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Discussions

Pan-Eurasian Experiment (PEEX):

Towards holistic understanding of the feedbacks and interactions in the land - atmosphere - ocean- society continuum in the Northern Eurasian region

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Abstract. The Northern Eurasian regions and Arctic Ocean will very likely undergo substantial changes during the next decades. The arctic-boreal natural environments play a crucial role in the global climate via the albedo change, carbon sources and sinks, as well as atmospheric aerosol production via biogenic volatile organic compounds. Furthermore, it is expected that the global trade activities, demographic movement and use of natural resources will be increasing in the Arctic regions. There is a need for a novel research approach, which not only identifies and tackles the relevant multi-disciplinary research questions, but is also able to make a holistic system analysis of the expected feedbacks. In this paper, we introduce the research agenda of the Pan-Eurasian Experiment (PEEX), a multi-scale, multi-disciplinary and international program started in 2012

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(https://www.atm.helsinki.fi/peex/). PEEX is setting a research approach where large-scale research topics are investigated from a system perspective and which aims to fill the key gaps in our understanding of the feedbacks and interactions between the land-atmosphere-aquatic-society continuum in the Northern Eurasian region. We introduce here the state of the art of the key topics in the PEEX research agenda and give the future prospects of the research which we see relevant in this context.

1. Introduction

The global environment is changing rapidly due to anthropogenic influences. As a result, mankind will be faced with several "Grand Challenges" in the 21st century (e.g. Smith 2010; Bony et al. 2015, IPCC; Randers 2012). Two of these challenges, climate change and air quality, are strongly influenced by human activities and their impacts on changing atmospheric composition, more specifically on the concentrations of greenhouse gases, reactive trace gases and aerosol particles. These changes are also reflected from and linked with the natural environments at large spatial scales. In the future, the arctic-boreal natural environment will play a crucial role in the global climate via the albedo changes, carbon sources and sinks as well as aerosol production via biogenic volatile organic compounds (Arneth et al. 2010; 2014; Ballantyne et al., 2012; Carslaw et al. 2010; Kulmala et al. 2014).

In order to advance our understanding on interlinked grand challenges further, we need a research approach that helps us to construct a holistic scientific understanding of the feedbacks and interactions within the continuum of land-atmosphere-aquatic-systems and society across different spatial and temporal scales. Therefore we have established the Pan-Eurasian Experiment (PEEX) program (https://www.atm.helsinki.fi/peex/), which is a multi-disciplinary, multi-scale research initiative focusing on understanding biosphere-ocean-cryosphere-climate-society interactions and feedbacks (Lappalainen et al., 2014, Kulmala et al., 2015). PEEX fills some of the most critical scientific gaps needed for a holistic understanding of the feedback mechanisms typical for the Northern Eurasian geographical domain. Boreal forests and peat lands characterize the vast land areas of Northern Eurasia, major part of them situated in the Russian territory. In addition to natural environments, the PEEX research program is also interested in different environments: from urban to

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countryside, from megacities to non-populated remote areas, from areas of dispersed settlements and sparsely-built environments to heavily-industrialized regions. Thus, the research approach covers the Arctic and boreal regions situated in Northern Eurasia, and also the marine environments of the Arctic Ocean. PEEX operates in an integrative way using tools from natural and social sciences such as in-situ and satellite observations, laboratory experiments, multi-scale models and statistical data analyses together with socio-economic analyses. The PEEX research agenda covers spatial scales from regional to global and temporal scales from seconds to decades (Kulmala et al. 2011b). The scientific results will be used for developing new climate scenarios on global and regional scales, for constructing reliable early-warning systems, and for the mitigation and adaptation planning of the Northern societies in the most efficient way. PEEX aims to contribute to climate policy concerning topics important to the Northern Eurasian environment helping societies in building a sustainable future.

2. System perspective approach

Earth (System) Sciences (ESS) has emerged as one of the most rapidly developing scientific fields. The recent growth of ESS has been facilitated by the importance to understand the fundamental scientific processes of climate change and air quality, as well as the increasing impact of this research area. The development has mainly taken place among natural sciences, while the collaboration between natural and social sciences to tackle climate change issues has started to emerge relatively slowly. A multi- and cross-disciplinary approach is needed to advance the solution-oriented understanding of grand challenges and to apply new knowledge for reliable climate scenario development, mitigation and adaptation, as well as early warning system development. In addition to enhanced collaboration between different branches of science, there is a need for a next generation of multidisciplinary scientists able to connect the scientific issues together with an understanding of societal dimensions related to the grand challenges.

Climate change can be considered as the main driving force for system changes and their feedback dynamics, especially in the Arctic-boreal regions. It has already been estimated that the future warming in Northern high latitudes regions will be, on average, larger than that to be experienced at

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lower latitudes (IPCC, 2013, 2014). The climate change driven processes taking place in the Arctic provide a good example on how important it is to quantify feedback dynamics and at the same time study the specific research topics from the land-atmosphere-hydrosphere-cryosphere-societal system perspective. E.g. the surface radiation balance regulates the melting and freezing of the pack ice, which in turn is a key climate regulator. Model simulations of Arctic clouds are particularly deficient, impeding correctly simulated radiative fluxes, which are vital for estimation of the snow/ice-albedo feedback (Vavrus et al., 2009). Important, yet poorly-quantified players in the Arctic atmospheric system and climate change are short-lived climate forcers (SLCF), such as black carbon and ozone. The climatic impacts of SLCFs are tightly connected with cryospheric changes of the land system, and associated with the human activities. Models display diverse and often poor skill in simulating SLCF abundances both at the surface and vertically through the troposphere at high latitudes (Eckhardt et al., 2015; Emmons et al., 2015; Monks et al., 2015).

PEEX is setting a research approach where the large-scale research questions are studied from a system perspective and which are also filling the key gaps in understanding of the feedbacks and interactions between the land, atmosphere, aquatic and societal systems in the Northern Eurasian region (Kulmala et al., 2015). We have structured the research agenda so that we have highlighted 3 thematic research areas per system (Fig.1). The identification of these key thematic research areas has been based on bottom-up approach by researchers coming from Europe, Russia and China and participating PEEX meetings and conferences starting from 2012. The researchers first introduced a wide spectrum of specific research topics relevant to Northern Eurasian region, which were then evaluated and classified. This bottom up process led to the so-called "system-based" structure with altogether twelve thematic research areas. This approach will piece by piece lead into a holistic system understanding and quantifying the most dominant feedbacks and interactions between the systems and in understanding the dynamics of Arctic-boreal biogeochemical cycles (e.g. water, carbon, nitrogen, phosphorus, sulfur). In our approach, climate change is key driver in the dynamics of the land, atmosphere, aquatic and societal systems (Kulmala et al. 2015). The large-scale thematic areas of each system and many of the research highlight topics introduced by the PEEX research agenda are fundamentally related to climate change driven shifting GHG and SLCF formation processes and their

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primary and secondary feedbacks between systems and bio-chemical systems. When styding the Arctic-boreal feedback loops in a wider context PEEX agenda addresses China as the most crucial source areas of atmospheric pollution having a significant impact on the chemical composition of the atmosphere over Northern Eurasia (Monks et al, 2015), keeping in mind that solving air quality – climate interactions is also the key to practical solutions on local air quality problems in China.

In this paper we introduce the state of the art of the selected thematic research areas and summarize the future research needs at large scale. This introduction serves a White Paper of the PEEX research community. The thematic research areas relevant to the Land System are related to "changing ecosystem processes" (2.1.1), "ecosystem structural changes and resilence" (2.1.2) and "risk areas of permafrost thawing" (2.3.1). In the Land System research agenda we address the following key issues: changing boreal forests biosmass, Arctic greening and permafrost processes. The main research areas of the Atmospheric System research are "the specific characterization of the atmospheric composition and chemistry" (2.2.1), "urban air quality" (2.3.2.) "the atmospheric circulation and weather" (2.2.3). In terms of atmospheric system we address oxidants, trace gases, greenhouse gases and aerosols as atmospheric key components. We highlight that the future advances in predictidicting the urban air quality and improving the weather forecasting are strongly based the the atmosphery boundary layer dynamics research (Holtslag et al. 2013).

The thematic research areas relevant to the Aquatic System are "the Arctic Ocean in the climate system" (2.3.1), "the Arctic maritime ecosystems" (2.3.2) and "the lakes, wetland and rivers systems" (2.3.3). Under these research areas, the topics like Arctic sea ice changes, marine gross primary production and Arctic pelac foodwebs under enviromental changes are focused. Lakes and large-scale riversystem have multiple roles and aspects of the physical environements starting from water chemisty and alge booming, and ending up to carbon and methane dynamics.

The thematic areas of the Societal System have a number of dimensions, but in the first phase the primary interest lies on studying the consequences of "the increasing use of natural resources" (2.4.1), on the growing number of "natural hazards" (2.4.2), and on "the social transformations" (2.4.3) in the Northern Eurasian region. We see the topics like future Siberian forest area together with fuel balance, forest fires effecting the carbon and nitrogen balance and sociental dimentions related to

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infrastructure degration as the most important future research areas. In Chapter 3 we investigate the connections and interlinks between those 4 systems.

2.1. Land system – state of the art and future research needs

2.1.1 Changing land ecosystem processes

In the future, many Arctic-boreal 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, production of aerosol precursor gases and surface albedo. We need to first develop methods for indentifying the land regions and processes that are especially sensitive to climate change. Only after that are we able 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 http://www.globalforestwatch.org/). 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). 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. Furthermore, permafrost, a dominant feature of Siberian landscapes, stores around 1672 GtC (Tarnocai et al., 2009). Boreal forests form the main vegetation zone in the catchment areas of large river systems, so they are an important part of the global water-energy-carbon feedbacks.

