1 TO INTERNATIONAL FORUMS, DESICION MAKERS AND NATIONAL AUTHORITIES

PEEX will collaborate closely with influential international organizations such as the intergovernmental panel on climate change (IPCC), the emerging international global sustainability initiative "Future Earth", and Digital Earth. Future Earth is a new 10-year research initiative developed by ICSU (the international council for science), the United Nations, the international social science council (ISSC), and the Belmont forum. Future Earth will move the focus of ICSU-led global environmental change research from basic science toward solution-oriented, cross-disciplinary research that is co-designed together with the end users (policy-makers, private sector, non-governmental organizations, citizens, media). Digital Earth is a global initiative aimed at harnessing the world's data and information resources in order to develop a virtual 3-D model of the Earth. This will be used to monitor, measure, and forecast natural and human activities on the planet.

One of the main goals of PEEX is to provide tools for scientists to produce results, which can reduce the uncertainties in the scientific knowledge utilized by policy makers in the PEEX region (Figure 74). Reducing these uncertainties requires multidisciplinary research with advanced measurement and modeling methods. However, an equally important aspect is mapping the needs of the end-users of the PEEX scientific results, and involving the end-users (governments, parliaments, funders, municipalities and cities, private sector, citizens, NGOs, media) in planning research that will address these needs. Different policy sectors and scientific disciplines will be invited to join the PEEX program, in order to be able to respond to challenges that require a multidisciplinary approach.

PEEX will contribute to solving major global challenges, and contribute significantly to solving socioeconomic challenges related to global sustainability and ecosystem-atmosphere-society interactions. Examples of these challenges include the interactions between climate change and the terrestrial, coastal, and marine environments, as well as agriculture, forestry, energy consumption, urban planning, and extreme events. PEEX will answer the needs of policy-makers in the region by producing assessments and policy briefs on relevant topics, and by maintaining an open dialogue with stakeholders and policy-makers. PEEX will also create communication channels internationally, and within each individual country, to ensure that new scientific understanding is available and ready to use at the policy level. A key concept in future Earth science is the co-designing of research together with stakeholders, scientists, and funders in order to produce the knowledge necessary for societies to cope with global change, and to transition to sustainable economies and practices.

PEEX is endorsed by the IGBP core project iLEAPS (integrated land ecosystem-atmosphere processes study). ILEAPS will bring visibility especially to the ecosystem-atmosphere-society interactions research within PEEX. Also, as part of

IGBP and the emerging Future Earth, iLEAPS can act as a channel for PEEX results to reach the policy level in different PEEX countries. Via iLEAPS, PEEX is linked to the Future Earth initiative, which will re-organize ICSU's global environmental change programs toward integrated global sustainability research. This requires the integration of social science and economics with natural sciences at all levels of research, from planning to implementation, and the interpretation of results. Finding the best ways to get these different communities to work together is challenging, but PEEX is well equipped to take the first steps in the Pan-Eurasian region on the road to solving the equation of one Earth and a growing human population.

6.2 TO SCIENCE COMMUNITIES AND THE PRIVATE SECTOR

Figure 75 Undergraduate and graduate students participating to an intensive field course in Hyytiälä, Finland. Photo by Ella-Maria Kyrö.

PEEX will contribute to the building of a new, integrated Earth system research community in the Pan-Eurasian region by opening its research and modeling infrastructure, and by inviting international partners and organizations to share in its 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 wellbeing of humans, societies, and ecosystems in the Arctic-boreal region.

Diversity exist on many levels. PEEX helps build bridges and trust among natural sciences and social sciences. PEEX supports mutual respect and the recognition of regional and national circumstances, and promotes gender balance.

Diversity of knowledge is essential for tackling grand challenges. Achieving this diversity requires combining knowledge of multiple fields of natural science as well as social sciences. The building of bridges between different fields of science is necessary for promoting open discussions, trust and respect among scientists from different disciplines.

