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Pavel Alekseychik^{*1}, Hanna K. Lappalainen¹, Tuukka Petäjä¹, Nina Zaitseva², Martin Heimann^{3,1}, Tuomas Laurila⁴, Heikki Lihavainen⁴, Eija Asmi⁴, Mikhail Arshinov⁵, Vladimir Shevchenko⁶, Alexander Makshtas⁷, Sergey Dubtsov⁸, Evgeny Mikhailov^{9,10}, Elena Lapshina¹¹, Sergey Kirpotin¹², Yulia Kurbatova¹³, Aijun Ding¹⁴, Huadong Guo¹⁵, Sungbin Park³, Joost V. Lavric³, Friedemann Reum³, Alexey Panov¹⁶, Anatoly Prokushkin¹⁶, Markku Kulmala¹

¹Department of Physics, University of Helsinki, PO Box 48, FI-00014 Helsinki, Finland

*** Corresponding author;** e-mail: pavel.alekseychik@helsinki.fi

² Department of Earth Sciences, Russian Academy of Sciences, Russia

³ Max Planck Institute for Biogeochemistry, Hans-Knöll-Straße 10, 07745 Jena, Germany

⁴ Finnish Meteorological Institute, Atmospheric Composition Research, PO Box 503, 00101 Helsinki, Finland

⁵ V.E. Zuev Institute of Atmospheric Optics SB RAS 1, Academician Zuev square, 634055 Tomsk, Russia

⁶ P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovskiy prospect, 117997 Moscow, Russia

⁷ Arctic and Antarctic Research Institute

⁸ V.V.Voevodsky Institute of Chemical Kinetics and Combustion, SB RAS, Institutskaya str., 3, Novosibirsk, Russia

⁹ Atmospheric Physics Department, St. Petersburg State University, St. Petersburg, Russia

¹⁰ Biogeochemistry and Multiphase Chemistry Departments, Max Planck Institute for Chemistry, Mainz, Germany

¹¹ Yugra State University, 16 Chekhova str., 628012 Khanty-Mansiysk, Russia

¹² Bio-Clim-Land Center of Excellence, Tomsk State University, Tomsk, Russia

¹³ A.N. Severtsov institute of ecology and evolution RAS, 33 Leninskyprospect, 119071 Moscow, Russia

¹⁴ Institute for Climate and Global Change Research & School of Atmospheric Sciences, Nanjing University, 210023 Nanjing, China

¹⁵ Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, 100094, China

¹⁶ I.V. Sukachev Institute of Forest, SB RAS, Krasnoyarsk, Russia

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

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

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

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

INTRODUCTION

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

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

The most important task of PEEX Research Infrastructure is to initiate motion towards high level Pan-Eurasian Observation Networks, which is based on a hierarchical SMEAR-type (Station for Measuring Ecosystem-Atmosphere Relations) integrated land-atmosphere observation system. As the

first step, maximal utilization of the existing ground infrastructure is planned. This measure will be superseded by upgrading the currently functioning sites or building new sites where necessary.

The potential PEEX ground-based research infrastructure is centered around the Flagship stations (supersites), supported by flux/advanced and standard stations [Hari et al. 2015, Kulmala et al. 2015]. The structure of the potential Flagship stations echoes that of the supersite SMEAR-II in Hyytiälä, Southern Finland, which is equipped for research into a broad spectrum of atmospheric physics, biogeochemistry and geophysics topics. Designed to address more specific and local processes, the Standard and Flux stations are supposed to provide a higher-definition view of the processes in different climates, biomes and vegetation communities. At least one Flagship station per each representative ecosystem or every 1000–2500 km should be founded in order to ensure sufficient coverage [Hari et al. 2015, Kulmala et al. 2015]. Worldwide, an optimal ground observation network would consist of about 20 supersites, 500 flux stations and 10000 standard stations [Hari et al. 2015], of which a large fraction would be situated within the PEEX domain, due to its great extent. However, in spite of the apparent scale of the problem, no attempt to summarize the existing ground-based observational site network for the PEEX region and identify the potential gaps has been attempted to date.