The forest biomass forms a climate feedback via the anticipated changes in nutrient availability and temperatures, impacting carbon sequestered both into the aboveground biomass and 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,

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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), see also Fig.2.

In summary, even small proportional changes in ecosystem carbon uptake and in the turnover of soil carbon stocks can switch terrestrial ecosystems from a net carbon sink to a carbon source, with consequent impacts on atmospheric CO_2 concentrations and global temperatures (e.g. Bala et al., 2013; Bodman et al., 2013, Mukhortova et al. 2015). This process has already been observed, particularly in disturbed forests of Northern Asia (Shvidenko and Schepaschenko 2014). Currently, we do not fully understand all the factors influencing carbon storage, or the links between biogeochemical cycles of

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carbon, water and nutrients in a changing climate. However, the changes in these processes may be large, and their impacts may either amplify or decrease climate change, especially in the high northern latitudes.

2.1.2 Ecosystem structural changes and resilience

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 aerosol budgets. Furthermore, natural and anthropogenic stresses, such as land use changes and biotic and abiotic disturbances, are shaping ecosystems in Arctic and boreal regions, and have many important feedbacks to climate (see e.g. the review by Gauthier et al., 2015). 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 magnitude of these changes. The recent studies come to a conclusion that current estimates very likely overestimate the resilience of global forests and particularly boreal forests (Allen et al., 2015). In some cases, the changes may lead to system imbalance and crossing a tipping point, after which the effects are irreversible. One of the most relevant research topics for the land system are to determine the structural changes and tipping points of the ecosystem changes in the Northern Pan Eurasian region.

Part of the expected ecosystem structural changes is related to the lengthening of the growing season taking place the Arctic-boreal regions due to climate change. The phenomenon called “Arctic Greening” is due to increased plant biomass growth and advancing tree lines, turning previously open tundra into shrubland or forest (Myneni et al., 1997; Xu et al., 2013). However, browning as a proxy of decreased productivity was observed during recent decades in many boreal regions (Lloyd and Bunn 2007), including vast territories of Central Siberia together with a general downward trend in basal area increment after the mid-20th century (Berner et al., 2013). Current predictions on the extent and magnitude of these processes vary significantly (Tchebakova et al., 2009; Hickler et al., 2012; Shvidenko et al., 2013). It has been 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). By 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. This has important biophysical consequences and climatic feedbacks. Changes in vegetation cover can e.g. lead to albedo changes and therefore higher net absorption of radiation of regions covered by forests compared to open vegetation (Jeong et al., 2011). This modifies the local heat and vapour fluxes, and affects boundary layer conditions as well as both local to larger-scale climate (Sellers et al., 1997).

Northern peatlands contain a significant part of the global soil organic matter reservoirs (45% of the world's soil carbon; Post et al., 1982), and comprise one of the world's largest GHG sources (in particular CH_4) (IPCC 2013). The hydrological conditions are a major factor in determining the functioning of peatlands as carbon source or sink, and the carbon balance of the vast northern peatlands is extremely sensitive to human influence, be it either management or climate change. For example, thawing of permafrost peatlands in tundra regions might change tundra ecosystems from a stable state into a dynamically changing and alternating land-water mosaic, with dramatic impacts on their GHG production (Heikkinen et al., 2004; Repo et al., 2009). Today, peatland management activities range from drainage and peat harvesting to establishing crop plantations and forests. A complete understanding of the climatic effects of peatland management remains a challenging question (Maljanen et al., 2010).

Northern ecosystems are frequently suffering from increased stresses and deterioration. There is seldom a single and clear cause for forest dieback, but rather the ecosystems are suffering from multiple stresses simultaneously (e.g. Kurz et al. 2008 a,b; Allen et al., 2010). 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. Such perturbations and disturbances can include long-term pollutant exposures, but also stochastic events such as fires, flooding, windstorms or insect population outbreaks, 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. 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*) or mountain bark beetle (*Dendroctonus ponderosae*), 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. Nöjd and Kauppi, 1995; Tikkanen, 1995; Kukkola et al., 1997) and in some regions of Siberia (Baklanov et al., 2013). Societal transformations may lead to abandoning of agricultural land or deterioration of previously managed forests.

2.1.3. Risk areas of permafrost thawing

The major part of the Northern Eurasian geographical region is covered by continuous permafrost. The fate of permafrost soils in high latitudes is important for global climate with regard to all greenhouse gases. Thawing of permafrost will also substantially alter the hydrological regimes, particularly in Northern Asia that will lead to increasing water stress in forests and explosive enlargement of fire extent and severity as well as post fire successions (Shvidenko et al. 2013). 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 (Bala et al., 2013). The major question is, how fast will the permafrost thaw proceed and how will it affect ecosystem processes and ecosystem-atmosphere feedbacks, including hydrology and greenhouse gas cycling.

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Understanding of the feedbacks between the carbon and water cycling, ecosystem functioning and atmospheric composition related to permafrost thawing is one of the important topics of the land system (Heimann and Reichstein, 2008; Schuur et al., 2009; Arneth et al., 2010). 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, 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 connection between the climate and the thermal conditions in the subsurface layers (soil and bedrock) is an important aspect. The warming of the atmosphere will inevitably result in the 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.

The permafrost dynamics affects methane fluxes in many ways. Hot spots such as mud ponds emitting large amounts of CH_4 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, physical destruction of surface in hilly areas, 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).

2.2 Atmospheric system - state of the art and future research needs

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2.2.1 Atmospheric composition and chemistry

Atmospheric composition plays a central role in the Northen Eurasian climate system. In addition to greenhouse gases and their biogeochemical cycling discussed in more detail in section 3.2, key compounds in this regard are ozone and other oxidants, carbon monoxide, numerous organic compounds as well as different types of aerosols and their precursors, SO_2 will be discussed in chapter 3. At the moment, there is a serious gap in our knowledge on tropospheric composition and chemistry over Russia and the China, with particularly few observations programs being active over Siberia (Crutzen et al., 1998; Ramonet et al., 2002; Paris et al., 2008; Kozlova et al., 2008; Uttal et al., 2015, Paris et al., 2010; Sasakawa et al., 2010; Saeki et al., 2013; Ding et al., 2013a, 2013b; Berchet et al., 2015; Heimann et al., 2014).

There is thus an urgent need for harmonized, coordinated and comprehensive greenhouse gas, trace gas and aerosol in-situ observations over Northern Eurasia and China (long-term transport aspect) comparable to European and circumpolar data observations. In Fig. 3 we illustrate the geographical coverage of the ground stations which will be part of the coordinated, coherent and hierarchic observation netwrok in the Norther Eurasian region and in China.

2.2.1.1 Main pollutants

Little is known about whether and how the regional ozone budget in northern Pan-Eurasia differs from that in the rest of the northern hemisphere (Ding et al., 2008; Berchet et al., 2013). Arctic tropospheric ozone is significantly influenced by long-range import of ozone and precursors from mid-latitude sources, as well as by boreal wildfires (Ding et al., 2009; Wespes et al., 2012). Observations from individual plumes suggest that O_3 production in boreal wildfire plumes may be weaker, or even turn into net destruction, compared to fire plumes at lower latitudes (Jaffe and Wigder, 2012). However, recent modeling work has suggested that boreal fires produce a substantial large-scale enhancement in summertime ozone at high latitudes, which appears to be highly sensitive to differences in partitioning of reactive nitrogen among models (Arnold et al., 2015). Given their importance for air quality and global greenhouse gas budget, more atmospheric measurements of O_3, its precursors and other

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pollutants over Siberia are needed (see Elansky, 2012). This is particularly the case in light of increasing local Arctic sources of ozone precursors (NOx, VOCs) from e.g. shipping and fossil fuel resource extraction (Roiger et al., 2015). Such datasets would be particularly useful for the evaluation of atmospheric chemistry models and satellite products.

The changes in the abundance of anthropogenic aerosols and their precursors in Northern Eurasia 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 anthropogenic aerosols 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. These aerosols cause large perturbations to the regional radiation budget downwind of major source areas in the Northern Eurasian region, 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 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; Meinander et al., 2015; Atlaskina et al., 2015).

The most important natural aerosol type over large parts of Eurasia is secondary organic aerosol 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 associated with BVOC emissions is the dominant source of aerosol particles and cloud condensation nuclei during summer time (Mäkelä et al., 1997; Kulmala et al., 2001; Tunved et al., 2006; Asmi et al., 2011; Hirsikko et al., 2011). The production of secondary organic aerosols associated with BVOC emissions has been estimated to induce large direct and ndirect radiative effects over the boreal forest zone (Spracklen et al., 2008; Tunved et al., 2008; Lihavainen et al., 2009, 2015; Scott et al., 2014). The few continuous measurement data sets from Siberia suggest similarities in the frequency and seasonal pattern of new particle formation events between Siberia and Nordic stations (Dal Maso et al., 2007; Arshinov et al., 2012; Asmi et al., 2015), yet little is known

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about the overall contribution of biogenic emissions to aerosol number or mass concentrations, or to the cloud condensation nuclei budget, in Pan-Eurasia.

Other important natural aerosol types in Pan-Eurasia are sea spray, mineral dust and primary biogenic aerosol particles. Sea spray aerosols makes an important contribution to the atmospheric aerosol over the Arctic Ocean and its coastal areas (Zábori et al., 2012, 2013), and influences cloud properties over these regions (Tjernström et al., 2013). 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 primary biological aerosol particles (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 arctic-boreal regions. Over Pan-Eurasia, PBAP typically contributes more than 20% of PM2.5 organic aerosol mass concentrations (Heald and Spracklen, 2009) and 25% of supermicron aerosol number concentrations (Spracklen and Heald, 2014). Ice nucleation, in general, is one of the key microphysical processes in the atmosphere that remain ill understood. However, a novel theoretical approach (Laaksonen, 2015; Laaksonen and Malila, 2016) has been shown to be superior to older theories in the case of water nucleation on solid surfaces, and it may open a completely new avenue in the studies of atmospheric ice formation.