A diversity of solutions is also essential for solving the grand challenges. Regional circumstances, ranging from climate and geography to culture and legislation, must be taken into account when making decisions: one shoe does not fit all feet. Thus, PEEX aims at giving recommendations and best practice protocols, but accepts the existence of diverse solutions that fit the regional circumstances. PEEX facilitates joint education and training, and promotes mutual recognition among the involved institutes, while ensuring that the requirements of the training programs, and the degrees obtained therein, comply with the legislation of each participating country.

A diversity of cultures is encountered both among nations, between different fields of science, and even between the working cultures of different institutes, or within the same institute. PEEX promotes the acceptance and equal appreciation of different cultures, and facilitates the discussion between cultures.

A diversity of innovation is needed for turning the PEEX ideas and solutions into commercial services and products. Novel ideas arise from a diverse mix of people, cultures, knowledge and solutions.

The diversity of knowledge, innovations, solutions *etc*. is ultimately based on the diversity of human beings. Diversity is inevitably present whenever more than one person is involved. PEEX acknowledges that people are different, and that personal growth, education and training may require different kinds of actions and support for different people. PEEX does not accept any kind of discrimination, and supports the promotion of equality, including gender balance and positive discrimination. PEEX aims at gender balance in decision-making boards, and maintains the principle of equal pay for equal work.

PEEX education program

One of the first activities of PEEX will be the establishment of a PEEX education 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 (Figure 75, Figure 76). 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.

The PEEX education program is founded on the concept of lifelong learning at multiple levels. Educational objectives range from raising the awareness of the general public to honing the expertise of senior scientists, and disseminating PEEX scientific outcomes to stakeholders.

The key objectives for researcher training and research career promotion within PEEX are: (i) to educate a 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, (ii) to educate multidisciplinary scientists with deep core understanding, having transferable skills to be readily applicable to working outside the academia, (iii) to establish relationships between PhDs with key European players in field of research, research infrastructure, service providers and research policy and (iv) to provide transversal training addressing all aspects of environmental observations, from data provision to data application in numerical models. For example, the 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 Earth System Models, and 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 where teachers take the role of facilitators rather than lecturers. Collaborative learning is carried out throughout the courses. 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.

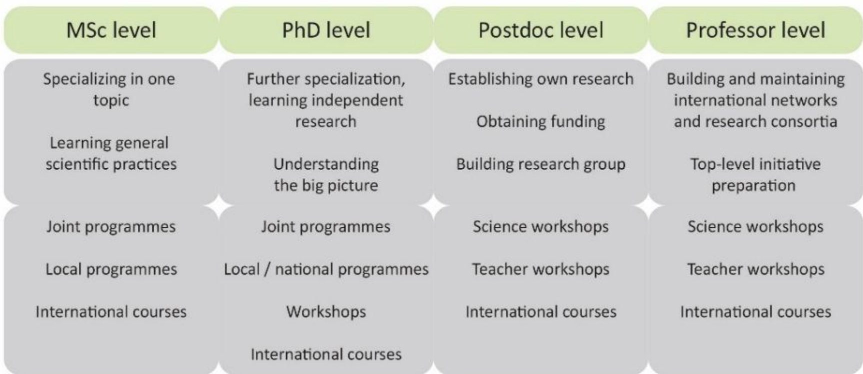

Figure 76 The PEEX education structure from MSc up to professor level.

The PEEX education program addresses the following themes:

Training of multidisciplinary skills and knowledge transfer skills applicable to a range of tasks in both public and private sectors: research on climate change and air quality, as well as the development of adaptation and mitigation plans, requires a combination of mastering core subject expertise (from master to PhD level), multidisciplinary understanding (PhD level) and supplementary social and “soft” skills (PhD to professor level) (Figure 76). The PEEX education program will engage PhD students, post docs, technical staff and experts in knowledge transfer, both via vertical knowledge transfer during courses held by world experts in different fields of science, and through lateral cross-disciplinary training by peers. The doctoral students involved in PEEX are enrolled in local and national doctoral programs participating in the PEEX program. Courses on key research questions with specialist lectures transfer knowledge from professors to students, and also among the professors and experts in the different PEEX fields of science. This promotes the emergence of new viewpoints on the complex multidisciplinary research questions of PEEX.