This study employs the ground-based observational infrastructure inventory conducted by the University of Helsinki together with the institutes of the Russian Academy of Sciences and Moscow State University. First, an overview of the existing facilities within Russia is presented, taking

into account their geographical distribution, representation of ecosystems and climates. Then, the needs of development in the ground-based observational site network are discussed. Station infrastructure in China is discussed shortly as well.

MATERIALS AND METHODS

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

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

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

Table 1. Land observation station metadata collected for the project

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

For the climate analysis, the Köppen-Geiger classification scheme was employed. The Köppen-Geiger approach classifies the climates according to the seasonality

and mean levels of precipitation and air temperature [Peel et al. 2007]. A raster Köppen-Geiger climate map by NASA Earth Data was used (http://webmap.ornl.gov/ogcdown/wcsdown.jsp?dg_id=10012_1).

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

RESULTS AND DISCUSSION

Geographical distribution of the stations

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

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

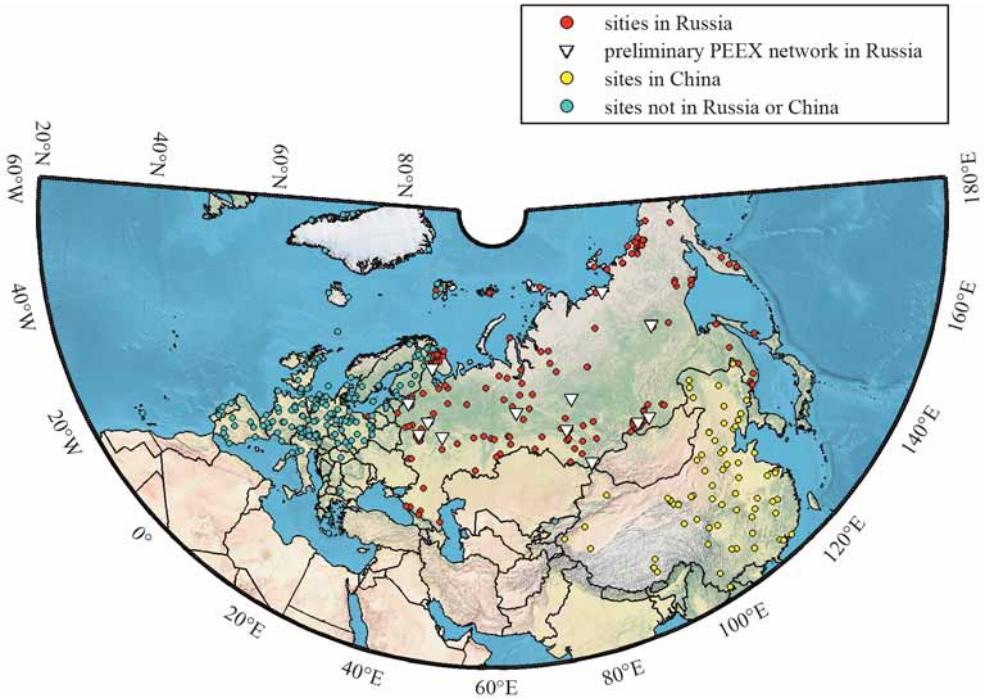


Fig.1. Locations of permanent ground-based observation stations in the PEEX domain on a satellite-derived land cover map [Lappalainen et al. 2016, manuscript in preparation].

