Overview: Recent advances on the understanding of the Northern Eurasian environments and of the urban air quality in China - Pan Eurasian Experiment (PEEX) program perspective

Hanna K. Lappalainen[1,2], Tuukka Petäjä[1,2], Timo Vihma[3], Jouni Räisänen[1], Alexander Baklanov[4], Sergey Chalov[5], Igor Esau[6], Ekaterina Ezhova[1], Matti Leppäranta[1], Dmitry Pozdnyakov[7], Jukka Pumpanen [8], Meinrat O. Andreae[9,42,43], Mikhail Arshinov[10], Eija Asmi[3], Jianhui Bai[11], Igor Bashmachnikov[7], Boris Belan[10], Federico Bianchi[1], Boris Biskaborn[12], Michael Boy[1], Jaana Bäck[13], Bin Cheng[3], Natalia Ye Chubarova[5], Jonathan Duplissy[1], Egor Dyukarev[14], Konstantinos Eleftheriadis[15], Martin Forsius[16], Martin Heimann[17], Sirkku Juhola[20], Vladimir Konovalov[18], Igor Konovalov[19], Pavel Konstantinov[5,33], Kajar Koster[13], Elena Lapsina [21], Anna Lintunen[1,13], Alexander Mahura[1], Risto Makkonen[3], Svetlana Malkhazova[5], Ivan Mammarella[1], Stefano Mammola[22,23], Stephany Mazon[1], Outi Meinander[3], Eugene Mikhailov[24, 25], Victoria Miles[6], Stanislav Myslenko[5], Dmitry Orlov[5], Jean-Daniel Paris[26], Roberta Pirazzini[3], Olga Popovicheva[27], Jouni Pulliainen[3], Kimmo Rautiainen[3], Torsten Sachs[28], Vladimir Shevchenko[29], Andrey Skorokhod[30], Andreas Stohl[31], Elli Suhonen[1], Erik S. Thomson [32], Marina Tsidilina[39], Veli-Pekka Tynkkynen [34], Petteri Uotila[1], Aki Virkkula[3], Nadezhda Voropay[35], Tobias Wolf[6], Sayaka Yasunaka [36], Jiahua Zhang[37], Yubao Qiu[37], Aijun Ding[38], Huadong Guo [37], Valery Bondur[39], Nikolay Kasimov[5], Sergej Zilitinkevich (‡)[1,2,3], Veli-Matti Kerminen[1] and Markku Kulmala[1,2,39,40,41]

[1]   Institute for Atmospheric and Earth System Research / Physics, Faculty of Science, University of Helsinki, Finland

[2]   Tyumen State University, Department of Cryosphere, 625003 Tyumen, Russia

[3]   Finnish Meteorological Institute, 00101 Helsinki, Finland

[4]   World Meteorological Organization, WMO, Geneva, Switzerland

[5]   Faculty of Geography, Lomonosov Moscow State University, Lenin Hills, 119991, Moscow, Russia

[6]   Nansen Environmental and Remote Sensing Center/Bjerknes Centre for Climate Research, Bergen, Norway

[7]   Nansen International Environmental and Remote Sensing Centre", Nansen Centre, NIERSC, St. Petersburg, Russia

[8]   Department of Environmental and Biological Sciences, PO Box 1627 (Address: Yliopistonranta 1 E), FI-70211 Kuopio, Finland

[9]   Max Planck Institute for Chemistry, Mainz, Germany

[10]   V.E. Zuev Institute of Atmospheric Optics (IAO) SB RAS, Tomsk, 634055, Russia

[11]   LAGEO, Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP-CAS), Beijing, 100029, PR, China

[12]   Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany

[13]   Institute for Atmospheric and Earth System Research /Forest Sciences, University of Helsinki, Helsinki, Finland

38 [14] Institute of Monitoring of Climatic and Ecological Systems SB RAS, Tomsk, 634055, Russia; Yugra State
39 University, Khanty-Mansiysk, 628012, Russia
40 [15] ERL, Institute of Nuclear and Radiological Science & Technology, Energy & Safety, NCSR Demokritos,
41 Attiki, Greece
42 [16] Finnish Environment Institute SYKE, Latokartanonkaari 11, 00790 Helsinki, Finland
43 [17] Max-Planck-Institute for Biogeochemistry, Jena, Germany
44 [18] Institute of Geography RAS, Moscow, Russia
45 [19] Institute of Applied Physics, Nizhny Novgorod, Russia
46 [20] Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland
47 [21] Yugra State University, Khanty-Mansiysk, 634012, Russia
48 [22] Finnish Museum of Natural History (LUOMUS), University of Helsinki, Helsinki, 00100, Finland
49 [23] Molecular Ecology Group (MEG), Water Research Institute (IRSA), National Research Council of Italy
50 (CNR), Verbania Pallanza, 28922, Italy
51 [24] St. Petersburg State University, 7/9 Universitetskaya nab, St. Petersburg, 199034, Russia
52 [25] Multiphase Chemistry and Biogeochemistry Departments, Max Planck Institute for Chemistry, 55020
53 Mainz, Germany
54 [26] Laboratoire des Sciences du Climat et de l'Environnement, IPSL CEA-CNRS-UVSQ, 91190 Gif-sur-
55 Yvette, France
56 [27] Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
57 [28] GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam, Germany
58 [29] P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russia
59 [30] A.M. Obukhov Institute of Atmospheric Physics, Moscow, Russia
60 [31] Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria
61 [32] Department of Chemistry & Molecular Biology, University of Gothenburg, Göteborg, 41296, Sweden
62 [33] Peoples' Friendship University of Russia (RUDN), Laboratory of sSart technologies for sustainable
63 development of urban environment under global changes, Moscow, Russian Federation
64 [34] Aleksanteri Institute, University of Helsinki, Helsinki, Finland
65 [35] V B Sochava Institute of Geography SB RAS, Irkutsk, 664033, Russia; Institute of Monitoring of Climatic
66 and Ecological Systems SB RAS, Tomsk, 634055, Russia
67 [36] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan
68 [37] Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, 100094, China
69 [38] Joint International Laboratory of Atmospheric and Earth System sciences (JirLATEST), Nanjing
70 University, Nanjing, China
71 [39] Institute for Scientific Research of Aerospace Monitoring "AEROCOSMOS", Moscow, 105064, Russia
72 [40] Aerosol and Haze Laboratory, Beijing Advanced Innovation Center for Soft Matter Sciences and
73 Engineering, Beijing University of Chemical Technology (BUCT), Beijing, China
74 [41] Guangzhou Institute of Geography, Guangzhou Academy of Sciences, Guangzhou, China
75 [42] Department of Geology and Geophysics, King Saud University, Riyadh, Saudi Arabia

76   43   Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA

78   **Corresponding author(s):** Hanna Lappalainen, hanna.k.lappalainen@helsinki.fi, Veli-Matti Kerminen, veli-

79   matti.kerminen@helsinki.fi

81   **Keywords**

82   Grand Challenges, climate change, land-atmosphere interactions and feedbacks, biogeochemical cycles, Arctic

83   Ocean, Northern Eurasia, China, Arctic marine ecosystem, atmospheric composition, air quality, Arctic

84   greening, land use change, permafrost, Pan-Eurasian Experiment (PEEX), Global Earth Observatory, Digital

85   Earth, Silk Road Economic Belt, Arctic societies, energy policy, boreal region, science diplomacy

87   **Abstract**

88   The Pan-Eurasian Experiment (PEEX) Science Plan, released in 2015, addressed a need for a holistic system

89   understanding and outlined the most urgent research needs for sustainable development in the Artic-boreal

90   region. Air quality in China and long-range transport of the atmospheric pollutants was also indicated as one

91   of the most crucial topics of the research agenda. This paper summarizes results obtained during the last five

92   years in the Northern Eurasian region. It also introduces recent observations on the air quality in the urban

93   environments in China. The main regions of interest are the Russian Arctic, Northern Eurasian boreal forests

94   (Siberia) and peatlands and on the mega cities in China. We frame our analysis against research themes

95   introduced in 2015. We summarize recent progress in the understanding of the land – atmosphere – ocean

96   systems feedbacks. Although the scientific knowledge in these regions has increased, there are still gaps in our

97   understanding of large-scale climate-Earth surface interactions and feedbacks. This arises from limitations in

98   research infrastructures and integrative data analyses, hindering a comprehensive system analysis. The fast-

99   changing environment and ecosystem changes driven by climate change, socio-economic activities like the

100   China Silk Road Initiative, and the global trends like urbanization further complicate such analyses. We

101   recognize new topics with an increasing importance in the near future, such as enhancing biological

102   sequestration capacity of greenhouse gases into forests and soils to mitigate the climate change and the socio-

103   economic development to tackle air quality issues.

106   1. INTRODUCTION

107   Earth system is facing major challenges, including climate change, biodiversity loss, ocean acidification,

108   epidemics and energy demand on a global scale (Ripple et al., 2017). These "Grand Challenges" are highly

109   connected and interlinked. This creates a need for an approach for a multidisciplinary scientific program, which

110   could deliver science based message to fast-tracked policy making (Kulmala et al., 2015). The recent estimates

111   based   on   the   observed   atmospheric   concentrations   of CO_2

112   (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) and business-as-usual scenario show that

113   humankind should find solutions to answer the Grand Challenges. Deep understanding on the feedbacks and

114   interactions between the land – atmosphere – ocean domains and accounting for social aspects in the regions

115   of substantial changes are needed for effective technical solutions, mitigation and adaption policy actions. The

116   northern regions (> 45°N), together with the arctic coastal zone and Siberian region in Russia, are among the

117   most critical areas for the global climate (Smith 2011; Kulmala et al., 2015; Kasimov et al., 2015).

118

119   The idea of the Pan-Eurasian Experiment (PEEX) (www.atm.helsinki.fi/peex), originated from a group of

120   Finnish and Russian scientists and research organizations in 2012, is a bottom-up research and capacity

121   building program concentrating on the sustainable development of the Arctic - boreal regions of the Northern

122   Eurasia under changing climate and socio-economic megatrends (Kulmala et al., 2015, Lappalainen et al.,

123   2016). The program was laid on four interconnected parts, namely research agenda, research infrastructures,

124   capacity building and societal impacts (Lappalainen et al., 2014; Kulmala et al., 2016a, Lappalainen et al.,

125   2017, Kulmala 2018). In addition to a strong involvement of the Russian partners, in 2013 the PEEX China

126   collaboration was established. China has a strong economic interest on the Arctic regions (Tillman et al. 2018).