Satellites provide information about spatial distributions of the column-integrated concentrations of aerosols (e.g., de Leeuw and Kokhanovsky, 2011) and various trace gases including ozone and its precursors (Burrows et al., 2011). These atmospheric constituents are generally retrieved using passive instruments which have a good sensitivity near the surface. However, retrieving information on the near-surface concentrations of pollutants requires assumptions on their vertical distributions. For instance, the retrieval of tropospheric ozone from satellite observations requires correction for the high concentrations in the upper troposphere and lower stratosphere. For aerosols, which can only be retrieved in clear sky conditions, the situation may be complicated when disconnect layers are present with different types of aerosols. A solution may be the retrieval of aerosol vertical variation or the height of the aerosol layer using, e.g. active instruments (lidars), or retrieval using spectrally-resolved

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observations in the Oxygen-A band (e.g. Hollstein and Fisher, 2013) or, instruments providing multiple viewing algorithms such as MISR (Nelson et al., 2013) or AATSR (Virtanen et al., 2014). Another complication for aerosols may be the vertical variation of the physical and chemical properties which render it difficult to obtain closure between column and ground-based in situ measurements (Zieger et al., 2015 and references cited therein). Nevertheless, good progress has been made in aerosol retrieval and column-integrated aerosol measurements (AOD) from satellites and ground-based observations compare favorably (e.g., de Leeuw et al., 2015; Kolmonen et al., 2015). Measurements of trace gases from space using wavelengths in the thermal infrared suffer from low sensitivity in the lower troposphere (Pommier et al., 2010). All these factors may render the comparison against local ground-based in-situ observations difficult, although a possible way out could be the use of chemical transport models constrained by the satellite column measurements (e.g., de Laat et al., 2009; Stavrakou, 2012; 2014), possibly together with sub-orbital airborne measurements of relevant species. Satellite-measured AOD has been successfully applied to obtain information on ground based aerosol mass concentrations (PM2.5) (Xu et al., 2015; van Donkelaar er al, 2015). Also the use of multiple satellite instruments, with different characteristics, is proposed to obtain more accurate information on transport of aerosols and trace gases and their vertical distribution (e.g., Naeger et al. 2015).

2.2.1.2. Large-scale pollutant transport and sources

Of particular interest is the pollutant transport to Arctic areas, where they can influence the radiation budget and climate by various ways (Stohl, 2006; Warneke et al., 2009; Meinander et al., 2013; Eckhardt et al., 2015). Model simulations suggest that European emissions dominate Arctic pollutant burdens near the surface, with sources from North America and Asia more important in the mid and upper troposphere (Monks et al., 2015). The impact and influence of China and its polluted megacities on Arctic and boreal areas is topic of key importance, given recent and rapid Chinese industrialization. Inter-continental pollution transport has also become of increased concern due to its potential influence on regional air quality. The pollutant export from North America and Asia has been characterized by intensive field campaigns (Fehsenfeld et al., 2006; Singh et al., 2006), but long-term research approaches are lacking.

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Emissions from forest fires (van der Werf et al., 2006; Sofiev et al., 2013) 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 carbon monoxide (Nédélec et al., 2005), as well as aerosol paticles. Aerosols emitted by forest fires are of particular interest, 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 Eurasia (Randersson et al., 2006). We need comprehensive top-down emissions estimates, using inverse modeling constrained by satellite observations, in order to provide quantitative information on the source strength of aerosols and trace gases emitted by open fires.

Air pollution in monsoon Asia has two main characteristics. First, the total pollutant emission rate from fossil fuel 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 concentrations of key pollutants, such as nitrogen oxides (Richter et al., 2005; Mijling et al., 2013) and their end-product ozone (Ding et al., 2008; Wang et al., 2009; Verstraeten et al., 2015), are still increasing. Second, in addition to the anthropogenic fossil fuel 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 during spring and in Siberia duing summer, whereas an intensive man-made burning of agricultural straw takes place in the north and east China plains. Dust storms frequently occur in the Taklimakan and Gobi deserts in northwest China, and thisdust is often transported over eastern China, southern China, the Pacific Ocean and even the entire globe (Nie et al., 2014). After mixing with other anthropogenic pollutants, biomass burning and mineral dust aerosols have been found to cause complex interactions in the climate system (Ding et al., 2013; Nie et al., 2014).

2.2.2. Urban air quality

The northern Eurasian urban environments are characterized by cities with strong anthropogenic emissions from local industry, traffic and housing in Russia and China, and by megacity regions with alarming air quality levels like those of Moscow and Beijing. Bad air quality has serious health effects

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and it damages ecosystems. In Beijing, for example, concentrations of atmospheric fine particles have been found to be over 10 times higher than the safe level recommended by the World Health Organization (WHO) (Zheng et al., 2015). Furthermore, atmospheric pollutants and oxidants play a central role in climate change dynamics via their direct and indirect effects on global albedo and radiative transfer. A deeper understanding of the unpredicted chemical reactions between pollutants and identification of the most relevant feedbacks between air quality and climate at northern high latitudes and in China is the most urgent task helping us to find also the practical solutions for the healthy air (Kulmala, 2015).

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 lowest layers of the atmosphere, thus increasing 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. In winter time, shallow and stably-stratified PBLs typical for northern Scandinavia and Siberia are especially sensitive to even weak impacts and, therefore, deserve particular attention, especially in the conditions of environmental and climate change (Zilitinkevich and Esau, 2009; Esau et al., 2012; Davy and Esau, 2014; Wolf et al., 2014 ; Wolf and Esau, 2014). 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, as well as dispersion and deposition of aerosols and gases, which are essential features of hot waves and other extreme weather events.

The worst air pollution episodes are usually associated with stagnant weather conditions with a shallow planetary boundary layer (PBL), which promotes the accumulation of intensively emitted pollutants near the surface. The lower PBL is also influenced by the heavy pollution itself through its direct or indirect effects on solar radiation and hence the surface sensible heat flux (e.g. Ding et al., 2013b). The boundary layer -air pollution feedback will decrease the height of the PBL and result in an even more polluted PBL (Ding et al., 2013b; Wang et al., 2014, Petäjä et al., 2016). Therefore, considering the complex land surface types (city clusters surrounded by agriculture areas) and pollution sources and improving our understanding of the associated feedbacks is very important for forecasting extreme air pollution episodes and for long-term policy making. In order 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.

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 the compounds produced by the surface fluxes or surface emissions from efficiently penetrating from the PBL into the free atmosphere. This means that the PBL height and turbulent fluxes through the PBL upper boundary control local features of climate and extreme weather events, such as the heat waves associated with convection, or the strongly stable stratification events triggering the air pollution (Zilitinkevich et al., 2015). This concept (equally relevant to the hydrosphere) illustrates the importance of modeling and monitoring the atmospheric PBL height, which varies from dozens to thousands of meters (Zilitinkevich, 1991; Zilitinkevich et al., 2007; Zilitinkevich and Esau, 2009). To carry our a comprehensive inventory of the PBL height over Northern Eurasia is urgently needed.

2.2.3. Atmospheric circulation and weather

The ongoing environmental change and its amplification in the Northern Eurasian pose special challenges to the prediction of weather-related hazards, and also to long-term impacts. A key question is how will the atmospheric dynamics (synoptic scale weather, boundary layer characteristics) change in Arctic and boreal regions. The recent changes in the Arctic sea-ice have been much more rapid than models and scientists anticipated about ten years ago. The role of Arctic Ocen in the climate system and sea-ice changes have impacted mid-latitude weather and climate, with central and eastern Eurasia among the regions with strongest effects (Vihma, 2014; Overland et al., 2015) (see section 2.3.1).

2.2.3.1 Atmospheric dynamics

The reliability of weather forecasts, and the extension of the time-range of useful forecasts is needed for minimizing economic and human losses from extreme weather and extreme weather related

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natural hazards. In Europe, this range is currently on average about 8−9 days (Bauer et al., 2015), which allows reliable early warnings to be issued for weather related hazards, such as windstorms 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). In the Northern Eurasian region, improved predictions can be used, for instance, to better prediction of thermal comfort conditions in Northen cities (Konstantinov et.al, 2014). A strong urban heat island effect has already been observed in urban areas of the Arctic with complex spatial and temporal structures (Konstantinov et al., 2015).

Understanding of the planetary boundary layer (PBL) processes are particularly important for improving the weather predictions. The representation of boundary layer clouds, and their further coupling to convection in stable conditions is not currently well understood. Quantification of the behavior of the PBL over the Northern Eurasian region is needed in analyses of spatial and temporal distribution of the surface fluxes, in predictions of microclimate and extreme weather events, and in modeling clouds and air quality.

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 by the inhomogeneties inthe 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.

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2.2.3.2 Global Electri Circuit

The global electric circuit (GEC) is an important factor connecting the solar activity and upper atmospheric processes with the Earth's environment, including the biosphere and 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 because of two reasons: the continuous operation of ionization sources, which provides an exponential growth of the 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.