Opening pre-existing courses at PEEX institutes to the whole community: the PEEX education plan includes the opening of existing courses at PEEX institutes for PEEX students from other institutes. Courses held regularly at other universities can be included in the curricula of individual students at the PEEX institutes. Courses can also be tailored to share special expertise, and to fit the needs of a specific institute. For example, a group specialized in *in-situ* observations or modeling approaches may broaden their expertize through an education exchange with an institute specialized in remote sensing, and *vice versa*. Courses can also include project based cases where natural and social sciences are brought together to solve particular climate change related issues, *e.g.* modeling of emissions and their climate effects through to adaptation measures. Education exchanges also promote peer to peer knowledge transfer through expert and professor exchange, and through interdisciplinary workshops focusing on the PEEX scientific questions.

Cross-disciplinary collaboration, international, interdisciplinary and intersectoral mobility: the PEEX institutes possess world-leading expertize on climate change in the Arctic and boreal regions. The knowledge transfer within PEEX facilitates peer support, and the build-up of a Pan-Eurasian network of experts. Training in “soft” skills and supporting skills is part of the knowledge transfer program. The student exchange program facilitates cross-discipline collaboration, and promotes mobility within Eurasia, specifically within nations in the Arctic and boreal region: northern Europe, Russia and China. Both national and international mobility is promoted on four levels: (i) between PEEX sites; (ii) between research fields (ecology-physics-technology-chemistry-meteorology-geography-social sciences); (iii) between research methodologies (theory-modeling-experiments-observations; *in-situ* observations; remote sensing observations; qualitative and quantitative research); and (iv) between universities, research institutes, companies and commercial activities, as well as political bodies at different policy-making levels. This mobility is implemented by organizing joint courses and workshops, and through researcher secondments.

Recognizing the importance of career development: master's degree and doctoral training is organized through national education programs. The objective of PEEX is to facilitate the education collaboration of national and regional programs as well as individual universities. PEEX recognizes the importance of career development, and the educational structure aims to cover all academic levels from PhD students to professors and institute leaders in the spirit of lifelong learning.

The actions supporting the creation and maintenance of a positive feedback loop in education include: (i) supporting the formation of formal and informal interdisciplinary and international supervision and peer support relationships (ii) facilitation of cross-supervision involving supervisors from two or more PEEX groups; (iii) annually organizing several joint international courses and workshops to directly support the students' research, and providing both core and transferable skills, and (iv) to ensure transparency and open information flow, contributing institutes will distribute advertisements and notifications of courses through a web portal.

Training the next generation of research infrastructure experts (best practices, twinning): in addition to building its own infrastructure in the Pan-Eurasian region, PEEX will engage the larger international scientific community by collaborating with, utilizing, and advancing major observation infrastructures such as the GAW, SMEAR, ICOS, ACTRIS, and ANAEE networks. PEEX will promote the adoption of standard methods and best practices in creating long-term, comprehensive, multidisciplinary observational data sets, and co-ordinate model and data comparisons and development. PEEX will also strengthen the international scientific community via an extensive capacity building program. PEEX promotes knowledge transfer and training, including facilitating open discussions among networks initially built for different fields of science, and building bridges between the communities behind the major observational infrastructures in the PEEX domain. Training actions aimed specifically at supporting the PEEX infrastructure and observation network include international courses on core topics, and workshops for agreeing on, teaching and refining best practices. Experts are encouraged to commit to lifelong learning, and to refresh and upgrade core and transferrable skills. Staff exchange and secondments are an essential part of expert training. Exchanges between institutes, and within or between research and monitoring infrastructures, are promoted. Knowledge transfer actions are bidirectional, and experts are expected to share their knowledge with their peers, as well as to lecture and teach the next generation.