127   Furthermore, China is already facing extensive environmental and air pollution challenges and has a major

128   interest to find technical solutions for environmental monitoring of the Silk Road Economic Belt Program

129   (SREB) (Kulmala 2018, Lappalainen et al., 2018). In Russia the program is an umbrella for several bilateral

130   scientific projects and activities (e.g. Chalov et al., 2015, 2018; Esau et al., 2016; Alekseychik et al., 2017;

131   Bobylev et al., 2018; Malkhazova et al., 2018; Kukkonen et al., 2020; Ezhova et al., 2018b; Ziltinkevich et

132   al., 2019; Petäjä et al., 2020 submitted; ; Bondur et al 2019 a,b,c,d,e,f; Yuanhuizi He et al, 2020), while in

133   China the primary focus is on the development of atmospheric in-situ stations and advanced air quality

134   monitoring in megacity environments (e.g. Ding et al., 2016 b; Yao et al., 2018; Ying et al., 2020; Wang et al.,

135   2020). Furthermore, PEEX is closely collaborating with the Digital Belt and Road (DBAR) Program

136   coordinated by the Institute for Digital Earth and Remote Sensing (RADI). PEEX collaboration with DBAR

137   is driven by a need for a novel in situ station network and ground based data as a complementary information

138   for the remote sensing in the Silk Road economic region. Long-term development on a "Station Measuring

139   the Earth Surface and Atmosphere Relations" (SMEAR) concept could provide baselines for this (Hari et al.

140   2016; Kulmala 2015, Kulmala 2018; Lappalainen et al., 2018).

141

142   The PEEX program is motivated by the need for obtaining scientific information that combines research in the

143   Arctic and boreal environments, and for understanding large-scale feedbacks and interactions operating in

144   land-atmosphere-ocean systems (Kulmala et al., 2004; Kulmala et al., 2016a; Vihma et al., 2019) and large-

145   scale weather impacts related to the Arctic amplification (e.g. Coumou et al., 2014; Vihma et al., 2020). One

146   of the scientific backbones of PEEX is the previously coordinated research frameworks and their synthesis.

147   For example, the latest comprehensive overview on the interactions between the atmosphere, cryosphere and

148   ecosystems at northern high latitudes was performed by the Nordic Center of Excellence in "Cryosphere-

149   atmosphere interactions in a changing Arctic climate", CRAICC) community (Boy et al., 2019). The PEEX

150   program can upscale the CRAICC results into a wider geographical context.

151

152   Climate change, as a main driver for environmental changes in the Northern Eurasian Arctic-boreal region and

153   China, sets environmental boundaries for the future socio-economic activities of these regions in general. The

154   harsh climate of this region puts a pressure on the ecosystems and living conditions of the local people (e.g.

155   IPCC, 2019). PEEX introduced fifteen large-scale research questions, which would also help us to fill the key

156   gaps in our holistic understanding of land-atmosphere interactions and their connections to societies living in

157   the northern Eurasian region (Kulmala et al., 2015; Lappalainen et al., 2018). This approach also sets the

158   framework of the current paper. Here we introduce the recent research progress in the large-scale scientific

159   themes relevant to the PEEX region.

160

161   Here we introduce the scientific results from PEEX scientific output, review the main results from PEEX

162   scientific papers and present an analysis of the key gaps in the current scientific understanding. We use the

163   PEEX research agenda structure (Kulmala et al. 2016, Lappalainen et al. 2018) as a reference and mirror new

164   a rising themes and results against this plan. The results are first discussed with a holistic approach and then

165   we categorize the advances through a set of identified feedbacks and interactions within the Arctic boreal

166   environment. We follow up with a discussion on the need for a future research infrastructure to be able to

167   provide relevant data and underline the future socio-economics development of the region setting the

168   boundaries for proposed new science-based concepts and technical solutions.

169   **2. RESULTS**

170   In the PEEX Science Plan we indicated four main thematic research domains: the land system, the atmospheric

171   system, the water system and the society with 15 thematic research areas and related large-scale research

172   questions (Q) presented in Table 1 (Lappalainen et al., 2015). This is the framework we re-visited and utilized

173   in the synthesis of new results of the PEEX community brought together in this paper. Furthermore, we

174   synthetized the results and discuss their contribution to the large - scale feedbacks and interactions in the Arctic

175   context in the sections below.

176

177   2.1. LAND ECOSYSTEMS

178

179   2.1.1 Changing land ecosystem processes (Q1)

180

181   *High-latitude photosynthetic productivity*

182

183   High-latitude terrestrial ecosystems are crucial to the global climate system and its regulation by vegetation.

184   These ecosystems are typically temperature limited, and thus also considered especially sensitive to climate

185   warming. Better understanding of interannual and seasonal dynamics and resilience of the photosynthetic

186   activity of forest vegetation as a whole is needed for the quantification of GPP and analyzing the carbon balance

187   of boreal forest. The carbon sink and source dynamics of the boreal forests have been intensively studied

188   during the last five years at Stations Measuring Atmosphere Ecosystem Relations (SMEAR) II station in

189   Finland (Hari & Kulmala 2005, Hari et al. 2009). Recent results show that the Norway spruce and Scots pine

190   ecosystems are rather resilient to a short-term weather variability (Matkala et al., 2020). Overall, the analyses

191   by Kulmala et al. (2019) and Matkala et al. (2020) on subarctic Scots pine and Norway spruce stands at the

192   northern timberline in Finland serve as examples of the canopy scale dynamics, showing that these ecosystems

193   are generally weak carbon sinks but have a clear annual variation. Kulmala et al. (2019) observed that there is

194   a difference between tree canopy photosynthesis compared to forest floor photosynthesis which starts to

195   increase after the snowmelt. Thus the models for photosynthesis should also address the snow cover period in

196   order to better capture the seasonal dynamics of photosynthesis of the Northern forests says Kulmala et al.

197   (2019).

198

199   The abundance of tree species, stand biomass, increasing tree growth and coverage of broadleaf species may

200   also affect biogenic volatile organic compound (BVOC) emissions from the forest floor and impact the total

201   BVOC emissions from northern soils. At least the stand type has been shown to affect BVOCs fluxes from the

202   forest floor in a hemi boreal - boreal region (Mäki et al., 2019). As a whole, BVOCs emitted by boreal

203   evergreen trees are connected to the photosynthetic activity with a strong seasonality and have a crucial role

204   to atmospheric aerosol formation processes over the boreal forest zone. BVOC emissions have low rates

205   during photosynthetically inactive winter and increasing rates towards summer (Aalto et al., 2015). High

206   emission peaks caused by enhanced monoterpene synthesis were found in spring periods simultaneously with

207   the photosynthetic spring recovery (Aalto et al., 2015). This suggests that monoterpene emissions may have a

208   protective functional role for the foliage during the spring recovery state, and that these emission peaks may

209   contribute to atmospheric chemistry in the boreal forest in springtime. Vanhatalo et al. (2018) studied the

210   interplay between needle monoterpene synthase activities, its endogenous storage pools and needle emissions

211   in two consecutive years at a boreal forest in Finland. They found no direct correlation between monoterpene

212   emissions and enzyme activity or the storage pool size. Monoterpene synthase activity of needles was different

213   depending on seasonality and needle ontogenesis. However, the pool of stored monoterpenes did not change

214   with the needle age (Vanhatalo et al., 2018). Also, clear annual patterns of primary biological aerosol particles

215   have been measured from a boreal forest, with late spring and autumn being seasons of dominant occurrence.

216 Increased levels of free amino acids and bacteria were observed during the pollen season in the SMEAR II
217 station in Finland, whereas the highest levels for fungi were observed in autumn (Helin et al., 2017).

218

219 Extensive measurements of Scots pine photosynthesis and modelling resulted in optimized predictions of the
220 daily behavior and annual patterns of photosynthesis in a subarctic forest (Hari et al., 2017). The study
221 connected theoretically the fundamental concepts affecting photosynthesis with the main environmental
222 drivers (air temperature and light), and the theory gained strong support through empirical testing.
223 Understanding stomatal regulation is fundamental in predicting the impact of changing environmental
224 conditions on photosynthetic productivity. Lintunen et al. (2020) showed that canopy conductance and soil-
225 to-leaf hydraulic conductance are strongly coupled, and that soil temperature and soil water content influences
226 canopy conductance through changes in belowground hydraulic conductance. In particular, the finding that
227 soil temperature strongly influenced belowground hydraulic conductance in mature, boreal trees may help to
228 better understand tree behavior and photosynthetic productivity in cold environments. Plant photosynthetic
229 rate is concurrently limited by stomatal and non-stomatal limitations, and recent modelling (Hölttä et al., 2017)
230 and empirical (Salmon et al., 2020) studies suggest that stomatal and non-stomatal controls are coordinated to
231 maximize leaf photosynthesis, i.e. non-stomatal limitations to photosynthesis increase with decreasing leaf
232 water potential and/or increasing leaf sugar concentration. This new approach allows to include the effect of
233 non-stomatal limitations in models of tree gas-exchange (Fig. 1).

234

235 Due to climate warming, it seems that trees in high-latitudes have been progressively decreasing their regional
236 growth coherence in the last decades (Shestakova et al., 2019). Shestakova et al. (2019) showed results that
237 unequivocally link a substantial decrease in temporal coherence of forest productivity in boreal ecosystems to
238 less temperature-limited growth that is concurrent with regional warming trends. This emerging pattern points,
239 for example, to an increasing dependence of the carbon balance on local drivers and the role of forests as
240 carbon sinks in the northern Ural region.

241

242 Vegetation gross primary production (GPP) is the largest CO_2 flux of the carbon cycle in terrestrial ecosystems
243 and impacts all of the carbon cycle variables (Beer et al., 2010). Ecosystem models usually overestimate GPP
244 under drought and during spring, late fall and winter (Ma et al., 2015). Several new methodological
245 improvements for a better quantification and scaling of GPP have been reported (Zhang et al., 2018; Pulliainen
246 et al., 2017; Kooijmans et al., 2019). The GPP, measuring photosynthesis, is crucially important for the global
247 carbon cycle and its accurate estimation is essential for ecosystem monitoring and simulation. Pulliainen et al.
248 (2017) introduced a new proxy indicator for spring recovery from in situ flux data on CO_2 exchange. This
249 made it possible to quantify the relation between spring recovery and carbon uptake and to assess changes in
250 springtime carbon exchange, demonstrating a major increase in the CO_2 sink. Zhang et al. (2018) introduced
251 a new water-stress factor that effectively mitigates the overestimation of GPP under drought conditions, while
252 Bai et al. (2018 a,b) developed a method for quantifying the evapotranspiration of crops by using a remote
253 sensing-based two-leaf canopy conductance model. These methods can provide novel insights into the

254   quantification of GPP under different conditions and, in general, into the impacts of biosphere-atmosphere

255   relations on a larger scale.