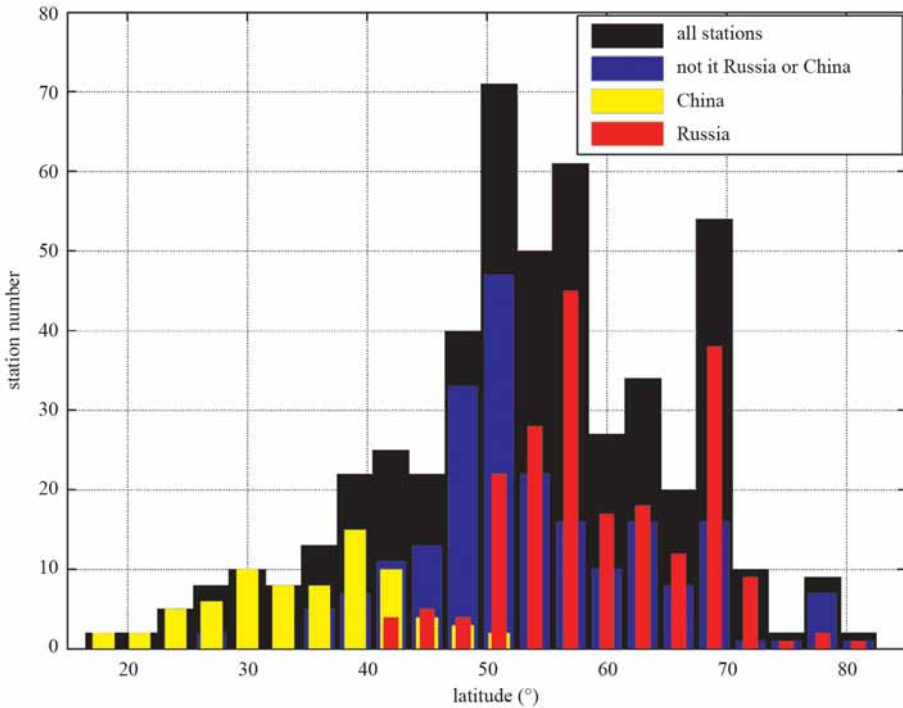


Fig.2. Latitudinal distribution of the stations.

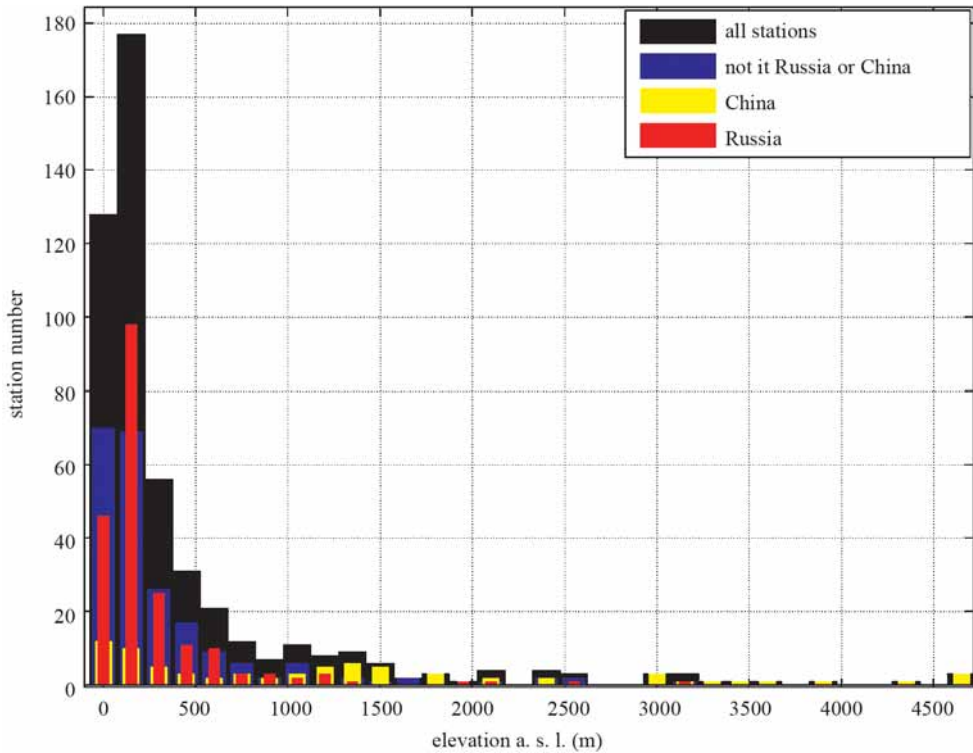


Fig.3. Altitudinal distribution of the stations.