Twinning. In the twinning activities, field stations in the PEEX domain are upgraded and expanded to become multidisciplinary observational infrastructures. Twinning involves two partners. One is the expert, in this case an existing, advanced field station or data processing facility, which shares its experience with the other, developing partner. Both partners commit to the twinning by signing an agreement on the long term process by which the infrastructure and protocols of the experienced partner are adapted to the conditions of the facility that is expanding its scope of expertize. The support for twinning provided by PEEX is purely immaterial, and funding for the development of instruments and facilities is obtained from other sources. In addition to twinning, PEEX promotes multi-institutional peer support and peer-to-peer knowledge transfer networks, and acknowledges that a person can be an expert giving lectures on one topic, while simultaneously remaining a novice in need of training on another topic.

Integration of research and education activities into larger frameworks: PEEX will support and strengthen the productive supradisciplinary research environment. PEEX will play an active role in science policy, and promote understanding of the multi-scale concept of science. PEEX will participate in the construction of environmental research infrastructures in its domain, and advocate open access to data, and open visualization of data. The PEEX initiative is promoted by the University of Helsinki, Finland. The University of Helsinki is also the site of a leading Centre of Excellence in Atmospheric Science ("from molecular and biological processes to the global climate"; ATM) which is actively proposing, and participating in, European-level initiatives for doctoral training, *e.g.* the Horizon 2020 Marie Skłodowska-Curie innovative training networks. PEEX-involved institutes also take part in other bilateral and regional doctoral training programs.

Table 2 PEEX education and training: examples of target groups, aims and actions

Target group	**Aim**	**Action**
Secondary school Teachers and pupils	Increasing awareness	Dissemination of PEEX topic material
Master and PhD students	Educating the next generation of scientists in PEEX domain	Local/regional programs, international courses and workshops
Young scientists	Technical expert retraining. Maintenance of infrastructure.	Best practices. International courses and workshops. Twinning.
Potential business partners and entrepreneurs	Commercial use of PEEX research results.	International courses and workshops.
Data operators	Meeting data standards.	Best practices. International courses and workshops. Twinning.
Senior scientists	Promoting interdisciplinary understanding.	International courses and workshops.
Stakeholders	Disseminating specific results on mitigation / adaptation.	Policy papers on PEEX scientific results.
Economy sectors	Promoting regional awareness of the PEEX observation system.	Contact node, information dissemination.
General public	Raising general awareness about Arctic climate change.	Transparent dissemination of PEEX scientific outcomes through a web portal.

6.3 TO THE GENERAL PUBLIC

Climate change is exposing new Arctic natural resources to exploitation. Objective information on the impact of global change on the Arctic and boreal regions is essential to ensuring that the increasing industrial and commercial activities in the Northern Pan-Eurasian are sustainable and responsible. In addition to decision makers also the general public needs reliable, unbiased estimates of the impacts of the new industrial activities, as well as information on the consequences of commercial activities. Themes such as "protecting the natural carbon sink" or "expose to extreme weather events" described in the section of "Impact on Society" will be part of the outreach agenda. PEEX-involved institutes can provide this information. The strong involvement of social sciences in PEEX facilitates raising public awareness of the impacts of consumer behavior on global change, as well as on the social changes occurring in the PEEX domain.

PEEX promotes the distribution of scientific information to the general public, as well as to science teachers in primary and secondary schools. This will be carried out for example by distributing outreach material and e-learning courses provided by the European Geophysical Union, such as geosciences information for teachers (gift, http://egu.eu/outreach/gift/), and webgeology flashed teaching resources from the university of Tromsø, Norway (http://ansatte.uit.no/webgeology/). PEEX also facilitates the use of distance learning, such as the training offered by the WMO to its members (http://www.WMO.int). In addition, PEEX promotes massive open online courses (MOOCs), online courses freely accessed via the internet and aimed at an unlimited number of participants. Metadata of image archives, already established by UNIGEO members, are being made openly available. One example of an extensive open access data source related to multidisciplinary boreal forest research is the smart-SMEAR database (http://avaa.tdata.fi/web/smart, Junninen *et al.*, 2009). Smart-SMEAR is extensively used at data analysis courses organized by the University of Helsinki.