256

257   Methods for satellite-based remote sensing of photosynthesis have been developed recently based on solar-

258   induced chlorophyll fluorescence signal, such as the OCO-2 product that has an improved spatial resolution,

259   data acquisition and retrieval precision compared to earlier satellite missions with solar-induced chlorophyll

260   fluorescence (SIF) capability, and allows for validation of the data directly against ground and airborne

261   measurements (Sun et al., 2017). Interpretation of the solar-induced chlorophyll fluorescence signal has also

262   been improved by many *in situ* studies. For example, Liu et al. (2019 a,b) simulated SIF in realistic 3D birch

263   stand reconstructed from terrestrial laser scanning data and found a large contribution of the understory layer

264   to the remote sensing signal.

265

266   *Vegetation changes*

267

268   The normalized difference vegetation index (NDVI) is used for detecting large-scale changes in vegetation

269   productivity. In the past decades, these changes basically are the increasing NDVI, called "greening", taking

270   place in the tundra regions and the decreasing NDVI, called "browning", in the Northern forest regions (Miles

271   and Esau, 2016). A deeper analysis behind these changes are needed. For example, in Northern West Siberia

272   only 18% of the total area had statistically significant changes in productivity either towards greening or

273   browning, and having these opposite trends for different species within the same bioclimatic zone. The

274   observed complexity of the patterns of variability and trends in vegetation productivity underlines the new

275   more detailed studies, how different forest types and species are responding to climate and environmental

276   change in the Northern environments (Miles and Esau, 2016). Also understanding the variations in small-scale

277   plant communities, seasonality and biogeochemical properties are needed for modeling the functioning of the

278   arctic tundra in global carbon cycling. Also the rapid development of the LAI during the short growing season

279   and the yearly climatic variation address the importance of optimal timing of the satellite data images when it

280   is compared with the field verification data in the Arctic region (Juutinen et al., 2017).

281

282   Vegetation indices and complex spectral transformations derived from processed long-term satellite data

283   (1973-2013) for areas around the cities of Arkhangelsk and Zapolyarny (Murmansk oblast) show the changes

284   in the state of the environment and reveal areas of peak anthropogenic impacts causing significant morphologic

285   changes in all kinds of geosystems and strongly affecting the Arctic natural ecosystems. These areas are

286   subjected to peak anthropogenic impact and are associated with specific industrial facilities (Bondur and

287   Vorobyev, 2015). Region-wide changes in the vegetation cover and the changes in and around several

288   urbanized areas in Siberia reveal a robust indication of the accelerated greening near the older urban areas.

289   Many Siberian cities have turned greener while their surroundings have been dominated by wider browning.

290   The observed urban greening could be associated not only with special tending of the within-city green areas

291   but also with the urban heat islands and succession of more productive shrub and tree species growing on

292 warmer sandy soils (Koronatova and Milyaeva 2011, Sizov and Lobotrosova 2016). Tundra and forest-tundra

293 biomes are sensitive to mean summer temperatures which increase production and greening. Taiga biomes are

294 sensitive to precipitation and soil moisture and increase production in wet summer (Miles et al., 2019).

295

296 *New methodologies determining Earth surface characteristics*

297 Earth surface characteristics are fundamental knowledge for the understanding and quantification land-

298 atmosphere processes. The methods for determining Earth surface characteristics from satellites are improving.

299 As an example, a method for recognition of the Earth surface types according to space images using an object-

300 oriented classification has been developed. The classification relies on Markov stochastic segmentation for

301 object extraction and supervised classification of the objects (Gurchenkov et al., 2017). Furthermore, a

302 prototype algorithm for hemispheric scale detection of autumn soil freezing using space-borne L-band passive

303 microwave observations was developed (Rautiainen et al., 2016) and is currently an operative soil freeze and

304 thaw product that delivers freely available data (*ftp://litdb.fmi.fi/outgoing/SMOS-FTService/*). The CryoGrid 3

305 land surface model provides improved descriptions of the possible pathways of ice-wedge polygon evolution

306 and describes better the complex processes affecting the ice-rich permafrost landscapes (Nitzbon et al., 2019).

307 In addition, there are new observations for validating satellite observations and permafrost models. Boike et

308 al., (2016) introduced a new, 16-year permafrost and meteorology data set from the Samoylov Island Arctic

309 research site, north-eastern Siberia. Terentieva et al. (2016) introduced maps used as a baseline for validation

310 of coarse-resolution land cover products and wetland data sets in high latitudes. Other examples of available

311 data for the model validation are "BC emissions from agricultural burns and grass fires in Siberia" by

312 Konovalov et al. (2018) and permafrost records at the Lena River delta" by Boike et al. (2016).

313

314 Tundra ecosystems are under pressure and intensifying permafrost thawing, plant growth and ecosystem

315 carbon exchange under the changing climate. The heterogeneity of Arctic landscapes is an extra challenge for

316 environmental monitoring. For example, remote sensing methods are not able to capture variations in moss

317 biomass, which is dominating the plant biomass and controlling soil properties in the Artic. The general

318 accuracy of landscape level predictions in the land cover type (LCT) is good , but the spatial extrapolation of

319 the vegetation and soil properties relevant for the regional ecosystem and global climate models still needs to

320 improved (Mikola et al., 2018). Furthermore, for the future, we need to have a land characterization, in order

321 to perform quantification and assessment of the ecosystem services at different scales using integrative

322 techniques and integrated field observations together with remote sensing and modelling at the landscape scale

323 (Burkhard et al., 2009, Fu and Forsius, 2015). In a smaller scale, the isotopic composition of carbon and oxygen

324 in peat can be used for the climate reconstruction (Granath et al., 2018).

325

326 2.1.2 Thawing permafrost (Q2)

327

328 *Observations of ground temperature evolution*

329

330   Permafrost regions of the Northern Eurasia are warming along with the climate (IPCC, 2019). During the
331   Global Terrestrial Network for Permafrost reference decade, 2007 - 2016, the temperature at the depth of zero
332   annual amplitude increased by $0.39\ ^\circ\text{C} \pm 0.15\ ^\circ\text{C}$ in the continuous permafrost zone and by $0.20 \pm 0.10\ ^\circ\text{C}$ in
333   the discontinuous permafrost zone. At the same time, the mountain permafrost warmed by $0.19 \pm 0.05\ ^\circ\text{C}$. The
334   global average of the permafrost temperature increased by $0.29 \pm 0.12\ ^\circ\text{C}$ (Biskaborn et al., 2019). The observed
335   trend in the continuous permafrost zone follows the air temperature trend in the Northern Hemisphere.
336

337   The changes in the permafrost region affects climate, hydrology and ecology from local to global scales
338   (Arneth et al., 2010; Hinzman et al., 2005). Several local studies focused on the difference introduced by
339   vegetation, soil and hydrological characteristics at the same site (Göckede et al., 2017, 2019). Göckede et al.
340   (2017, 2019) presented findings on shifts in energy fluxes from paired ecosystem observations in northeast
341   Siberia comprising a drained and a corresponding control site. Drainage disturbance had triggered a suite of
342   secondary shifts in ecosystem properties, including alterations in vegetation community structure, which in
343   turn influenced changes in snow cover dynamics and surface energy budget. First, the drainage reduced heat
344   transfer into deeper soil layers, which may lead to shallower thaw depths. Second, the vegetation change due
345   to the drainage led to an increase in albedo, which decreased the total energy income, or net radiation, into the
346   system. Third, the drainage reduced water content available for evapotranspiration, which resulted in reduced
347   latent heat flux and increased sensible heat flux transferring more energy back to the atmosphere. The reported
348   affects led to surface and permafrost cooling (Göckede et al., 2019).
349

350   Kukkonen et al. (2020) compared temperature data from several shallow boreholes in the Nadym region,
351   Siberia, and predicted permafrost evolution for different climate scenarios. The Nadym area represents a
352   typical site located in the discontinuous permafrost zone. Kukkonen et al. (2020) found that the permafrost
353   thawed most rapidly in low-porosity soils, whereas high-porosity soils in the top layer (e.g., peatland) will
354   retard thawing considerably. Similarly, the depth of a seasonally frozen layer and the temperature regime of
355   peat soils in the oligotrophic bog in the southern taiga zone of Western Siberia showed significant differences
356   at sites with high and low levels of bog waters (Kiselev et al., 2019). Both Kukkonen et al. (2020) and Kiselev
357   et al. (2019) results are in line with previous conclusions on the importance of volumetric water content and
358   unfrozen water content for soil thermal properties governing heat transfer and phase change processes
359   (Romanovsky and Osterkamp, 2000). Locally, the sites with thin snow cover (e.g., hill tops) demonstrated
360   higher resistance to the thawing (Williams and Smith, 1989; Kukkonen et al., 2020). To follow-up on the
361   development of permafrost thaw in different soil types require continuous and comprehensive observations
362   during the coming decades.
363

364   *Changing GHG fluxes and VOCs due to permafrost thaw*
365

366   Biogenic GHG emissions are strongly connected with permafrost conditions and changes in other related
367   environmental conditions, such as soil temperature and moisture conditions. Here we discuss recent results on