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

WMO-GAW, eddy-covariance and aerosol measurement sites

PEEX aims to promote the use of state-of-the-art measurement techniques for aerosol and flux measurements. Aerosol measurement tools falling into this category include e.g. differential mobility particle sizers (DMPS), whereas the relevant flux measurement technique is eddy-covariance (EC). The sites in Russia equipped with aerosol or EC instrumentation are shown in Fig. 4. The emerging spatial distribution of the sites,

while covering the main geographical units of Russia, still leaves extensive areas empty. The existing EC flux and aerosol measurements are concentrated in the Western part of European Russia, around the populated areas of West and central Siberia, around the Baikal Lake and along the Arctic Ocean coast. Some areas, including the North-East of European Russia, Urals, great parts of Siberia and the Russian Far East are not covered by measurements at all. A number of stations contribute to the Global Atmospheric Watch network (WMO-GAW), providing data on precipitation chemical composition, total ozone and greenhouse gas concentrations from different parts of Russia.

Recent developments in the ground-based measurement station network

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

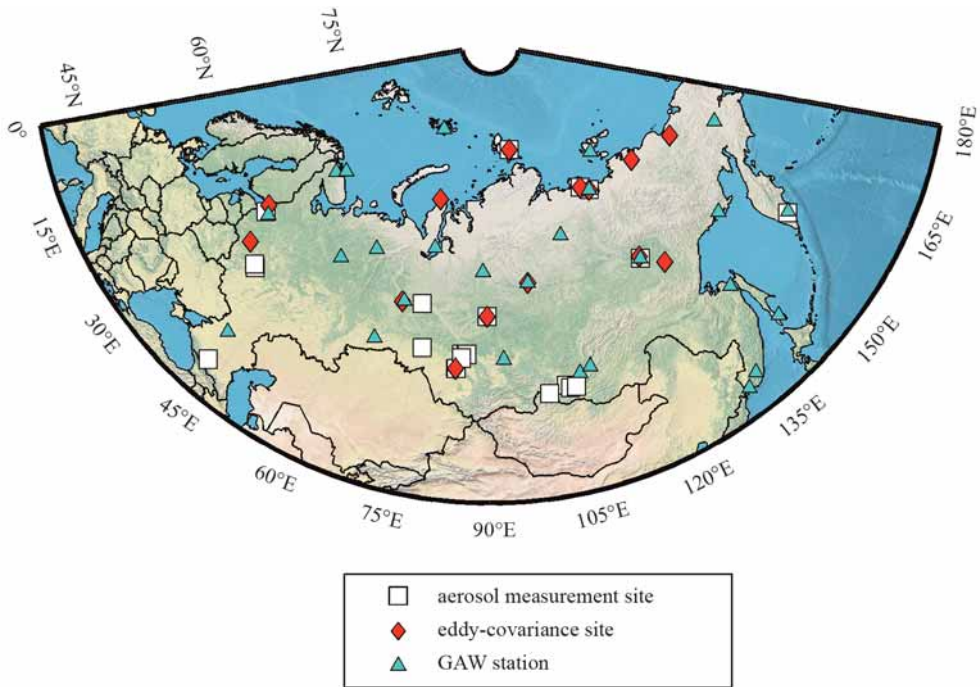
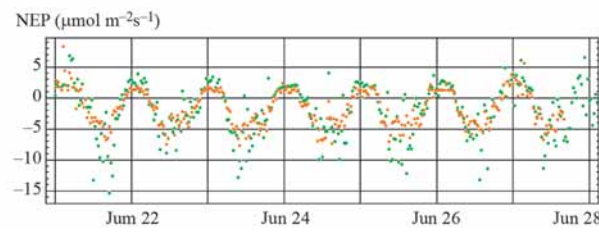
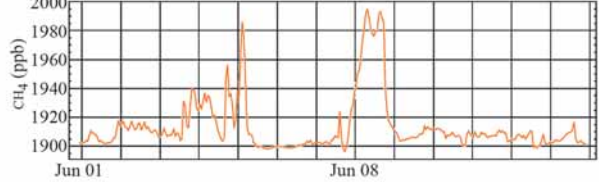
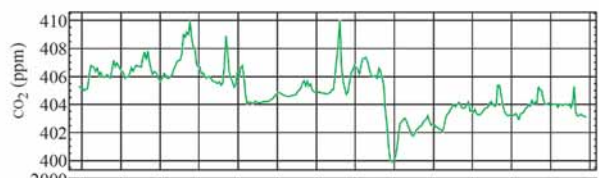
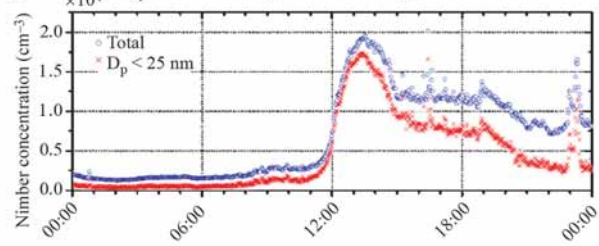
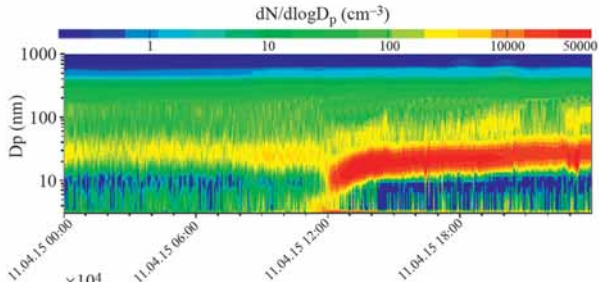
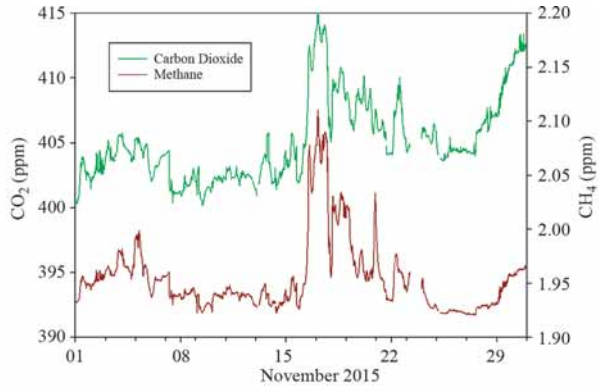