7. IMPLEMENTATION

During the first two-three years in action, after the kick-off meeting in Helsinki in October, 2012, PEEX has taken the first steps towards the PEEX implementation. The PEEX Science Plan has been written based on a bottom-up approach. The very early versions of the science plan were produced as summaries of the topics introduced in the PEEX meetings (Helsinki in 2012 and Moscow, Hyytiälä, the China PEEX Kick-off in 2013 and St. Petersburg, Russia in 2014). Furthermore, PEEX-Working Groups has provided input for the content of PEEX Science Plan and the ideas for implementing the PEEX program.

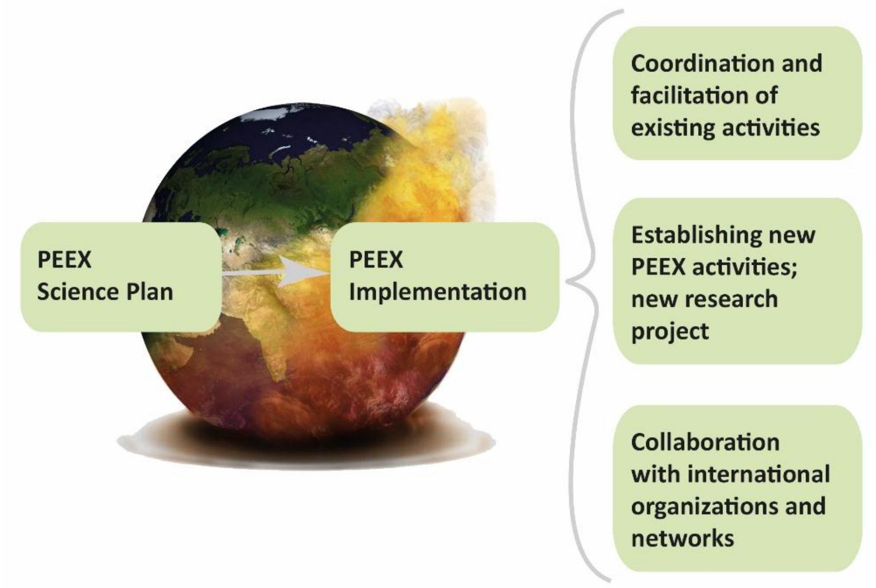

Figure 77 Components of PEEX implementations.

The PEEX implementation will consist of (i) co-ordination and facilitation of existing activities (research-infrastructure-education) in the PEEX domain, (ii) establishing new PEEX activities such as research projects or new measurement sites and (iii) collaboration with international organization and networks to find synergies and common activities, (iv) opening a dialogue with stakeholders and end-users. The implementation of PEEX research and infrastructure program is focused on providing (early warning) services to society and new, reliable information for policy making (Figure 77). Tentative time frame for carrying out the preparatory work is in minimum 10 years (Figure 78) .