368   the observed emissions from these permafrost perspectives and, later in the section 2.2.1, address the
369   connections between GHG fluxes and the other environmental factors, like deforestation and forest fires.
370
371   During the permafrost thaw, even small changes in the soil carbon cycle can turn over a terrestrial ecosystem
372   from a sink to a source (Schuur et al., 2008). Natali et al. (2019) based their analysis on the winter time carbon
373   loss on the regional in situ observations of CO2 fluxes and estimated it as 1,662 TgC per year, which is more
374   than predicted by the process models estimates. Furthermore, Natalie et al. (2019) says that even if the soil
375   CO_2 loss would be enhanced due to winter warming, the growing season may start earlier and also onset the
376   carbon uptake under warmed climate conditions. For a better understanding of these connections and the spatial
377   and temporal dynamics in the Arctic carbon cycle we need more observations from permafrost ecosystems.
378   Additional flux measurements are urgently needed to understand the variation between the current
379   measurements and, especially extended measurements on the CH_4 emissions to better quantify their role in the
380   carbon balance. For example, a new data assimilation system gives Arctic carbon sink equal to -67 g C m^{-2}
381   yr^{-1}, but this average value is associated with very high uncertainties. Furthermore, these estimates do not
382   include methane, which is even more difficult to evaluate (López-Blanco et al., 2019). Based on the field flux
383   measurements, the Carbon Cycle Report 2018 (Schuur et al., 2018) estimates Eurasian boreal wetland being a
384   source of 14 Tg CH_4 per year. On the other hand Kirschke et al. (2013) estimations, based on atmospheric
385   measurements, ends up to the value of 9 Tg CH_4 per year. Locally, methane fluxes measured in 2005-2013
386   showed significant year-to-year variations. Interestingly, the observed variation in North America, specifically
387   in the Hudson Bay lowlands, appear to have been driven partly by the soil temperature, while in the Western
388   Siberian lowlands the variability was dependent on the soil moisture (Thompson et al., 2017). The comparison
389   of high-resolution modelling of atmospheric CH_4 to CH_4 observations already in 2012 from the East Siberian
390   Arctic Shelf (ESAS), a potentially large CH_4 source, also confirms that methane releases are highly variable
391   and inhomogeneous (Berchet et al., 2016).
392
393   Long-term flux measurements provide us insight into the carbon sink - source dynamics. The flux
394   measurements from the moist tussock tundra in the north-eastern Siberia indicated that drainage effects on the
395   carbon cycle and how the tundra changed to a weaker CO_2 sink and CH_4 source. Another relevant observation
396   was that the time outside the growing season influences the carbon balance of ecosystem processes, especially
397   during the zero-curtain period (Kittler et al. 2017). This is in line with similar studies in Alaska (Commane et
398   al., 2017; Euskirchen et al., 2017). Therefore, the autumn temperature was identified as a major driving factor
399   describing the differences between the annual GHG fluxes. Notably, however, the seasonal amplitudes of CO_2
400   concentrations in Siberia were found to be significantly higher than those in the North American continent,
401   likely due to the more intense biological activity here (Timokhina et al., 2015a). A recent study showed that
402   the Siberian carbon cycle is a major contributor to the Northern Hemisphere amplitude of CO_2 variation (Lin
403   et al., 2020).
404

405   The observations from the non-permafrost sites may give us a clue on the future dynamics of fluxes as the

406   permafrost is thawing. The chamber measurements of CH_4 and CO_2 fluxes from a non-permafrost site in the

407   Siberian peatland in August, 2015, showed that the highest values of methane fluxes were obtained in burnt

408   wet birch forest and the lowest values in seasonally waterlogged forests (Glagolev et al., 2018). The fluxes can

409   vary even between different sites of a bog as measured by Dyukarev et al. (2019). Net ecosystem exchange

410   (NEE), ecosystem respiration (ER) and gross primary production (GPP), based on the measured CO_2 fluxes at

411   a ridge-hollow complex bog and a model for ridge and hollow sites at oligotrophic bog in Middle Taiga Zone

412   of West Siberia, showed that a two-year-average NEE at the hollow site was 1.7 times higher than at the ridge

413   site (Dyukarev et al., 2019). The ecosystem processes are influenced by drying in tundra ecosystems. Kwon et

414   al. (2019) reported from Alaska that drying in the tundra ecosystems increased contributions of modern soil

415   carbon to the ecosystem respiration but, at the same time, decreased contributions of old soil carbon. These

416   changes were attributed mainly to modified soil temperatures at different soil layers due to the altered thermal

417   properties of organic soils following drainage. Furthermore, the drainage lowered CH_4 fluxes by a factor of 20

418   during the growing season, with post drainage changes in microbial communities, soil temperatures, and plant

419   communities also affecting the flux reduction in an Arctic wetland ecosystem (Kwon et al., 2017).

420

421   Voigt et al. (2016) reported that, under warming conditions, the vegetated tundra in north-eastern European

422   Russia shifted from a GHG sink to a source. The positive warming response was dominated by CO_2; however,

423   N_2O emissions were also significant. N_2O was emitted not only from bare peat, already identified as a strong

424   source, but also from the vast vegetated peat areas not emitting N_2O under current climate conditions. These

425   results are explained by dynamics between the temperature, nitrogen assimilation by plants and soil microbial

426   activity, having a strong impact on future GHG balance in Arctic (Voigt et al., 2016; Gil et al., 2017). Studying

427   N_2O emissions in the typical permafrost peatland in Finnish Lapland, it was concluded that ca 25% of the

428   Arctic territory are the areas potentially emitting nitrous oxide (Voigt et al., 2017). It seems that there is positive

429   feedback mechanism between the permafrost thawing and the moisture regime. Predicting soil response to

430   climate change or land use is central to understanding and managing N_2O. According to recent results N_2O

431   flux can be predicted by models incorporating soil nitrate concentration (NO_3^-), water content and temperature

432   (Pärn et al., 2018).

433

434   In addition to CO_2 and CH_4, thawing or collapsing of arctic permafrost can release volatile organic compounds

435   (VOCs). Li et al. (2020a) examined the release of VOCs from thawing permafrost peatland soils sampled from

436   Finnish Lapland in laboratory. The average VOC fluxes were four times as high as those from the active layer,

437   and mainly attributed to direct release of old, trapped gases from the permafrost. These results demonstrate a

438   potential for substantive VOC releases from thawing permafrost and suggests that future global warming could

439   stimulate VOC emissions from the Arctic permafrost.

440

441   2.1.3 Ecosystem structural change (Q3)

442

Changes in microbial activity

Climate change is likely to cause increased tree appearance on open peatlands, but we do not know how this vegetation change influences the below-ground microbiology and composition. Changes along bog ecotones at three Russian peatland complexes suggested that tree encroachment may reduce the trophic level of *Testate Amoeba* communities and reduce the contribution of mixotrophic *Testate Amoebae* to primary production. Thus, it seems that increased tree recruitment on open peatlands will have important consequences for both microbial biodiversity and microbial-mediated ecosystem processes (Payne et al., 2016). We also need to understand better the dynamics affecting the bacteria, fungi and other related species in the ground air layer. Recent studies by Korneykova and Evdokimova (2018) and Korneikova et al. (2018 a,b) showed the influences of anthropogenic sources (Copper-Nickel Plant) and acidic soils in Russian northern taiga and tundra on the portion of the airborne fungi and on the structure of algological and mycological complexes (Korneikova et al., 2018 a,b). New methods were reported on how to improve soils conditions, which were developed on all kinds of materials made or exposed by human activity that otherwise would not occur at the Earth's surface, referred as "Technosol engineering" (Slukovskaya et al., 2019) and how to monitor climate change impacts on the functional state of bogs by using *Sphagnum* mosses (Preis et al., 2018).

Effects of forest fires on soils

Forest fires, a significant environmental factor in the Northern Eurasian region, change soil chemical and physical properties and may influence greenhouse gas (GHG) fluxes and emissions of BVOCs. Recent results indicate that a slower post-fire litter decomposition has a clear impact on the recovery of soil organic matter following forest fires in northern boreal coniferous forests due to accumulated soil organic matter. The soil recover relates to slow litter composition and reduced enzymatic and microbial activity (Köster et al., 2016).

Post-fire studies of the long-term evolution of bacterial community structure and function, are sparse. Sun et al. (2016) showed that the major drivers influencing bacterial community are soil temperature, pH and moisture. Furthermore, Köster et al. (2015) analyzed the long-term effects of fire on soil CO_2, CH_4 and N_2O fluxes in pine forest stands in the Finnish Lapland and discussed the role of microbial bio mass in this context. Köstner et al. (2015) did not detect significant effect on the CO_2 emissions nor on the N_2O fluxes , but there were long-lasting strengthening of the CH_4 sink the soil acted as a CH_4 sink, and this change in CH_4 uptake resulted from the fire was long-lasting. Interestingly, Köster et al. (2018) did not find a similar kind of long-term effect on the CH4 sink dynamics in the studies carried out in Siberia.

Forest wildfires also regulate the BVOC emissions from boreal forest floors by changes in the ground vegetation. Total BVOC emissions from forest floor decreased after forest fire and then again increased along with the succession of forests (Zhang-Turpeinen et al., 2020). For a comparison, Bai et al. (2017) showed that

480 biomass burning resulted in increased BVOC emission fluxes and ozone concentration above canopy in a
481 subtropical forest in China
482
483 2.2. ATMOSPHERIC SYSTEM
484
485 Concerning critical atmospheric processes and large-scale climate implications, we concentrate here on
486 greenhouse gases and aerosol particles over Northern Eurasia and Arctic, urban air quality, and issues related
487 to the weather and atmospheric circulation. We summarize the recent measurements on the atmospheric
488 composition relevant to sink and source dynamics in Siberia, on the sources and properties of atmospheric
489 aerosols in Arctic – boreal environments, including black carbon and dust in the atmosphere and snow, and on
490 the methodological and model developments related to atmospheric chemistry and physics (Q4, section 2.2.1).
491 Furthermore, we introduce new results and observations on atmospheric pollution in rural, suburban and mega
492 city environments in China and Russia (Q5, section 2.2.2). We briefly show some recent results related to
493 synoptic scale weather in the Artic boreal regions, such as cold and warm episodes, cyclone density dynamics,
494 circulation effect on temperature and moisture, cloudiness in Arctic, on clouds and planetary boundary layer
495 (Q6, section 2.2.3).
496
497   2.2.1   Atmospheric composition and chemistry (Q4)
498
499 *Boreal forests carbon balance*
500
501 As already discussed in section 3.1.1, the boreal forests as a carbon sink and the related role of forestation have
502 been under international debate. It seems that early snowmelt increases springtime carbon uptake of the boreal
503 forests of Eurasia and North America and shows a major advance in the CO_2 sink (Pulliainen et al., 2017). A
504 scenario of a complete global deforestation by Scott et al. (2018), combining radiative forcing to CO_2, surface
505 albedo and short-lived climate forcers (SLCFs), suggests that global deforestation could cause 0.8 K warming
506 after 100 years, with SLCFs contributing 8% of the effect. However, deforestation as projected by the RCP8.5
507 scenario leads to zero net radiative forcing from SLCF, primarily due to nonlinearities in the aerosol indirect
508 effect. Tuovinen et al. (2019) showed that methane fluxes vary strongly with wind direction in a tundra
509 ecosystem with heterogeneous vegetation. By combining very high-spatial-resolution satellite imagery and
510 footprint modelling, they were able to estimate the relation between the main land cover types and the
511 ecosystem level measurements. CH_4 emissions mainly originated from wet fen and graminoid tundra patches,
512 whereas the areas of bare soil and lichen acted as strong CH_4 sinks (Tuovinen et al. 2019. Refer to Tsuruta et
513 al. (2017) posterior mean global total emissions during 2000-2012 were 516±51 Tg CH_4 yr^{-1}, which indicates
514 that the emissions increased by 18 Tg CH_4 yr^{-1} from the period 2001-2006 to the period 2007-2012. This
515 increase be explain by increased emissions from the South America temperate region, the Asia temperate
516 region and Asia tropics.
517