Fig.4. Eddy-covariance, aerosol measurement sites and GAW stations in Russia. A satellite-derived land-cover raster image is shown on the background.

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

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

Fig.5. (next page) a–b) A photo and a graph showing several days of the CO_2 and CH_4 concentration data from the newly established Cape Baranova station, Bolshevik island (Finnish Meteorological Institute/ Arctic and Antarctic Research Institute, Russia); c–d) a photo and an aerosol formation event registered on 11 April 2015 at the Fonovaya station, Tomsk (Institute of Atmospheric Optics SB RAS); e–f) a photo and CH_4 concentration time series from the new greenhouse gas monitoring station at Ambarchik (Max Planck Institute for Biogeochemistry); g–h) a photo and eddy-covariance net ecosystem productivity time series from ZOTTO station (Max Planck Institute for Biogeochemistry / I. V. Sukachev Institute of Forest, SB RAS). The green data points in (h) correspond to the Scots Pine forest measurements and the orange dots to the ombrotrophic bog measurements.



Representation of climates by the measurement network

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

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

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

of the boreal types *Dfd* are also represented by a disproportionately small number of stations.

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

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

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

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

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

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

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

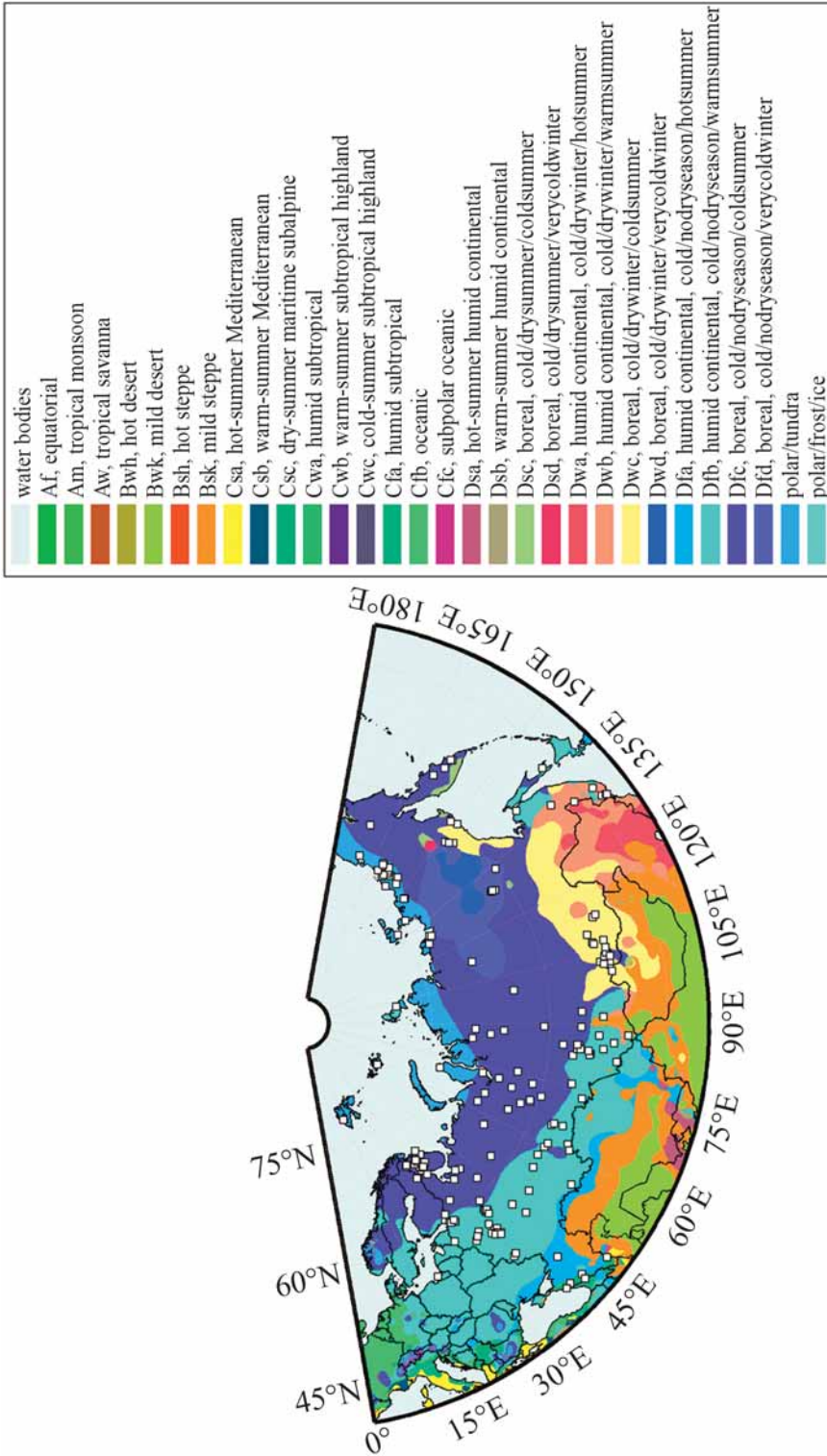


Fig. 6. Measurement sites in Russia shown against the Köppen-Geiger climate map. The measurement station locations are marked with white squares.

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

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

The nucleus of the future comprehensive infrastructure, the PEEEX Preliminary Station Network, unifies a number of stations representing many parts of Russia. The participating Russian stations currently include: Yakutsk, Nizhni Novgorod/Moscow/Borok cluster, Petergof, Fonovaya station (Tomsk), White Sea Biological Station, Tiksi, Novosibirsk, ZOTTO (Krasnoyarsk Krai), Tyumen, Baikal/Irkutsk/Ulan Ude cluster, Mukhrino Field Station (Khanty-Mansijsk Autonomous Region), Aktru station (Altai Republic), Central Forest Nature Reserve (Tver region). WMO-GAW stations are

potential members of the PEEEX network as well. These stations will form the core of the future PEEEX station network. Outside Russia, the PEEEX Preliminary Phase Observational network includes the SMEAR-type stations in Finland (SMEAR-I-II-II-IV), Estonia (SMEAR-Järviselja) and China (SMEAR-Nanjing), and the ecosystem station network in China.

CONCLUSIONS

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

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

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

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

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

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