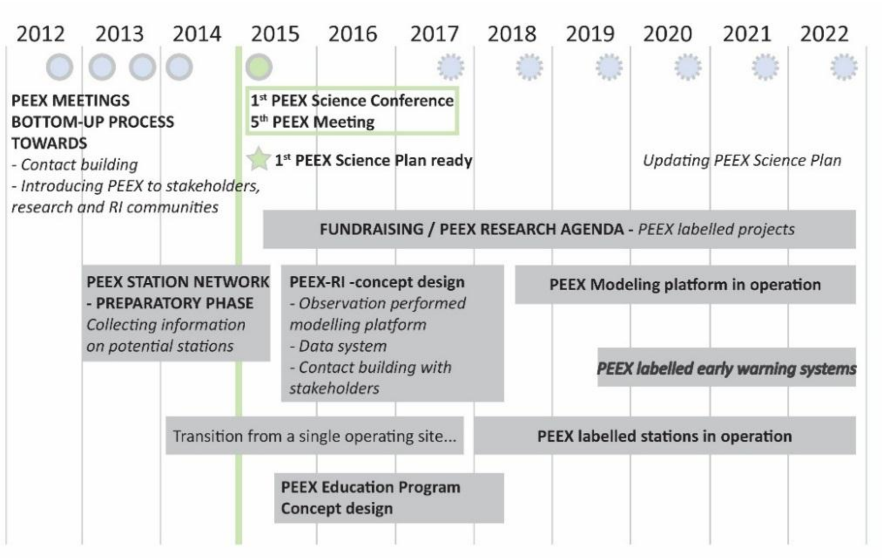

Figure 78 PEEX tentative schedule.

Co-ordination and facilitation of existing activities

One of the strategically most important tasks of PEEX is to fill the observational gap in atmospheric *in-situ* data in the Siberian and across Northern Pan-Eurasian region and to initiate the process towards standardized and harmonized data procedures throughout the PEEX domain. To underline the importance of this step, PEEX will start the implementation of its Science Plan by establishing a detailed conceptual design for a Pan-Eurasian observation network. In the first phase, the Pan-Eurasian observation network will be built on the infrastructure of the existing station network and remote sensing activities. The detailed plans for the technical requirements, instrument setup, data flow, data storage and data distribution will be made jointly with the PEEX contributing research institutes via a bottom-up approach (see Lappalainen *et al.*, 2014b). This implementation is built upon experiences acquired during the first two years, in 2012-2014, where we collected metadata information of the potential atmospheric and ecosystem ground stations particularly in Russian boreal and Arctic regions (Figure). At the moment the database contain information on 171 different stations. The next step is to include information on the stations in China. After having the station metadatabase ready we will (i) analyze the capacity of the existing observation infrastructure to serve as a basis of the PEEX observation program and (ii) identify what type of new infrastructures are needed in the PEEX domain. PEEX will find synergies with the major European land-atmosphere observation infrastructures

The detailed design of the PEEX modelling platform will be developed in a co-aligned manner with the PEEX observation network. As a first result of the PEEX modelling platform preliminary phase, the PEEX modelling team will make an inventory of available modelling tools fitting the PEEX purposes, illuminating the main gaps in the existing modelling tools, and suggest a plan for their development and improvement. Furthermore, the synergies with satellite and ground based data and models will be identified.

The first activities of the PEEX Education Program will be the PEEX-labelled/benchmarked courses provided by the PEEX contributing institutes, and a web based education module. The first PEEX- benchmarked courses category aim at harmonizing the PEEX observation platform and procedures from measurements to data processing. The courses organized by the contributing institutes are posted by the organizers to PEEX website serving as a channel to share expertize within the PEEX contributing institutes. Examples of the PEEX labelled courses are Nordforsk funded CRAICC-PEEX Workshops, 2nd ACTRIS Winter School and 10th Summer School on Atmospheric Aerosol Physics, Measurement, and Sampling (https://www.atm.helsinki.fi/peex/index.php/education).

Establishing new PEEX activities

The PEEX Science Plan - research agenda is a thematic umbrella for several specific funding applications and new research projects. PEEX will actively apply for funding from multiple sources on national, Nordic and European levels. The first funding applications will be targeted to the opening calls of the Nordfrosk and EU-HORIZON-2020 programmes, and toward Russian and Chinese research funding programmes. The examples of the first PEEX-labeled programs are the CRAICC-PEEX (2014-2015) and The Future Arctic - Assessment & Scenarios" (FAAS) Worskshops funded by Nordforsk and the ATM-FCoE and AEROCOSMOS collaboration project titled as ""Development of methods for monitoring of the dynamics of natural and anthropogenic emissions of trace gases and aerosols in the atmosphere based on satellite data and modeling results".