518   Analysis of the trends and the diurnal, weekly and seasonal cycles of CO_2 and CH_4 mixing ratios derived from

519   the long-term data of the "Japan–Russia Siberian Tall Tower Inland Observation Network" showed that the

520   frequency of identified events of elevated concentration differs for CO_2 and CH_4 and may reach up to 20% of

521   days in some months (Belikov et al., 2019). These observations made it possible to reduce uncertainties in the

522   biosphere surface CO_2 uptake (Kim et al., 2017). Although the CO_2 uptake in boreal Eurasia estimated by Kim

523   et al. (2017) was about 30% lower than that obtained without the assimilation of Siberian observation data,

524   Siberia still remains a key contributor to the terrestrial CO_2 sink in the Northern Hemisphere.

525

526   There are tendencies of significant growth or suppression of soil CO_2 fluxes across the types of human impact

527   on cryogenic ecosystems in Russia (Karelin et al., 2017). Human footprint on the methane exchange between

528   the soil and atmosphere is mediated by drainage. However, all types of human impact suppress the sources

529   and increase the sinks of methane to the land ecosystems. The nitrous oxide (N_2O) flux grew under the

530   considered types of human impact. The human footprint on soil greenhouse gases fluxes is comparable to the

531   effect of climate change at an annual to decadal timescales.

532

533   Wildfires in Siberia lead to a parallel increase of the CO_2 concentration at the Russian Arctic. During 2010–

534   2017, CO_2 concentrations increased by 20 ppm in Tiksi at a coast of Laptev Sea and by 15 ppm at the Cape

535   Baranov station (Ivakhov et al., 2019). At the ZOTTO tower site in central Siberia, atmospheric CO_2

536   concentration increased an average by 2.0 ppm yr^{-1} during 2006-2013, but showed large interannual variations.

537   The highest increase were found in 2010 and 2012 (3.6 and 4.3 ppm yr^{-1}, respectively), when large wildfires

538   released huge amounts of CO_2 in Siberia (Timokhina et al., 2015b). Repeated wildfires in boreal forests can

539   combust a portion of the thick organic soil layer characteristic of this ecosystem, and change the forests from

540   a carbon sink into a carbon source (Walker et al., 2019). In a study on the fire chronosequence of the central

541   Siberian permafrost soil showed that soils being affected by fires over decades acted as a CO_2 sources (Köster

542   et al., 2018). The CO_2 emissions from the soil increased with increasing time since the last fire. However, there

543   were no similar effect on CH_4 emissions, and soils acted as a CH_4 sink without connection to forest fires. In

544   addition to CO_2, wildfires also release large amounts of other trace gases and aerosols. Emission factors of

545   several trace gases and aerosols from Siberian fires measured from the Trans-Siberian railway were reported

546   by Vasileva et al. (2017). The impact of Siberian fires as elevated aerosol concentrations was at times observed

547   to extend up on the Arctic coast (Asmi et al., 2016).

548

549   *Arctic methane (CH_4) balance*

550   Deep understanding of methane emissions dynamics in the Arctic is needed for the identification and

551   quantification of the GHG-related feedbacks and global methane cycle (Dean et al., 2018). The main source

552   of methane in Arctic during winter is anthropogenic; on a smaller scale, emissions from oceans including The

553   Eastern Siberian Arctic Shelf (ESAS) can play an important role. During warm season, the balance is

554   dominated by emissions from wetlands and freshwater bodies. Thonat et al. (2017) employed CHIMERE

555   model for the assessment of the methane cycle in Arctic. They reported that all methane sources, except

556   biomass burning, contributed to measurements at six study sites. That study emphasizes the importance of a
557   joint model-measurements approach for studies of complex phenomena at large spatial scales. Accounting for
558   OH oxidation and soil uptake, sinks of methane, improved the agreement between observed and modelled
559   methane concentrations (Thonat et al., 2017). Peltola et al. (2019) up-scaled CH_4 fluxes measured at 25
560   northern wetland sites and showed three different maps of wetland distribution with the annual methane
561   emissions varying from 31- 38 $Tg(CH_4)\,yr^{-1}$. (For the monthly up scaled CH_4 flux data products see
562   *doi.org/10.5281/zenodo.2560163*). Multiple sources, together with different spatiotemporal dynamics and
563   magnitudes, are influencing the total Arctic CH_4 budget and addresses the need for the further improved
564   assessments (Peltola et al., 2019, Thonat et al., 2017).
565

566   *Northern Eurasian carbon monoxide (CO)*
567   Analysis of the long-term trends in atmospheric composition in remote Northern Eurasia (1998–2016) showed
568   that the total column carbon monoxide (CO) amount has been stabilized or increased in summer and autumn
569   months, whereas the total column CH_4 amount has increased since 2007 (Rakitin et al., 2018). The changes in
570   the global photochemical system, especially changes in the ration between the sources and sinks for minor
571   atmospheric chemical species, could explain these trends (Skorokhod et al., 2017). A comparative study
572   (1998–2014) on the atmospheric total column CO amount in the background and polluted regions of Eurasia
573   indicated that this amount has decreased remarkably in the Moscow urban environments compared to the
574   background regions (0.9–1.7% per year) (Wang et al., 2018a).
575

576   *Northern Eurasian Ozone (O₃)*
577   Atmospheric measurements of ozone, its precursors and other pollutants over Siberia are important for the
578   atmospheric chemistry modelling, satellite products validation and comparisons between Siberia and other
579   regions of the Northern Hemisphere. Isoprene and monoterpenes together with nitrogen oxides impact
580   tropospheric O_3 formation and lead to an increase in the daytime ozone-forming potential (OFP) in urban
581   environment. It was demonstrated that monoterpenes have a major contribution to tropospheric O_3 formation,
582   especially in cities in Siberia having high atmospheric NOx concentration (10-20 ppb) and daytime
583   temperatures (>25 °C) (Berezina et al., 2019). In contrast, isoprene is dominating the O_3 formation and the
584   increasing OFP in the Far East cities with the increasing population size. The isoprene-derived OFP can
585   originate from deciduous vegetation growing in city environments or nearby regions, or from an anthropogenic
586   isoprene source. The monoterpene-derived OFP was found to be the lowest in medium-size cities and the
587   highest in small cities (Berezina et al., 2019). The total contribution of benzene and toluene to photochemical
588   O_3 production was found to be up to 60–70% in urbanized environments, indicating anthropogenic pollutant
589   sources (Skorokhod et al., 2017). In addition to atmospheric chemistry, the connection between O_3, UV
590   radiation and health effects needs to be addressed in the populated urban environments of Siberia. Chubarova
591   et al. (2019) estimated that winter O_3 depletion in northern regions of Siberia is not critical, but much weaker
592   O_3 reduction in the early spring can lead to dangerous levels of erythema UV radiation.
593

594   *Sources and properties of atmospheric aerosols in boreal and Arctic environments*

595

596   Atmospheric new particle formation (NPF) is the largest contributor to the number concentration of aerosol

597   particles in the global troposphere. During the past couple of decades, NPF has been measured in more than

598   10 boreal forest sites (Kerminen et al., 2018). The annual frequency of NPF event days varies between about

599   10 and 30% in the boreal forest zone, being the highest in the western part of this region and lowest in the

600   northern edge and Siberian part of it. Similar high nucleation frequencies were found at two very remote sites

601   in boreal North America (Andreae et al., 2019). In contrast, annual NPF event frequencies below 2% were

602   reported from central Siberia (Wiedensohler et al., 2019). Similarly, in the northern Siberia on the Arctic coast,

603   NPF events were mainly connected with marine and coastal air masses and rarely observed in continental air

604   masses (Asmi et al., 2016). Seasonally, NPF tend to be most frequent during spring, even though high NPF

605   event frequencies can also be observed during summer or autumn. Winter-time NPF is rare throughout the

606   boreal forest region. In the Arctic, NPF appears to be a major aerosol particle source from spring to summer,

607   after which this source collapses during autumn and practically absent over the whole winter (Freud et al.,

608   2017). 20 years of NPF observations in a boreal forest at the SMEAR II station in Finland show higher

609   frequency of NPF events under clear-sky conditions in comparison to cloudy conditions (Dada et al. 2017).

610   Also oxidized organic vapors showed a higher concentration during the clear-sky NPF event days, whereas the

611   condensation sinks and some trace gases had higher concentrations during the nonevent days. In spring, a

612   threshold for the combined values of ambient temperature and condensation sink was found. Above this

613   threshold, no clear-sky NPF event could be observed.

614

615   The overall importance of atmospheric NPF in boreal and Arctic areas depends on the growth of freshly-

616   formed particles cloud condensation nuclei. In the boreal forest environment, both observations and model

617   simulations indicate that the growth particles is tied strongly with the oxidation products of biogenic volatile

618   organic compounds originating from forest ecosystems (Paasonen et al., 2018; Östrom et al., 2017). The

619   important compound group in this respect are monoterpenes, even though also sesquiterpenes were found to

620   have high secondary organic aerosol yields in boreal forest environments (Hellén et al., 2018). The observed

621   particle growth rates were found to increase with an increasing particle size and to be highest during summer

622   time (Paasonen et al., 2018). The chemistry of new particle growth in the Arctic atmosphere is not well

623   characterized, even though available observations suggest that this growth is associated mainly with biogenic

624   emissions from high-latitude marine areas (Giamarelou et al., 2016; Heintzenberg et al., 2017; Kecorius et al.,

625   2019).

626

627   Wildfires are an important source of particulate pollutants on a global scale and are affecting both on air quality

628   and climate (Andreae, 2019; Bondur et al., 2020). Satellite observations indicate that the annual burned area

629   by wildfires in Russia decreased by a factor of 2.6 during 2005–2016 owing to early detection and suppression

630   of fire sources, whereas in Ukraine the relative size of burned-out areas increased by a factor of 6–9 from

631   2010–2013 to 2014–2016 (Bondur et al., 2017; 2019 d). For Siberia, Ponomarev et al. (2016) reported a strong

632 increase both in number and burned areas based on satellite data, 1996-2015. Based on their data, the burned

633 areas in Siberia doubled from 2005 to 2016. While biomass burning emissions have been measured widely

634 over Russia (Bondur, 2016; Bondur and Ginzburg, 2016; Bondur et al., 2019 d), there is still a need for further

635 information on the atmospheric composition of wildfire emissions and related emission ratios from the Siberian

636 region. Fire experiments provide important information on the emission and aging characteristics of smoke

637 aerosols (e.g. Kalogridis et al., 2018).