2.3 Aquatic system - state of the art and future research needs

2.3.1 The Arctic Ocean in the climate system

The essential processes related to the interaction between the Arctic ocean and other components of the Earth system include the air-sea exchange of momentum, he and matter (e.g. moisture, aerosol, trace gases, CO_2, and CH_4), and the dynamics and thermodynamics of sea ice. The most dramatic change in the Arctic Ocean has been the rapid decline of the sea ice cover. Since the early the 1980s, the Arctic sea ice extent has decreased by roughly 50% in summer and autumn (Cavalieri and Parkinson 2012), while the winter sea ice thickness in the central Arctic has decreased by approximately 50 % (Kwok and Rothrock 2009). Arctic sea ice changes have serious teleconncetions. Despite the warming climate, wintertime cold spells in East Asia have become more frequent, stronger and longer lasting in

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this century compared with the 1990s (Kim et al., 2014). It also seems that the strong decline of the Arctic sea ice has favored atmospheric pressure patterns that generate cold-air outbreaks from the Arctic to East Asia (Mori et al., 2014; Kug et al., 2015; Overland et al., 2015). The reasons for and the future evolution of the sea ice decline, as well as its effects on the ocean, atmosphere and surrounding continents are among the actual study topics of the Arctic climate system. Other major issues include the role of the ocean in the Arctic amplification of climate change, greenhouse gas exchange between the ocean, sea ice and atmosphere, and aerosol budgets in the marine Arctic (Smedsrud et al., 2013). The key question here is related to the changes of sea ice extent and thickness, and to the terrestrial snow cover change.

Many of the processes considered to be responsible for the Arctic amplification of climate warming are related to the ocean and sea ice (Döscher et al., 2014). Among these, the snow/ice albedo feedback has received the most attention (e.g. Flanner et al., 2011). This feedback is the 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 beging. 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 increased heat transports from lower latitudes to the Arctic (Polyakov et al., 2010; Döscher et al., 2014) and fall-winter energy loss from the ocean (Screen and Simmonds, 2010). Furthermore, the melting of sea ice strongly affects evaporation, and hence the water vapor and cloud radiative feedbacks (Sedlar et al., 2011), and the PBL thickness which controls the sensitivity of the air temperature to heat input into the PBL (Esau et al., 2012). The relative importance of the mechanisms affecting the Arctic amplification of climate warming are not yet well known (See also Pithan and Mauritsen, 2014; Cohen et al., 2014).

The rapid decline of the Arctic sea ice cover 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, including the role of black carbon (see Bond et al. 2013), behind the past and ongoing sea ice evolution. Several processes have contributed to the decline of

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Arctic sea ice cover, but the role of these processes needs better quantification (Smedsrud et al., 2013; Vihma et al., 2014). Further studies are needed on the impacts of changes in cloud cover and radiative forcing (Kay et al., 2008), atmospheric heat transport (Kapsch et al., 2013) and oceanic heat transport (Döscher et al., 2014). 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), changes in the phase of precipitation (Screen and Simmonds, 2011), and large-scale interaction between the sea ice extent, sea surface temperature distribution and atmospheric dynamics (cyclogenesis, cyclolysis and cyclone tracks) as discussed e.g. by Outten et al. (2013).

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). In the future, research has to 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 a particular need to study the effects of Arctic sea ice decline on Eurasian weather and climate (Section 2.2.3) Another poorly studied problem related to the Arctic Ocean is the role of sea ice as a source of aerosol precursors, and in the gas exchange between the ocean and atmosphere (Parmentier et al., 2013). Preliminary results of field studies at the drifting stations North Pole 35 and 36 (Makshtas et al., 2011) showed that the shrinking sea ice cover could be the reason for increasing CO_2 uptake from the atmosphere over 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, and may have important effects on the structure of sea ice. Increased snow load on a thinner ice may in the future cause flooding of sea water on ice in the Arctic, which results in the formation of snow ice. Increased snow melt and rain, on the other hand, results in increased percolation of water to

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the snow-ice interface, where it re-freezes, forming super-imposed ice (Cheng et al., 2008). 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 opened some, albeit limited, possibilities for the 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 (Liu et al., 2012; Stroeve et al., 2012). On the other hand, the reduction of the 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 a thin ice is very sensitive to unpredictable anomalies in the atmospheric forcing. For example, in August 2012 a single storm caused a reduction of the sea ice extent by approximately 1 million km^2. The reduced sea ice extent in the winter months has significant impacts on convective clouds. Observations revealed gradual increasing frequency of the convective cloud fields over Norwegian and Barents Seas (Chernokulsky and Mokhov, 2012; Esau and Chernokulsky, 2015). The unusually strong atmospheric convection and weaker virtual potential temperature inversions create favorable conditions for the extreme Arctic cold outbreaks and meso-scale cyclones known as Polar Lows (Kolstad et al., 2009).

It is 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 (see section 2.3.1). To improve preparedness, new observational evidence is therefore needed to reduce uncertainties in the system dynamics both on short and longer time-scales.

2.3.2 Arctic marine ecosystem

The ice cover of the Arctic Ocean is undergoing fast changes, including a decline of summer ice extent and ice thickness (see 2.3.1). 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. The key topic of future research is the joint effect of Arctic warming, ocean freshening, pollution load and acidification on the Arctic marine ecosystem, primary production and carbon cycle.

New ice-free areas of the Arctic Ocean could result in a pronounced growth of the annual gross primary production (GPP), increased phytoplankton biomass and a loss of ice-rich algae communities associated with the low ice sheet surface (Bluhm et al., 2011). Progressive increase of oil and natural gas drilling and transportation over the shelf areas will be escalating the environmental changes of the Arctic marine ecosystems. Furthermore, there is a risk of irreversible changes in the marine Arctic productivity and key biogeochemical cycles, and the potential for CO_2 absorption by marine ecosystem. Processes involving the Arctic may also affect adjacent boreal areas.

We do not know how the climatically-induced increase in GPP and phytoplankton biomass influence the productivity of higher trophic levels of the Arctic ecosystem. In typical Arctic ecosystems, the most important consumers are large-sized herbivorous copepods, which have lifecycles synchronized with the temperature as well as the seasonal algae dynamics (Kosobokova, 2012). Another important consumer community are the small-sized herbivorous copepods, which are important especially in shelf ecosystems. An increase in the 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. Our current understanding on the role of small copepods in the Arctic ecosystems is limited (Arashkevich et al., 2010). An increase in surface water temperature may “open the Arctic doors” for new species, and change the Arctic pelagic food webs, their energy flows and biodiversity.

Increases in the Artic sea temperature may lead to populations from neighboring regions penetrating the Arctic ecosystem and changing the structure and functioning of native ecosystems. For example, a 1.5 °C water temperature increase in the Bering Sea during the mid-1970s allowed the Alaskan 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 ecosystems. However, the appearance of aggressive new species even in low numbers may

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dramatically impact the sensitive Arctic ecosystems and have effects on the future regulation of international fisheries in the Arctic.

We have only recently begun to understand the processes that regulate freshwater-marine ecosystem interactions in estuarine zones (Flint, 2010). The mechanisms determining the impact of riverine waters over the Arctic shelves and the central deep-basin, and their dependence on specific climatic forces, are still poorly understood. In order to determine the impact of riverine waters, it is important to locate the new flagship-stations or permanent observation points in the estuaries of large Siberian rivers. The changing riverine discharge to the Arctic shelves may amplify 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 materials of terrestrial origin, including organic matter and nutrients, annually delivered to the artic shelves, and further to the Arctic basin (Gustafsson et al., 2011). Human driven land use changes to drainage basins, and associated river systems, have the potential to increase the speed of delivery of pollutants to Arctic sea..

2.3.3 Lakes, wetlands and large-scale river systems

In the last decade, the combined effects of air pollution and climate warming on fresh-water systems 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). It is important to understand 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 these changes affect livelihoods, agriculture, forestry and industry. The water chemistry of 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 current ground-based stream flow-gauging network over the Norther Eurasian region 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.

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 led to changes in the geochemical cycles of sulphur, nitrogen, 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). Environmental pollution problematics includes also the waterborne spreading of nutrients and pesticides from a local 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. One example of important study area is the Selenga river basin, which 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 Yenisei 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. 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).

In addition to water chemistry, 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 of this matter effectively disappears from the carbon budget of the terrestrial ecosystem (Huotari et al., 2011). 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. 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). Long-term measurements carried out during all seasons in the littoral zone of Lake Baikal showed that maximum CO_2 sink and emission rates are observed in August and December (during the pre-ice period), respectively, and the total CO_2 flux from the atmosphere into the littoral zone of Lake Baikal was estimated to be 3–5 $g \cdot CO_2 \cdot m^{-2}$ (Domysheva et al., 2013).

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 Eurasian region on eutrophication, accompanied by blooms of cyanobacteria. Besides, the northern Eurasian region is characterized by thaw lakes, which comprise 90% of the lakes in the Russian permafrost zone (Romanovskii et al., 2002). These lakes, which are formed in melting permafrost, have long been known to emit CH_4. The latest observations of the lakes in the permafrost zone of northern Siberia indicate that they are releasing much more CH_4 into the atmosphere than previously thought. Rather than being emitted in a constant flow, 95 % of CH_4 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).

One direct consequence of climate change is the avalanche reproduction of toxic cyanobacteria (*Nodularia, Microcystis, Anabaena, Aphanizomenon, Planktothrix*) and diatoms (*Pseudo-nitzschia*) (Moore et al., 2008; Paerl and Huisman, 2009). These blooms occur in ponds, lakes, reservoirs and bays of the sea. Cyanobacteria and diatoms 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.

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Water conservation has received an 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). In China, the river systems are dominated by rivers flowing from the Tibetan plateau to the Pacific Ocean. Yangtze 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 losses. 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.

2.4 Social system - – state of the art and future research needs

2.4.1 Land use and natural resources

The fundamental large-scale task is to estimate, how the 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 will influence the environments and societies of the Northern Eurasian region. For example, the industrial development of Siberia should be considered one of most important drivers of future land use and land cover changes in Russia. Siberia is a treasure chest of natural resources of 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).