Collaboration with international organizations and networks

PEEX will collaborate with several international organizations and networks. PEEX is linked to the Belmont Forum and the Future Earth initiative via the European hub for Future Earth. PEEX forms the Arctic-boreal node of the European Hub. In Finland PEEX will also be collaborating and be part of the Helsinki University "Russian Hub". Furthermore, PEEX will be active player towards the Arctic Council, the Nordic Council and other corresponding organizations.

The most important research collaborators for PEEX will initially be the Nordic centers of excellence and IIASA – the International Institute for Applied Systems Analysis. Research infrastructure development will be carried out in interaction with the global earth observation system of systems (GEOSS). GEOSS connects PEEX to the GEO (intergovernmental group on earth observations) cold regions activities. PEEX is already listed by GEOSS among other global research infrastructures and international programs enhancing arctic data-information and co-ordination. These include the Sustaining Arctic Observation Networks (SAON), the Svalbard Integrated Earth Observing System (SIOS), the WMO Global Cryosphere Watch and Global Atmospheric Watch (WMO GCW, GAW),the International network for terrestrial research and monitoring in the Arctic (INTERACT), the Conservation of Arctic flora and fauna (ABDS-ABA/CAFF), and the Monitoring the climate change in the cryosphere (CRYOCLIM) networks.

In China, PEEX is interested in to collaborate with the Silk Road Economic Belt initiative. One of the most popular terms for China's diplomatic achievements in 2014 is the strategy called "One Belt, One Road," i.e., the New Silk Road Economic Belt, which links China with Europe through Central and Western Asia, and the 21st Century Maritime Silk Road, which connects China with Southeast Asian countries, Africa and Europe. China-led Silk Road Economic Belt and the 21st Century Maritime Silk Road initiatives could prove a framework for solving environmental problems in Asia. The new "Silk Road" is more a network than a fixed route through the continental hinterland (Figure 79).

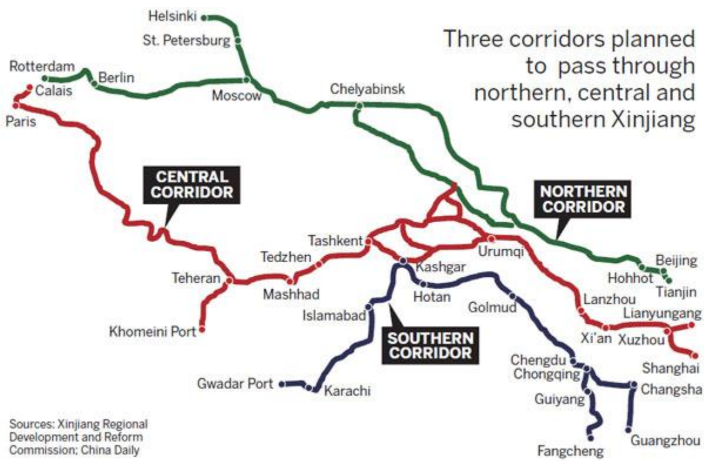

Figure 79 New Silk Road.

PEEX co-ordination and management

PEEX activities are coordinated by the PEEX headquarters (HQ) located at the University of Helsinki, Finland. The PEEX headquarters are supported by the PEEX program offices (PO) in Moscow and Beijing. The PEEX HQ and POs are the main bodies coordinating the PEEX fundraising and outreach activities, and assist the PEEX Preparatory Phase Committee. The PEEX Preparatory Phase Committee consists of representatives from the most active institutes contributing to PEEX in Europe, Russian and China Appendix-2.

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- Institute of Geographical Sciences and Natural Resources Research, CAS
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Denmark
- Danish Meteorological Institute (DMI)

Estonia
- Estonian University of Life Sciences
- Tartu Observatory
- University of Tartu

France
- CERES-ERTI (Environmental Research and Teaching Institute)
- CNRS (Centre National de la Recherche Scientifique)
- Laboratoire de Glaciologie
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Finland
- Finnish Meteorological Institute
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