638

639 Luoma et al. (2019) presented a detailed trend analysis for aerosol optical properties at the SMEAR II station

640 in Finland. They found a statistically significantly decreasing trend for the scattering coefficient, and even a

641 stronger decreasing trend for the absorption coefficient during 2006 – 2017. These trends are very likely

642 indicative of decreasing influence of anthropogenic emissions, with the contribution from emissions containing

643 black carbon decreasing even faster.

644

645 Measurements of carbonaceous aerosols over central Siberia during 2010-2012 showed that in fall and winter,

646 high concentrations of such aerosols were caused by long-range transport from the cities located in southern

647 and southwestern regions of Siberia (Mikhailov et al., 2015a). In spring and summer, pollution levels were

648 high due to regional forest fires and agricultural burning in the Russian-Kazakh region. The variability of the

649 background concentration of organic aerosols correlated with the air temperature in summer, implying that

650 biogenic sources dominated the formation of organic particles at that time of the year (Mikhailov et al., 2015b).

651 Overall, it seems that the atmospheric pollution originating from the biomass burning and anthropogenic

652 emissions is significantly affecting the Siberian region. In summer, precipitation is removing the pollutants

653 from the air and leading to relatively clean atmospheric conditions this region (Mikhailov et al., 2017).

654

655 At circumpolar sites over the Arctic, aerosol optical properties were found to vary both seasonally and spatially

656 (Schmeisser et al., 2018). Arctic haze aerosols in late winter and spring are characterized by increased

657 concentrations of sulfate, whereas in summer rich organic chemistry seems to be associated with vegetation,

658 local urban and shipping sources as well as secondary aerosol formation influenced by emissions from low

659 latitude Siberia (Popovicheva et al., 2019a). In a longer perspective, Arctic observations show large decreases

660 in both sulfate and black carbon concentrations since the early 1980s (Breider et al., 2017).

661

662 Observations on the elemental composition of surface aerosols on the coastal Kandalaksha Bay of the White

663 Sea were indicative of the dominance of biogenic aerosol particles during summer time, with heavy metal

664 concentrations in aerosols being at Arctic background levels (Starodymova et al., 2016). Increases in Ni and

665 Cu concentrations were observed in air masses arriving from the western part of the Kola Peninsula indicative

666 of emissions from the smelters in that region.

667

668 *Black carbon and dust in the atmosphere and snow*

669

670   Black carbon (BC) is a potentially large contributor to climate forcing in the Arctic region, however, the
671   assessment of its pollution is hampered by the lack of aerosol studies in Northern Siberia (Popovicheva et al.,
672   2019). Spatial variability of Arctic BC was studied using a harmonized dataset from 6 circumpolar Arctic
673   observatories (Backman et al., 2017). These data suggested significant spatial and seasonal variability
674   (Schmeisser et al., 2018), addressing a need for more year-round data. BC observations (Sep 2014 – Sep 2016)
675   at the Hydrometeorological Observatory Tiksi at a coast of the Laptev Sea showed a seasonal variation, with
676   the highest concentrations (up to 450 ng/m^3) from January to March and the lowest (about 20 ng/m^3) - for June
677   and September. During winter, stagnant weather and stable atmospheric stratification resulted in accumulation
678   of pollution, depending also on wind direction and air masses transport (Popovicheva et al., 2019a).

679

680   For Arctic, important sources of BC include industrial regions of Northern Europe, gas flares of the oil fields
681   in the North Sea and Siberia, and Siberian biomass burning (Shevchenko et al., 2015; Konovalov et al., 2018).
682   For example in 2012 approximately a quarter of the biogenic BC emissions from Siberia after fire season were
683   transported into the Arctic (Konovalov et al., 2018). Popovicheva et al. (2017a) analyzed the BC origins over
684   the Russian Arctic seas together with simulated BC concentrations. Concentrations were observed to be high
685   (100-400 ng m^{-3}) in the Kara Strait, Kara Sea and Kola Peninsula, and extremely high (about 1000 ng m^{-3}) in
686   the White Sea. It seems that the gas-flaring emissions from the Yamal-Khanty-Mansiysk and Nenets-Komi
687   regions affected the measurements made in the Kara Strait (northerly 70 °N) region, while the Near
688   Arkhangelsk (White Sea) region was connected to the biomass burning in mid-latitudes. The combustion from
689   the Central and Eastern Europe were also identified as important BC sources.

690

691   Atmospheric aging promotes internal mixing of BC with other aerosol constituents, leading to enhanced light
692   absorption and radiative forcing. The in-situ observations at Arctic stations demonstrated absorption
693   enhancement due to the internal mixing of BC, which is a systematic effect and should be considered for
694   quantifying the aerosol radiative forcing in this region (Zanatta et al., 2018).

695

696   Regional modelling of the Arctic aerosol pollution showed that the main sources of the pollution e.g. BC
697   deposition over snow originates from long-term anthropogenic emissions and biomass burning and are main
698   contributors to direct aerosol radiative effects in the region (Marelle et al., 2018). A scenario of the increasing
699   shipping in the Arctic Ocean in summer 2050 indicates that shipping emissions could become the main source
700   of surface aerosol and the flaring of the BC. Kühn et al. (2020) assessed the effects of different BC mitigation
701   measures on Arctic climate and showed that reducing BC emissions by the Arctic Council member states can
702   reduce BC deposition by about 30 % compared to the current situation. A full execution of recommendation
703   by the Arctic Council member and observer countries could reduce the annual global premature deaths due to
704   PM by ~9 % by 2030 (Kühn et al. 2020). Evangeliou et al. (2018) estimated the origin of elemental carbon
705   (EC) in snow and showed that for western Siberia where gas flaring emissions is a major contributor, the model
706   underestimation was significant. Furthermore, the model was evaluated by independent BC measurements in
707   snow over the Arctic showed and, again, the model underestimated BC concentrations, especially in spring.

708

709   Climatically significant cryosphere effects of light-absorbing, high-latitude dust can be similar to the albedo

710   and melt effects of BC (Peltoniemi et al., 2015; Svensson et al., 2016, 2018; Meinander et al. 2020ab). Iceland

711   is the most significant source for European Arctic dust and plays a role in the cryosphere-atmosphere-biosphere

712   interactions and feedbacks (Boy et al., 2019; Dragosics et al., 2016, Dagsson-Waldhauserova and Meinander

713   2019). Dust storms from technogenic mining industry tailing dumps on the Kola Peninsula are also an

714   important source of local atmospheric pollution for neighbor cities, e.g., Apatity and Kirovsk (Amosov et al.,

715   2020). Besides regional-scale dust storms from deserts in Kazakhstan, Mongolia and China are significant

716   sources of aerosol pollution not only for these regions, but also for the Northern Asia.

717

718   *Methodological and model developments related to atmospheric chemistry and physics*

719

720   Several methods to characterize the atmospheric chemistry were introduced or improved. Motivated by the

721   ability of atmospheric ion measurements to identify new particle formation (NPF) events in the atmosphere

722   (Leino et al., 2016), a new classification method for atmospheric NPF was developed (Dada et al., 2018). The

723   new method is complementary to the traditional event analysis and it can also be used as an automatic way of

724   determining new particle formation events from large data sets. Zaidan et al. (2018b) used mutual information

725   approach to identify key factors contributing to the NPF. This method can be used in the atmospheric studies

726   also to discover other interesting phenomena and relevant variables. The NPF is directly observed by

727   monitoring the time evolution of ambient aerosol particle size distributions. A new machine learning-based

728   approach, a Bayesian neural network (BNN) classifier, points out the potential of these methods and suggest

729   further exploration in this direction (Zaidan et al., 2018a).

730

731   The condensation sink, being proportional to the surface area of an aerosol population, is one of the major

732   parameters controlling NPF. A simple model for the time evolution of the condensation sink in the atmosphere

733   for intermediate Knudsen numbers was developed to describe the coupled dynamics of the condensing vapor

734   and the condensation sink (Ezhova et al., 2018a). The model gives reasonable predictions of condensation sink

735   dynamics during periods of particle growth by condensation in the atmosphere. A new empirical relation

736   between the atmospheric cloud condensation nuclei (CCN) concentration and aerosol optical properties was

737   derived (Shen et al., 2019), making it possible to estimate CCN concentrations at sites with continuous

738   observations of aerosol optical properties.

739

740   Empirical models of solar radiation were developed and used for calibrations of solar radiometers (Bai, 2019).

741   This method can be used to calibrate all kinds of solar radiometers. A solar radiation model combined with

742   ceilometer and pyranometer measurements was used to classify clouds at SMEAR II (Ylivinkka et al., 2020)

743   It opens new possibilities for studies of aerosol-cloud interactions.

744

745 Che et al. (2016) made an inter-comparison of three satellite (AATSR Level 2) aerosol optical depth (AOD)
746 products (SU, ADV and ORAC) over China. The SU algorithm performs very well over sites with different
747 surface conditions in mainland China from March to October, but slightly underestimates AOD over barren or
748 sparsely vegetated surfaces in western China. The ADV product has the same precision and error distribution
749 as the SU product. The main limits of the ADV algorithm are underestimation and applicability. The ORAC
750 algorithm has the ability to retrieve AOD at different ranges, including high values of AOD, but its stability
751 deceases significantly with an increasing AOD, especially when AOD > 1.0.

752

753 One of the major problems for both interpretation of satellite data and applications of empirical models of solar
754 radiation is related to elevated aerosol layers in the atmosphere. It was demonstrated that their origin can be
755 attributed at a higher confidence when back trajectories are combined with lidar and radiosonde profiles
756 (Nikandrova et al., 2018).

757

758 A progress has been made with regards to black carbon measurement methods. A representative value for the
759 multiple scattering enhancement factor, a fundamental quantity correcting atmospheric black carbon
760 measurement using an aethalometer, was derived for the first time in the Arctic environment (Backman et al.,
761 2017). By analyzing BC measurements made with an Aethalometer in Nanjing, Virkkula et al. (2015) showed
762 that the compensation parameter of a widely-used data processing method depends both on single-scattering
763 albedo and backscatter fraction of the aerosol. The multiple-scattering correction factor of quartz filters and
764 the effect of filtering particles mixed in snow was estimated by Svensson et al. (2019) who applied the method
765 for analyzing light absorption and BC in snow samples taken from the Finnish Lapland and the Indian
766 Himalayas.