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 decrease in agricultural activities. There has also been a significant reduction in agricultural land use, and its partial replacement by zonal forest ecosystems (Lyuri et al., 2010). According to recent estimates, the total area of abandoned agricultural land in Russia in 1990s-2010s is at about 57 million ha, of which 18 million ha have been restored by forests and 6 million ha of this are located in Asian Russia (Schepaschenko et al.,2015). 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, in case relevant management programs for the forests re-established on abandoned lands are be implemented.

The dynamics of land cover, particularly forests, have been 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, basically before the middle of the 1990s. This large increase is explained by improved quality of forest inventories in remote territories, natural reforestation, mostly during the Soviet era as a result of forest fire suppression, and 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 a dramatic decline in the quality of forests, unsustainable use of forest resources and insufficient governance and forest management in the region including frequent occurrence of illegal logging, natural and human-induced disturbances (Shvidenko et al., 2013).

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

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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 (Kotilainen et al., 2008).

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 a 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 will continue to dominate the economy in the majority of these territories for the next decades.

A crucial factor in greenhouse gas emission dynamics is the fuel balance. In Russia, features of the fuel balance has led to an increased pollution. On average, specific emissions in northern and eastern cities of Russia, where coal accounts for most of the power generation, are three times higher than in cities where power is generated mainly from gas or fuel oil (Bondur, 2011a). The geographical location, undeveloped infrastructure, harsh climate and coal burning are the main reasons for increased levels of anthropogenic pollution in these areas (Bondur and Vorobev, 2015; Bondur 2014). 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 to some extent: 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, leading to 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 et al. 2013).

2.4.2 Natural hazards

2.4.2.1 Extreme weather and occuring fires

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 (IPCC 2013. 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. New knowledge is needed for improving the forecasting of extreme weather events, for understanding the effect of wildfires on radiative forcing and atmospheric composition in the region, for estimating the impacts of weather extremes on major biogeochemical cycles, and for understanding the effects of disturbances in forests on the emissions of BVOC and VONs (volatile organic nitrogen) (Bondur, 2011b, 2015; Bondur, Ginsburg, 2016). 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?

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The number of large hydrometeorological events in Russia that cause substantial economic and social losses has increased by more a factor of two from 2001 to 2013 (State Report, 2014). The main hazards are related to atmospheric processes on various temporal and spatial scales, including strong winds, floods and landslides caused by heavy precipitation, fires caused by drought and extreme temperatures. High temperatures and long droughts can substantially decrease the productivity and cause high die-back 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.

In order 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 related to strong winds and heavy precipitation and anticyclones related to drought and fires episodes. 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; Bondur, 2011b, 2015). 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”, that is irreversible transformation of the forest cover for long periods (Shvidenko and Schepaschenko, 2013, Bondur, 2011b, 2015). Megafires also lead to specific weather conditions over the affected areas that are comparable in size with large-scale

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pressure systems (~30 million ha and more). The annually burned area in the Russian territory was estimated to be 8.2±0.8·10^6 ha during 1998-2010, and 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) wass estimated to be 121±28 Tg C $year^{-1}$ (Shvidenko et al., 2011). Current model projections suggest that the number of fires will double by the end of this century. The extent of catastrophic fires escaping from the control and fire intensity are projected to increase. Due to increased severity of fire and deeper soil, 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 ecosystems, including the soil. These changes include: (i) 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; Kulmala L. et al. 2014); (ii) fire alters the microbial community structure in the soil, as well as the structure of the vegetation (Dooley and Treseder, 2012; Sun et al., 2015); (iii) 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., 2014) and (iv) fire is one of the crucial drivers controlling the dynamics of the carbon stock of boreal forests (Jonsson and Wardle, 2010; Köster et al., 2014).

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.

2.4.2.2 Permafrost degradation and infrastructures

The degradation of permafrost will cause serious damage both to infrastructure and to ecosystems and water systems in the Northern Eurasinan region. This includes, for example, damage to pipe-lines and buildings, deformation of roads and railroads in Russia, Mongolia and China, variations in the ion distribution in soil water in young and ancient landslides, cryogenic landslides, spatial and temporal changes of grass and willow vegetation, saline water accumulation in local

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depressions of the permafrost table, and formation of 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 section 2.1.1, 2.1.2), there are numerous infrastructural issues related to possible changes in the thickness and temperature of the frozen part of the subsurface, and thus in the 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 this 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 (United Nations Environment Program, 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 (United Nations Environment Program, 2013).

2.4.2.3 Changing sea environments and the risk of accidents in coastal regions

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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, the sea level rise and continuing permafrost degradation leads to significant coastal erosion, and to the possibility of a collapse of coastal constructions such as lighthouses, ports, houses, *etc*. In this region, the sea level rise is coupled to the permafrost degradation in a complex way, and should be focused on in future studies.

Understanding and measuring artificial radionuclides in marine ecosystems are needed for improving emergency preparedness capabilities, and for developing 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 and 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 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 future focus should be put 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.

2.4.3 Social transformations

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Climate and weather strongly affect the living conditions of Northern Eurasian societies, influencing people's health, incidence of diseases and 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. There is a need to analyzes the scientific background and robustness of the adaptation and mitigation strategies (AMS) of the region's societies, their resilience capacity, with special emphasis on the forest sector and agriculture. The future research needs are in understanding which ways are populated areas vulnerable to climate change; how can their vulnerability be reduced, and their adaptive capacities improved; what responses should be identified to mitigate and adapt to climate changes.

Health issues are also important in multidisciplinary studies of north Eurasia, as the living conditions of both humans and livestock are changing dramatically. Short-lived climate forcers (SLCF), such as black carbon, ozone and aerosol particles, are important players in both air quality and Arctic climate change and their impacts are not yet quantified. 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. 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 a significant regional and seasonal variation (Zolotokrylin et al., 2012).

Both northern and eastern Eurasian have small and diminishing populations, mainly due to the migration outflow started in the 1990s due to severe and unfavorable living conditions combined with changing state policies with respect to the development of northern territories. 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 1990s. 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, 2007b). The population change in northeastern Russia was particularly remarkable: the Chukotka autonomous okrug lost 68 % of its population, the Magadan Oblast lost 59 % and the Kamchatka Krai lost 33 %.

Geographical and ethnic factors influence the demography and settlement pattern in the region. Geographical factors include environmental conditions and mixture of urban and rural territories. 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 remained mostly intact, with only small decreases in population, while the latter disappeared entirely or were 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 Northern Eurasian cities and towns situated in the less favoured regions are currently incapable of mitigating unfavorable impacts. The impact of 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, tincidence of diseases, adaptation potential and economic development in general. Furthermore, it is important to explore the interactions between the 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; Tynkkynen, 2010). 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

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as well as accident like leakages in gas and oil pipelines. Such systems would be useful for federal, regional and local authorities, as well as for local communities.

It should also be taken into account that the majority of the world's ethnic groups are small and engaged in culturally specialized methods of subsistence, so 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. But even more threatening are the indirect effects. The immediate environment of small ethnic groups is often vulnerable to the adverse impact of majority populations representing governments and nations. The effects of climate change may lead to a rapid and massive transfer of majority populations to areas previously inhabited by small ethnic groups.

3. From process studies towards system understanding and quantification of feedbacks of arctic-boreal regions

The system understanding helps us to understand the behavior of feedbacks between the land, atmosphere, aquatic and societal/economic systems. To be able to provide a system understanding, we need to understand the individual processes, and based on process understanding we are then able to quantify different biogeochemical cycles. Via biogeochemical cycles, the energy and matter flows are linked to a wider system context, which enables us to analyze the feedback phenomena. Feedbacks are essential components of our climate system, as they either increase or decrease the changes in climate-related parameters in the presence of external forcings (IPCC, 2013).

The effects of climate change on biogeochemical cycles are still inadequately understood, and there are many feedback mechanisms 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 (Kulmala et al., 2004; Tunved et al., 2006; Kulmala et al., 2011a; Hirsikko et al.,

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2011) and aerosol-cloud interactions (McComiskey and Feingold, 2012; Penner et al., 2012; Rosenfeld et al., 2014).

The northern 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 PEEX research agenda is addressing the most relevant research topics related to the prosesses dynamics in the land, atmospheric, aquatic and society systems relevant to Northern regions. PEEX also aims to quantify the range of emissions and fluxes from different types of ecosystems and environments and links to ecosystem productivity (see also Su et al., 2011; Kulmala and Petäjä, 2011; Bäck et al., 2010). This new knowledge helps us to combine a holistic view on the changes in biogeochemical cycles and feedbacks in the future Arctic-boreal system (Fig 4). PEEX will 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).

Holistic representations of feedback loops potential relevant to Arctic-boreal systems have been given by Charlson et al. (1987), Quinn and Bates (2011) and by Kulmala et al. (2004; 2014). The "CLAW" hypothesis ("CLAW" acronym refers to Charlson, Lovelock, Andreae and Warren) connects the ocean biochemistry and climate via a negative feedback loop involving cloud condensation nuclei production due to the dimethylsulfoniopropionate (DMSP) and DMS biosynthesis from Cyanobacteria and algae based photosynthesis (e.g. Quinn and Bates, 2011; Ducklow et al., 2001; O'Dowd et al., 2004; de Leeuw et al., 2011; Malin et al., 1993; O'Dowd and de Leeuw, 2007). The COBACC (COntinental Biosphere-Aerosol-Cloud-Climate) hypothesis suggests two partly overlapping feedback that connect the atmospheric carbon dioxide concentration, ambient temperature, gross primary production, biogenic secondary organic aerosol formation, clouds and radiative transfer (Kulmala et al., 2004; 2014; also see section 2.1.1.). The quantification of these feedback loops under changing climate is crucial for reliable Earth system modelling and predictions.