767

768 Measurement of atmospheric sub-10 nm particle number concentrations has been of substantial interest
769 recently. A new high flow differential mobility particle sizer (HF-DMPS) was built, calibrated and operated
770 in field conditions for one month (Kangasluoma et al. 2018). The counting uncertainties of the HFDMPS were
771 reduced by about 50% as compared to the traditional DMPS. The HFDMPS detected about two times more
772 particles than the DMPS in size range of 3–10 nm. Below 3 nm, the HF-DMPS is currently limited by the
773 inability of diethylene glycol to condense on biogenic particles. For collecting BVOC samples, a novel
774 collection method offering portability and improved selectivity and capacity was developed. A solid-phase
775 microextraction (SPME) Arrow sampling (Barreira et al. 2018) can be used for static and dynamic collection
776 of BVOCs in the field conditions. A significant improvement on sampling capacity was observed with the new
777 SPME Arrow system over SPME fibers. A fully automated online dynamic in-tube extraction (ITEX)–gas
778 chromatography/mass spectrometry (GC/MS) method was introduced for continuous and quantitative
779 monitoring of VOCs in air (Lan et al. 2019). The stability and suitability of the developed system was validated
780 with a measurement campaign, and the ITEX method provided 2–3 magnitudes lower quantitation limits than
781 established methods. Parshintsev et al. (2015) introduced a new, fast analysis method for the desorption
782 atmospheric pressure photoionization high-resolution (Orbitrap) mass spectrometry (DAPPI-HRMS). The

783 DAPPI results agreed with the aerosol particle number measured with an established method and was found
784 to detect different compounds and giving complementary information about the aerosol samples.

785

786 Fragmentation of molecular clusters inside mass spectrometers is a significant uncertainty-source in many
787 chemical applications. A novel model, capable of quantitatively predicting the extent of fragmentation of
788 sulfuric acid clusters was developed (Passananti et al. 2019). The fragmentation cannot be described in terms
789 of rate constants under equilibrium conditions, because clusters accelerate under electric fields (Zapadinsky et
790 al. 2019). A model describing an energy transfer to the cluster internal modes caused by collisions with residual
791 carrier gas molecules was developed. The model can be used to interpret experimental measurements done
792 with atmospheric pressure interface mass spectrometers.

793

794 Recently, new atmospheric aerosol instruments have been deployed in the PEEX area. At the Beijing
795 University of Chemical and Technology (BUCT), the Aerosol and Haze Laboratory (AHL) was established, a
796 permanent laboratory with a focus on characterizing air pollution in a comprehensive manner from a long-term
797 perspective. Several chemical compounds are measured continuously by the state-of-the-art instruments at
798 AHL in connection to atmospheric trace gases, aerosol particle size distributions and mass concentrations,
799 particle chemical composition on the levels from molecules, clusters and nanometer to micrometer sized
800 particles. The first results showed increased cluster mode particle number concentrations during NPF events,
801 whereas during haze days accumulation mode particle number concentrations were high (Zhou et al., 2020).
802 During these measurements, an evidence was found on significant nighttime sulphuric acid production,
803 yielding gaseous sulphuric acid concentrations of 1.0 to $3.0 \times 10^6 \, \text{cm}^{-3}$ (Guo et al., ACPD 2020).

804

805 Besides Beijing, measurements have been performed in several other locations inside the PEEX area. We used
806 novel instrumentation to measure new particle formation and its precursors at the background Fonovaya station
807 in Tomsk region (Russia, Siberia), at the Värriö subarctic research station (Finland), in Ny-Ålesund (Svalbard,
808 Norway) and on the German icebreaker, the Polarstern, during the MOSAIC project. As an example, the first
809 results from Fonovaya station are shown in Fig. 2. Thanks to these deployments, in the next years we will be
810 able to understand the identity of NPF precursors in those remote places. This will help to elucidate the human
811 impact on aerosol formation and therefore aerosol-cloud interactions at high latitudes. In Siberia, we will
812 finally understand why new particle formation occurs infrequently, and hopefully also identify the human role
813 in this phenomenon. In the Arctic, we will understand the marine influence on new particle formation and will
814 find out the detailed mechanism that leads to the formation of the initial clusters.

815

816 Model developments were made at several scales. Aerosol-radiation and aerosol-cloud interactions are among
817 the main sources of uncertainties in climate models, and detailed information on anthropogenic aerosol number
818 emissions is needed to improve this situation. Anthropogenic aerosol number emissions in current large-scale
819 models are usually converted from the corresponding mass emissions in pre-compiled emission inventories
820 using very simplistic methods. In the global aerosol-climate model ECHAM-HAM, the anthropogenic particle

821 number emissions converted originally from the AeroCom mass emissions were replaced with recently-
822 formulated number emissions from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)
823 model (Xausa et al., 2018). However, revisions are still needed in the new particle formation and growth
824 schemes currently applied in global modeling frameworks.

825

826 For regional and urban scales, a fully integrated /online coupled meteorology-chemistry-aerosol model Enviro-
827 HIRLAM was developed (Baklanov et al., 2017) and tested for several applications in Europe, Russian Arctic
828 and China (Shanghai) (Mahura et al., 2018, 2019). Key issues for seamless integrated chemistry–meteorology
829 modeling for Earth System prediction were analyzed and formulated (Baklanov et al., 2018), highlighting the
830 scientific issues and emerging challenges that require proper consideration to improve the reliability and
831 usability of these models for three main application areas: air quality, meteorology, and climate modeling.
832 Baklanov et al. (2018) also presents a synthesis of scientific progress in the form of answers to nine key
833 questions, and provides recommendations for future research directions and priorities in the development,
834 application, and evaluation of online coupled models.

835

836 2.2.2 Urban air quality and megacities (Q5)

837

838 The rapid urbanization and growing number of megacities and urban aglomerations requires new types of
839 research and services that make the best use of science and available technology. There are urgent needs for
840 examining what the rising number of megacities means for air pollution, local climate and the effects these
841 changes have on global climate (Baklanov et al., 2016). Such integrated studies and services should assist cities
842 in facing hazards, such as storm surge, flooding, heat waves and air pollution episodes, especially in changing
843 climates (WMO, 2019). We discuss here the recent observation on the atmospheric pollution in China and
844 Russia.

845

846 *Air quality in China – recent observations*

847

848 China is one of the regions with highest concentrations of fine $PM_{2.5}$ in the world (Wang et al., 2017a). This
849 has serious consequences on air pollution and the associated visibility reduction (haze) and adverse health
850 effects (Zhao et al., 2017). The number of haze days in China has been growing during the recent decades, but
851 detailed understanding of the factors governing the occurrence of haze is still not clear. A key feature of haze
852 formation seems to be an increased inorganic fraction of the aerosol, suggesting that the reduction of nitrate,
853 sulfate and their precursor gases would improve air quality and visibility in China (Wang et al., 2019). In
854 northern China, $PM_{2.5}$ concentrations declined over the period 2013–2017, and approximately half of the inter-
855 annual variability in this region was attributed to atmospheric circulation changes (Li et al., 2020b). The
856 maximum daily 8-h average O_3 concentrations increased over most of northern China during the same time
857 period, with again large influences due to atmospheric circulation on daily basis (Liu et al., 2019b).

858

859   Measurements in urban China demonstrated a relative frequent occurrence of atmospheric new particle

860   formation (NPF), characterized typically by high particle formation rates and strongly size-dependent growth

861   of newly-formed particles (Kulmala et al., 2016b; Wang et al., 2017b; Chu et al., 2019). Since the first reported

862   sub-3 nm particle measurements in China a few years ago (Xiao et al., 2015), new insight into the formation

863   pathways of molecular clusters and their growth have been obtained, including the relative roles of gaseous

864   sulfuric acid, amines, ammonia and organic vapors in these processes (Yao et al., 2018; Yan et al., 2021).

865   While high pre-existing particle loadings appear to suppress NPF during severe haze periods in Chinese

866   megacities, it is unclear how NPF is possible at all under less but still quite polluted conditions typical for these

867   environments (Kulmala et al., 2017). Overall, the available observations suggest NPF to be a major source of

868   aerosol particles in urban China, with potentially large effects on haze formation (Kulmala et al., 2021) and

869   cloud properties (Chu et al., 2019).

870

871   Urban measurements of particle number size distributions give deep understanding into the sources and

872   atmospheric processing of fine particles. The longest urban continuous record is from the SORPES station in

873   the Yangtze River Delta (Qi et al., 2015), whereas the broadest size range (1.5 nm – 1 μm) was measured in

874   the winter Beijing atmosphere (Zhou et al., 2020). The latter study found clear differences in particle sources

875   in different size ranges: NPF was in general the largest source of clusters and nucleation mode (<25 nm)

876   particles, while traffic contributed to all the size ranges and dominated both cluster and nucleation modes on

877   haze days. Aitken mode (25–100 nm) particles originated mainly from local emissions, with additional

878   contributions from regional and transported pollution as well as from the growth of nucleation mode particles.

879   Regional and transported pollution were identified as the main source of accumulation mode (>100 nm)

880   particles.

881

882   Air pollution and chemical transformation, including annual and seasonal variations of the concentrations of

883   atmospheric constituents, were analyzed for North China for 2005–2015 by Bai et al. (2018a). A

884   photochemical link relating the production of fine PM and O_3 was detected. In particular, the VOCs

885   contribution in chemical and photochemical reactions was found to be prominent in summer. An intensive

886   measurement campaign (SORPES station, Yangtze River Delta) was carried out to investigate sulfate

887   formation and associated nitrogen chemistry (Xie et al., 2015). That study highlighted the effect of NOx in

888   enhancing the atmospheric oxidizing capacity, and indicated a potentially very important impact of increasing

889   NO concentrations on particulate pollution formation and regional climate change in East Asia. In Changzhou,

890   a highly-populated city in the Yangtze River Delta, primary organic aerosol concentrations outweighed

891   secondary ones, indicating an important role of local anthropogenic emissions in aerosol pollution (Ye et al.,

892   2017). The measurement also showed the abundance of organic nitrogen compounds in water-soluble organic

893   aerosol, suggesting that these compounds are likely associated with traffic emissions.