In the context of the COBACC feedbackloop, the key large-scale research questions are the changing cryospheric conditions and consequent changes in ecosystem feedbacks affecting the Arctic-boreal climate system and weather. Furthermore, we should estimate the net effects of various feedback

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effects (CLAW, COBACC) on land cover changes, photosynthetic activity, GHG excahnges, BVOC emssions, aerosol and cloud formation and radiative forcing in regional and global scales. In our analysis, we should also take in account the urbanization processes, social trasformations (see section 2.4.3), which are changing the regional climates. In this task we should also study the key gaps of the buogeochemical cycles.

3.1 Hydrological cycle

Climate change may profoundly affect most of the component in the hydrological cycle, giving rise to positive or negative feedbacks (Fig 5). While variations in the hydrological cycle often take place at regional or local scales, they can also give rise to large-scale or even global changes. Knowledge of the hydrological cycle in general and particularly related to permafrost is crucial for predicting the resilience and transformation of forest ecosystems coupled with permafrost (Osawa et al. 2009).

In addition to permafrost processes, other important issue in high latitudes is precipitation. Precipitation is a critical component of the hydrological cycle, having a 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 different components of hydrological cycle like precipitation, evapotransipiration, CCN formation etc. This is especially true in the high-latitude regions, in which observations and measurements are particularly sparse, and 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) (Fig.5). Global precipitation is retrieved at very high spatial and temporal resolution by combining microwave and infrared satellite measurements (Sorooshian et al., 2000; Kummerow et al., 2001; Joyce et al., 2004; Huffman et al., 2007). 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. Mu et al., 2007; Su et al., 2007; Fisher et al., 2008; Sheffield et al., 2010). The water storage change component can be obtained from satellite data, and the water level in

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lakes and large-scale river systems can be estimated from satellite altimetry with special algorithms developed for terrestrial waters (Berry et al., 2005; Velicogna et al., 2012; Troitskaya et al., 2012; 2013).

3.2 Carbon cycle

It is not clear how future climate will modify incoming (NPP) and outgoing (e.g., HSR) carbon fluxes to and from terrestrial ecosystems. It is likely that the transformation of Russian forests is a tipping element for the climate system by end of the century over huge areas, even though uncertainties in such forecast are significant (Gauthier et al. 2015). The role of boreal and Arctic lakes and catchment areas in carbon storage dynamics is poorly quantified (Fig.6).

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 by the land-ecosystem approach (Shvidenko et al., 2010a; Schepaschenko et al., 2011; 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 above 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 recent decades (Myneni *et al.*, 1997; Zhou *et al.*, 2001), while future predictions are uncertain. The Net Ecosystem Carbon Budget (NECB) or Net Biome Production (NBP) are 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).

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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 SOM (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).

Arctic warming is promoting terrestrial permafrost thaw and shifting hydrologic flowpaths, leading to fluvial mobilization of ancient carbon stores (Karthe et al., 2014). Observed permafrost thaw acts as a significant and preferentially degradable source of bioavailable carbon in Arctic freshwaters, which is likely to increase as permafrost thaw intensifies causing positive climate feedbacks in response to on-going climate change (Mann et al., 2015). Significant differences in fluvial carbon input between headwaters and downstream reaches of large Arctic catchment (Enisey and Lena) have been identified, the problem very poorly explained yet. At the same time fluvial export by largest rivers considered to be an order of magnitude less than coastal erosion in the Arctic – dat arpoved by (Semiletov et al, 2011) estimated The Lena's particulate organic carbon export two orders of magnitude less than the annual input of eroded terrestrial carbon onto the shelf of the Laptev and East Siberian seas.

Although inland waters are especially important as lateral transporters of carbon, their direct carbon exchange with the atmosphere, so-called outgassing, has been recognized to be a significant component in the global carbon budget (Bastviken *et al.*, 2011; Regnier et al., 2013). 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 the lake size and gas saturation, and especially small lakes are relatively large sources 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.

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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 (Pumpanen et al., 2014), 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 (Huotari et al, 2013). Also the role of VOC emissions as a part of the carbon budget needs to be quantified.

3.3 Nitrogen cycle

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). Only cryptogamic covers and certain organisms living in symbiosis with plants are capable of nitrogen fixation, making nitrogen the main growth-limiting nutrient in terrestrial ecosystems (Elbert et al. 2012; Lenhart et al. 2015). Human perturbations to the natural nitrogen cycle have, however, significantly increased the availability of nitrogen in the environment (Fig.7). 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).

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. 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 hence contribute to the positive radiative forcing of greenhouse gases (Repo et al., 2009; Elberling et al., 2011).

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In natural terrestrial ecosystems, nitrogen availability limits ecosystem productivity, linking the carbon and nitrogen cycles closely together (Gruber and Galloway, 2008). The increasing temperatures due to climatic warming accelerates nitrogen mineralization in soils, leading to increased nitrogen availability and transport of reactive nitrogen from terrestrial to aquatic ecosystems. This perturbed and accelerated nitrogen cycling may lead to large net increases in the carbon sequestration of ecosystems (Magnani et al., 2007). 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). However, the feedback mechanisms from increased perturbations of the nitrogen cycle may change the dynamics of the emissions of other greenhouse gases hence complicating the overall effects. For instance, the stimulated carbon uptake of forests due to increased atmospheric nitrogen deposition, can largely be offset by the simultaneously increased soil N_2O emissions (Zaehle et al., 2011). In the Arctic, the melting permafrost may lead to high emissions of N_2O (Repo et al., 2009; Elberling et al., 2010), which may significantly influence the global N_2O budget.

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).

3.4 Phosphorus cycle

Phosphorus (P) is, together with nitrogen (N), one of the limiting nutrients for terrestrial ecosystem productivity and growth, while 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, the main reservoirs are in continental soils, where phosphorus in mineral form is bound to soil parent material and in ocean sediments (Fig.8).

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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).

Southwestern Siberian soils have lately been reported to contain high concentrations of plant-available phosphorus (Achat et al., 2013), which may enhance the 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.

In soils, phosphorus is found mainly in mineral form and bound to the soil parent material such asapatite 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). Southwestern 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.

3.5 Sulfur cycle

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Sulfur is released naturally through volcanic activity, as well as through weathering of the Earth's crus. 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_2SO4) 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.

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

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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 (Fig. 9). 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.

4. From system understanding to mitigation and adaptation strategies and decision making

Climate change and weather extremes are already affecting the living conditions of Northern Eurasian societies. The vulnerability of the Northern environments and societies, including their adaptive capacity and buffering thresholds, varies greatly depending on their current and future physical environment as well as their demographic structure and economic activities. The PEEX program as a whole is built on four pillars, namely (i) research, (ii) research infrastructure, (iii) impact on society and (iv) knowledge transfer and capacity buiding. The scientific outcome of the first two pillars will be addressing the future state of the physical environment and its interactions and feedbacks with the demographic structure and economic activities in the Arctic boreal system. The periodic PEEX assessments will be delivered for constructing mitigation and adaptation strategies of the

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Northern societies and for use of regional and governmental decision making. The PEEX approach is applicable to China, when taking into account the specific geographical, climatological and social characteristics of that region.

The integrative approach of the PEEX first two pillars provides both analytical and operational answers to our research questions which can be utilized in solving interlinked grand challenges using pillars iii) and iv). These will also contribute to the Earth System sciences (ESS) questions as a whole (see ESS questions: Schellnhuber et al., 2004). The implementation of the PEEX research agenda starts with process studies in the frame of three main topics determined for the land, atmosphere, aquatic and social systems of the Northern Eurasian region. The research approach is designed to answer the analytical questions on the major dynamical patters and feedback loops relevant to Earth system science in the Northern context. The PEEX program has defined altogether 12 large-scale research questions for the 12 main topics in the Northern Eurasian domain (Kulmala et al., 2016). At the same time, PEEX sticks to several operational ESS questions, including "what level of complexity and resolution have to be achieved in Earth System modelling?", "what are the best techniques for analyzing and predicting the irregular events?", "what might be the most effective global strategy for generating, processing and integrating relevant Earth system datasets?", and "what are the most appropriate methodologies for integrating natural science and social science knowledge?" (Schellnhuber et al., 2004).

In terms of the level of complexity and resolution in Earth System modelling, PEEX builds on a multi-scale modelling and observation approach originally introduced by Kulmala et al. (2009). PEEX will construct its own multi-scale modelling platform (Lappalainen et al. 2014). In terms of generating, processing and integrating relevant Earth system datasets, a detailed conceptual design of the PEEX research infrastructure (RI) will include a concept design of coherent in-situ observation network, coordinated use of remote sensing observations and standardized and harmonized data procedures as well as a data system. One of the first tasks of PEEX -RI is to fill in the observational gap in atmospheric in-situ and ground base remote sensing data in the Northern Eurasia, especially in Siberia. This approach is based on the coordination of existing observation activities (Alekseychik et al., 2016), but also making plans for a new infrastructure needed. PEEX-RI development will be largely based on the SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) concept (Kulmala et al. 2016),

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which has been developed by University of Helsinki, Division of Atmospheric Sciences together with Division of Forest Ecology starting from 1995 (Hari and Kulmala, 2005; Hari et al., 2016). The SMEAR-concept provides a state-of-the-art foundation for establishing a PEEX observation system to be integrated into the global GEOSS data system. Furthermore, detailed design of greenhouse gas, aerosol, cloud, trace gas measurements and observation of biological activity 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), GAW (Global Atmospheric Watch), and AnaEE (the experimentation in terrestrial ecosystem research).

PEEX is interested in developing the most appropriate methodologies for integrating natural science and social science knowledge as part of the operational ESS questions indicated by Schellnhuber et al. (2004). The first-priority tasks in this case is to establish an integrated information background, needed also for zoning and urban planning of Arctic and boreal areas (Ribeiro et al., 2009; Hunt and Sanchez-Rodriquez, 2009; Shvidenko et al. 2010; Skryzhevska et al., 2015). An information background would the first step serving the development of a common language of integrated studies. Furthermore, it could provide a platform for compatible definitions and classification schemes. For example, we need spatially and temporally explicit descriptions of terrestrial ecosystems, landscapes, atmosphere and hydrosphere. A common information background would be a unified base for the PEEX modelling platform and for the development of integrated modelling clusters which could combine ecological, economic and social dimensions. It could used as a benchmark for historical assessment of future trajectories of land cover, state and resilience of ecosystems, stability of landscapes, and dynamics of environmental indicators of environment. The already exiting Integrated Land Information System could provide a common basis for combining all historical knowledge about the region and all scientific results obtained by past, current and future studies across the region (e.g. Schepaschenko et al., 2011; Shvidenko and Schepaschenko, 2014).

In addition to data services, PEEX is developing procedures for integrating and linking natural science and social science knowledge and data. As one example, we need to analyze data on emission sources together with population health risk factors, environment pollution, food security, drinking

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water quality, changes in the spreading areas of infectious diseases, and changes in the general epidemiological situation (Bityukova and Kasimov, 2012; Malkhazova et al., 2013). Via novel multidisciplinary data interfaces and data procedures, we are able to connect satellite observations with inverse modeling, provide fast updates to emission inventories, estimate the emission for the climate models, and, in the end, provide climate and air quality scenarios and the storylines of the future development of the arctic-boreal region (Fig. 10).

In terms of strategic questions of the ESS, such as “what is the optimal mix of adaptation and mitigation measures to respond global change?” or “what is the structure of an effective and efficient system of global and development of institutions?”, PEEX is an active player in creating direct contacts with the stakeholders so that its scientific information and services will receive an optimal impact on decision making. Furthermore, the PEEX approach endorses the Earth System Manifesto. (https://www.atm.helsinki.fi/peex/images/manifesti_peex_ru_hub2.pdf) which addresses three strategic tasks: (i) construction of novel observation systems, (ii) finding consensus addressing necessary mitigation and adaptation actions in different parts of the world, and (iii) operational prerequisites for technological development to moderate the global change towards the sustainable Earth System. In this framework, PEEX will work closely with influential organizations, such as the Intergovernmental Panel for Climate Change (IPCC) delivering PEEX assessment of Arctic-boreal region, the Future Earth acting as an Arctic-Boreal Hub, and the Digital Earth via demonstrating novel methods integrating in situ data to satellite observations.

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as such been listed as GEOSS - Gold region project, IGBP-iLEAPS Arctic and boreal regional node, Digital Earth, Arctic Council – SAON Task, one of the main collaborators of the International Eurasian Academy of Sciences (IEAS) and Future Earth Arctic- boreal hub.

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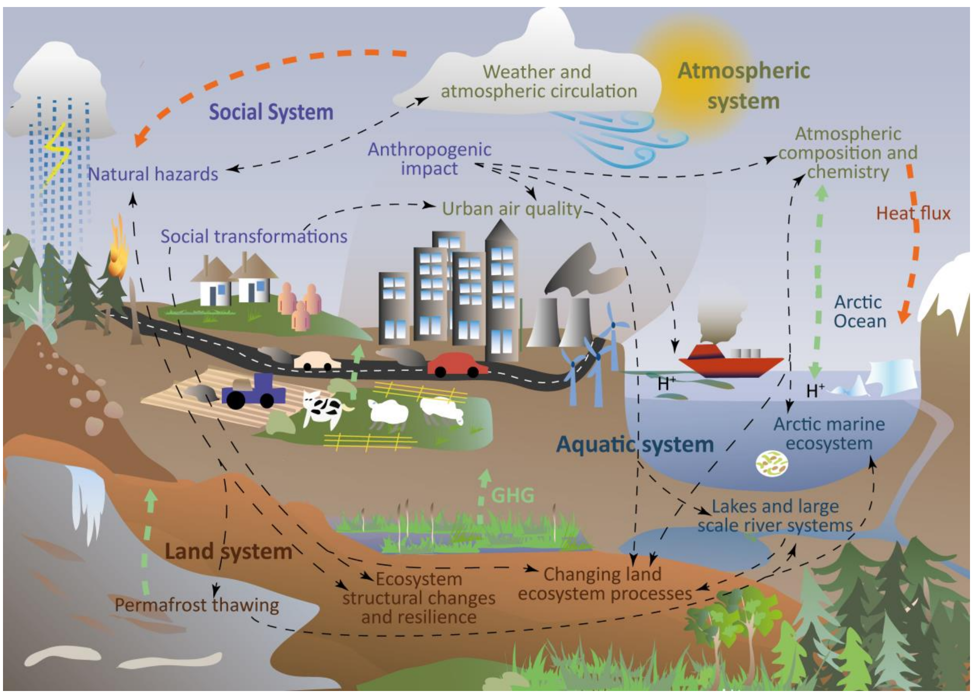

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Figure 1: The thematic research areas relevant to the Northern Eurasian land system include Land-Topic-1 “changing ecosystem processes”, Land-Topic-2 “ecosystem structural changes and resilience” and Land-Topic--3 “risk areas of permafrost thawing”. For the atmospheric system they are Atmosphere-topic-1 “atmospheric composition and chemistry”, Atmosphere-topic -2 “Urban air quality”, are Atmosphere-topic-3, “atmospheric circulation and weather”, for the aquatic system they are Aquatic-Topic-1 “Arctic Ocean in the climate system” , Aquatic-Topic-2 “maritime ecosystems”, Aquatic-Topic-3 “Lakes and large river systems” and for the social system they are Society-Topic-1 “natural resources and anthropogenic activities”, Society-Topic-2 “natural hazards” and Society-Topic-3“social transformations”.

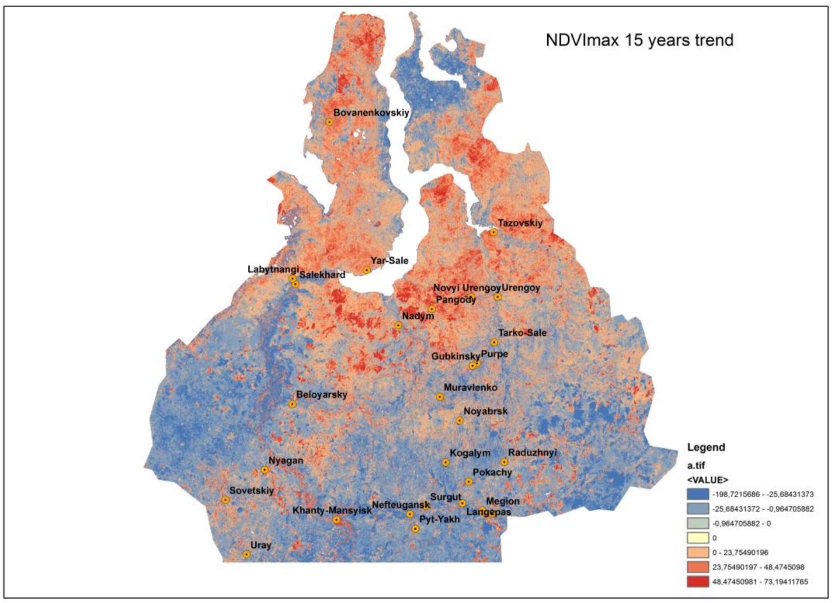

Figure 2: Linear trends in the annual maximum Normalized Difference Vegetation Index (NDVI) obtained from analysis of the MODIS 0.25 km data product for 2000-2014.

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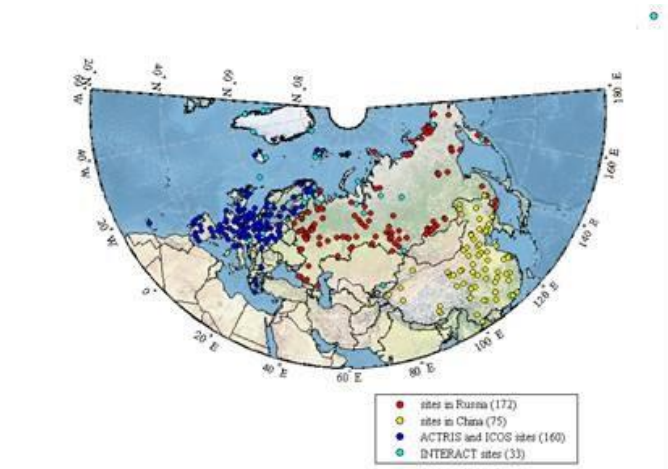

Figure 3: The map demonstrates the existing ACTRIS (Aerosols, clouds and trace gases Research Infrastructure Network) and ICOS (Integrated Carbon Observations System) stations in Europe (blue), stations making atmospheric and/or ecosystem measurements in Russia (red), INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic) stations in Russia (light blue) and China Flux stations in China (yellow). However, all of these stations need certain upgrade.

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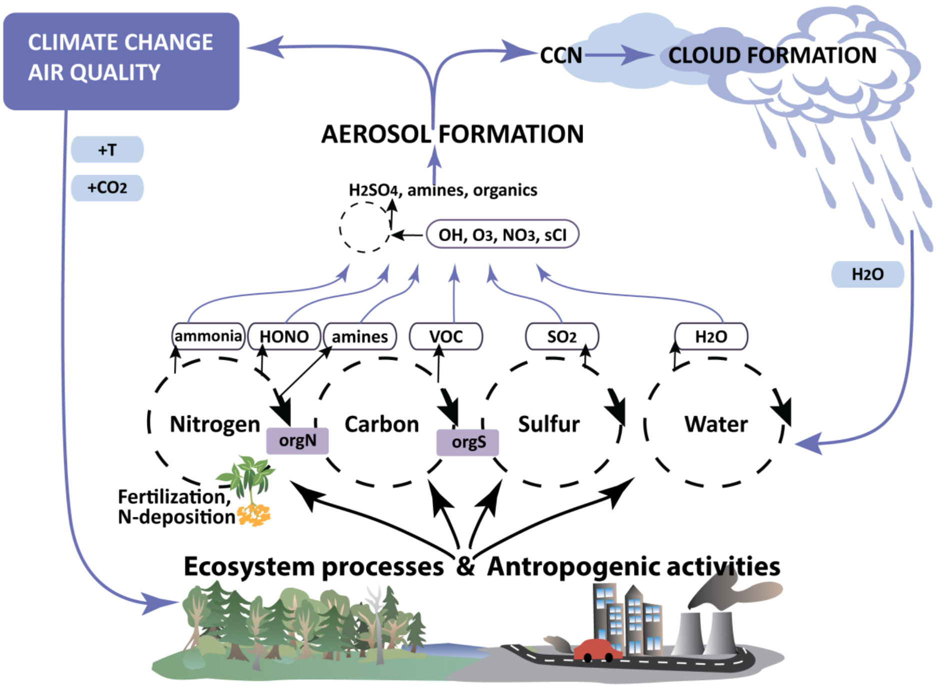

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2645 Figure 4: In urban and industrialized regions, the process understanding of biogeochemical cycles
2646 includes anthropogenic sources, such as industry and fertilizers, as essential parts of the
2647 biogeochemical cycles.

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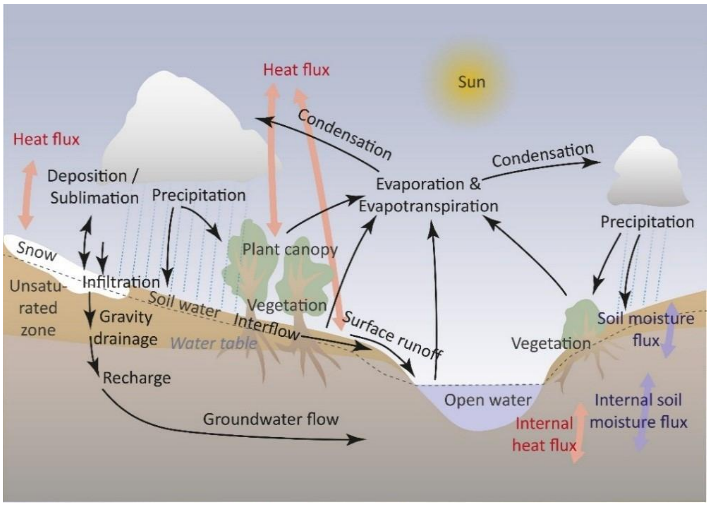

Figure 5: Hydrological cycle schematics.

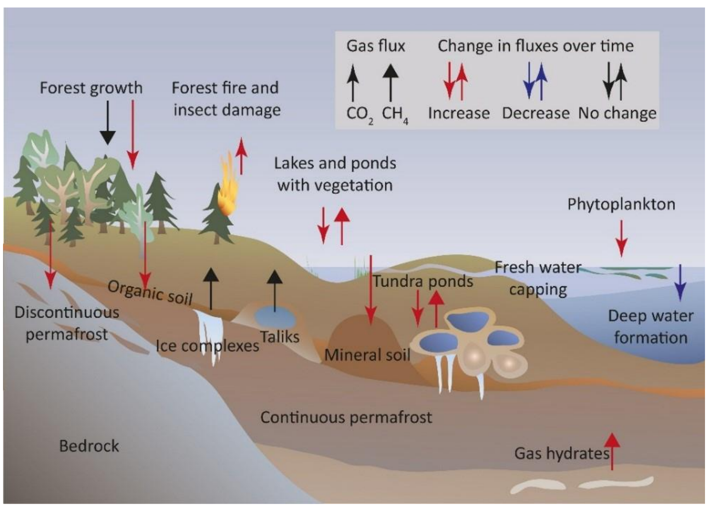

Figure 6: Carbon cycling in the Arctic will change as the climate warms. Figure after ACIA, 2004. (Impacts of a Warming Arctic: Arctic Climate Impact Assessment (ACIA) Overview Report).

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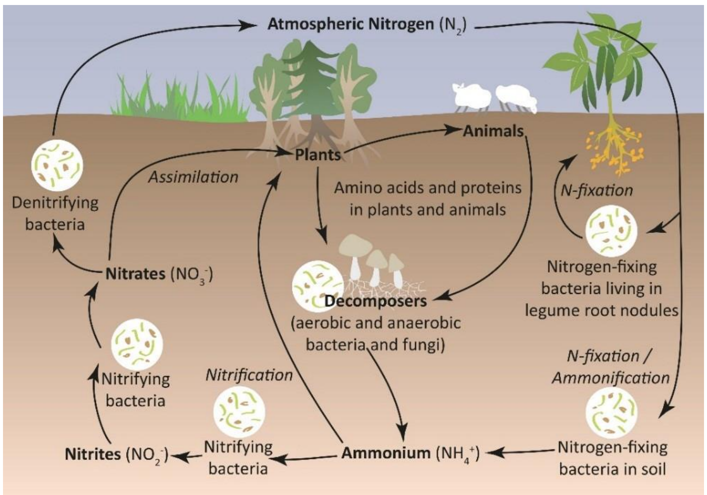

Figure 7: Schematic figure for terrestrial nitrogen cycle.

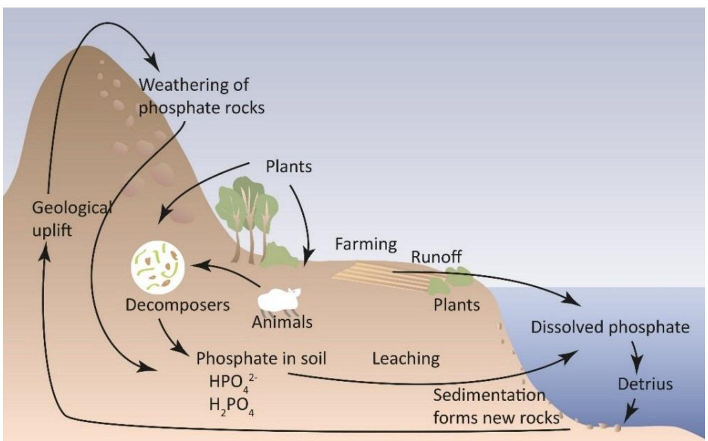

Figure 8: Schematic figure of the phosphorus cycle.

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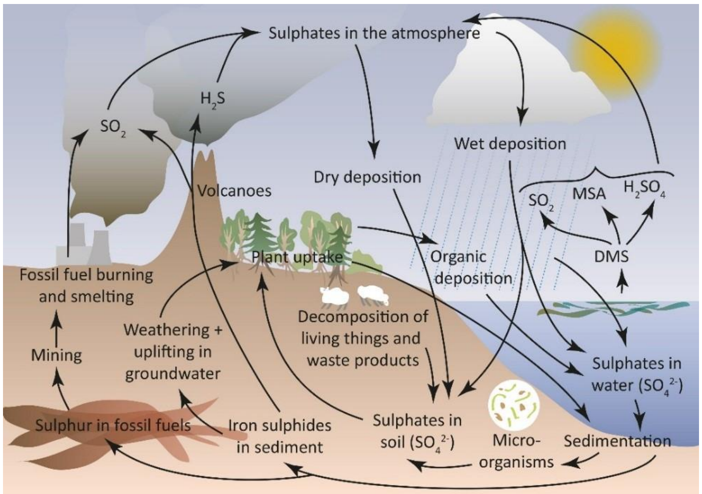

Figure 9: Schematic figure of the sulfur cycle.

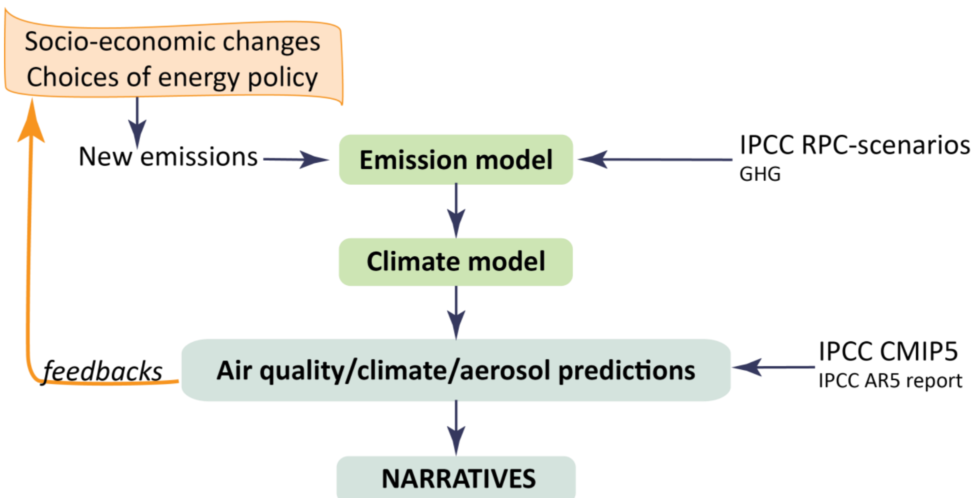

Figure 10. An example of the study approach to be implemented by PEEX for integrating natural science and social science knowledge and generating climate predictions and narratives of the Northern regions.