894

895   Aerosol impacts on warm cloud properties were investigated over three major urban clusters in Eastern China

896   and East China Sea using multi-sensor satellite observations (Liu et al., 2017, 2018). In addition to the amount

897 of aerosol, evidence was provided that aerosol types and environmental conditions need to be considered to
898 understand the relationship between cloud properties and aerosols. Aerosol-cloud interactions were found to
899 be more complex and of greater uncertainty over land than over ocean.

901 The atmospheric boundary layer (ABL), and especially its dynamic behavior, is central to the evolution of
902 near-surface air pollution. Using atmospheric observations combined with theoretical arguments, Petäjä et al.
903 (2016) proposed a feedback mechanism connecting ABL properties with PM. According to such mechanism,
904 high concentrations of PM enhance the stability of an urban boundary layer (BL) decreasing its height, thus
905 causing further accumulation of pollution inside BL. Ding et al. (2016a) and Wang et al. (2018b) demonstrated
906 an important role of BC aerosols in this feedback using model simulations combined with observations. A tight
907 connection between the BL height and pollutant concentration, and indications of the presence of the above
908 feedback mechanism, was also found based on comprehensive observations made on a 325-m tower in Beijing
909 (Wang et al., 2020). In line with the proposed mechanism, Shen et al. (2018) showed that aerosol optical
910 properties evolve clearly during the development of multi-day pollution episodes in heavily polluted regions,
911 such as East China:. In order to understand these feedbacks, Kulmala (2018) emphasized the crucial role of
912 continuous, comprehensive measurements on a network of flagship stations in tackling the air pollution
913 problem in urban China and megacities elsewhere in the world. The first such station in China, the SORPES
914 station located in the Yangtze River Delta, has been operating since 2011 (Ding et al., 2016b).

Anthropogenic emissions and environmental pollution in Russia

918 In the complex situation of the plurality of emissions, an important research task remains in the Moscow
919 megacity environment for the assessment of the air quality and potential sources through aerosol composition
920 analyses. Moscow aerosol pollution has been studied using a special AeroRadCity-2018
921 experiment (Chubarova et al., 2019) and satellite data with the application of new MAIAC/MODIS aerosol
922 algorithm with a 1-km resolution (Zhdanova et al., 2020). An advanced source apportionment for this
923 environment was performed using combined Fourier-transform infrared spectroscopy data and statistical
924 principal component analysis (Popovicheva et al., 2020b). The main principal component loadings revealed
925 the source impacts of transport, biomass burning, biogenic, dust and secondary aerosol in spring. Identification
926 of biomass burning-affected periods discriminated the daily aerosol composition change with respect to air
927 mass transport and number of fires detected in the surrounding areas. Measurements of particulate BC were
928 conducted at an urban background site (Meteorological Observatory of MSU) during spring period of 2017-
929 2018 (Popovicheva et al., 2020c). The mean BC concentrations displayed significant diurnal variations, with
930 a poorly prominent morning peak and minimum at daytime. BC mass concentrations were higher at nighttime
931 due the shallow boundary layer and intensive diesel traffic. Aerosol optical thickness (AOT) over Moscow
932 showed a pronounced seasonal cycle, with a summer maximum and winter minimum (Chubarova et al.,
933 2016a). It was found that during 2001–2014, the monthly-mean values of AOT declined by 1–5% per year,
934 and this decline was attributed the decreased emissions of aerosols and their precursors.

In general, the atmospheric environment over remote areas of Siberia and Northern Asia is relatively clean compared with other surrounding regions of Asia and Eastern Europe (Baklanov et al., 2013). However, air pollution from Siberian industrial centers poses significant environmental threats. For Siberian cities (e.g., Norilsk, Barnaul, Novokuznetsk), the air quality is among the worst in the Russian and European cities. Similar to Arctic cities, stable atmospheric stratification and temperature inversions dominate for more than half a year. This leads to pollution accumulation near the surface, and influences ecosystems and people. Moreover, not only severe climatic conditions, but also manmade impacts on the environment in industrial areas and large cities have intensified. The impacts manifest themselves as the pollution of environment, land use changes, hydrodynamic regimes and local climate. Ultimately, these impacts feedback to people affecting their health and well-being.

Although anthropogenic emissions and environmental pollution in the Barents Euro-Arctic region are relatively low in comparison with other industrially developed areas of Europe, there are several severe 'hot spots', mostly in the Russian part of this region. The Kola Peninsula, despite the presence of areas with undisturbed nature in the eastern part, is the most industrially developed and urbanized region in the Russian Arctic. The main polluters are the smelters of the Severonickel (Monchegorsk, central part of the peninsula) and the Pechenganickel (Nickel and Zapolyarnyi near the Russian-Norwegian border) enterprises. For comparison, the emissions of SO_2 only from the Nickel smelter are 5-6 times larger than the total Norwegian emissions (NILU, 2013). In 2015 the Norilsk Nickel in Siberia - the biggest mining and the metallurgical complex - emitted about 1.9 million tons of SO_2 (GGO, 2016). With the nickel factory (located in the southern part of the city), the copper factory (just to its north), and the metallurgical plant (12 km to the east), the city of Norilsk is caught between heavy industry no matter which way the wind will blow. The Blacksmith Institute declared in 2007 that Norilsk is one of the top 10 worst-polluted places in the world. The impacts of emissions are manifested as deterioration of forest ecosystems, acidification of soils and surface waters (Derome and Lukina, 2011), even at considerable distances from the smelters. Heavy metals and alkaline pollutants contaminate areas around the sources of pollution within a few hundred kilometres, while acid sulphates can be transported over long distances (Mahura et al., 2018).

A recent analysis on the total deposition and loading on the population in North-Western Russia and the Scandinavian countries from the continuous sulfur emissions from the Cu-Ni smelters in Murmansk indicates the dominance of wet deposition, especially in winter time (Mahura et al., 2018). North-Western Russia is more influenced by the Severonikel emissions compared to countries of the Scandinavian Peninsula. The cities of the Murmansk region (Kola Peninsula) are under higher impacts. On a yearly scale, the individual loadings on population are at the largest level (up to 120 kg/person) in the Murmansk region, much lower (15 kg/person) in northern Norway, and the smallest (< 5 kg/person) in eastern Finland, Karelia Republic and Arkhangelsk region. Distinct seasonal variability was identified, with the lowest contribution during summer and highest contribution during winter-spring in Russia, spring - in Norway, and autumn - in Finland and Sweden.

973

974 Referring to a "Russian urban emission statistical analysis" for 2017 (GGO, 2019), the highest atmospheric
975 emissions of PM were observed in Siberian and Ural cities. In Novokuznetsk the observed PM was the highest
976 (> 30 000 tons per yr) while emissions from other cities such as Angarsk, Omsk and Chelyabinsk were less (>
977 20 000 tons per yr). For the gaseous compounds, such as SO_2, the maximum emissions included very high
978 from Siberian cities (e.g. Norilsk, Novosibirsk, Novokuznetsk, Omsk, Ufa, Irkutsk, Angarsk) and from North-
979 West European Russia cities (Zapolyarny, Nickel, Monchegorsk). High NO_2 emissions were observed in
980 Novosibirsk, Omsk, Angarsk and Chelyabinsk. The CO integral urban emissions depend on a city size. These
981 varied from less than 10 Gg yr^{-1} (for small regional centers like Vladimir, Kursk, Samara) to 406 and 804 Gg
982 yr^{-1} for large metropolitan areas such as St. Petersburg and Moscow. As a whole, analysis of spatio-temporal
983 variation of the trace gases in the boundary layer over Russian cities indicated significant emission variations
984 between the urban environments and remote sites (Elansky et al., 2016).

985

986 Cities, being not isolated systems, may distribute as much pollution to the surrounding areas as they receive it
987 from the outside or from remote regions. The analysis of the transboundary atmospheric transport between
988 Russian Siberia and bordering countries (e.g. China, Kazakhstan, Mongolia) is part of a mutual risk assessment
989 for urban areas/ cities and their surroundings. For example, city of Ulaanbaatar (Mongolia) suffers from high
990 levels of pollution due to excessive airborne PM emanating from coal combustion mixes with traffic emissions
991 and resuspended soil resulting in variable chemical source profiles (Gunchin et al., 2019). Long-range transport
992 from remote sources might be also additional contributor. Moreover, there are indications (Jaffe et al., 2004)
993 that such transport of biomass burning emissions from Siberia could lead to pollution episodes and impact on
994 surface ozone as far as in western North America.

995

996 2.2.3 Weather and atmospheric circulation (Q6)

997

998 The observed evolution of weather and climate represents the combined effects of external forcing (changes
999 in the concentrations of greenhouse gases and aerosols etc.) and internal variability, related to a large extent to
1000 the atmospheric circulation. It is also affected by local factors, particularly urban heat islands in cities. Here
1001 we discuss these interconnected processes, focusing on cold and warm episodes, cyclone density and
1002 atmosphere-ocean interaction, effects of circulation on temperature and moisture, cloudiness in the Arctic, and
1003 boundary layer dynamics relevant to the Arctic-boreal region.

1004 *Cold and warm episodes*

1005 The Arctic warming, and the Arctic amplification, have been associated with changes in atmospheric large-
1006 scale circulation together affecting the European winter temperatures. In large parts of Europe, severe cold
1007 (warm) winter events are significantly correlated with warm (cold) Arctic episodes (Vihma et al., 2020). Air
1008 mass trajectory analysis revealed that air masses associated with extreme cold (warm) events typically

1046   The effects of large-scale circulation on moisture, cloud and longwave radiation mostly occur through the

1047   impact of horizontal moisture transport (Nygård et al., 2019). Evaporation is typically not efficient enough to

1048   shape those distributions, and much of the moisture evaporated in the Arctic is transported southward (Nygård

1049   et al., 2019). Strong moisture transport events avail a large part of the northwards moisture transport. The

1050   meridional net transport is only a small part of the water vapor exchange between the Arctic and mid-latitudes

1051   (Naakka et al., 2019). When a high-pressure pattern across the Arctic Ocean from Siberia to North America is

1052   lacking, the amount of moisture, clouds, and downward longwave radiation is anomalously high near the North

1053   Pole (Nygård et al., 2019). Using vertically-integrated water vapor as a metric, the Arctic (north of 70°N) has

1054   since 1979 experienced a robust moistening trend that is in absolute numbers the smallest in March and the

1055   largest in August (Rinke et al., 2019). However, the relative trends are the largest in winter. Although different

1056   atmospheric reanalysis are consistent in spatiotemporal trend patterns, they scatter in the trend magnitudes.

1057

1058   Analysis of moisture and aridity estimated using the web-GIS "CLIMATE" and the ECMWF ERA-Interim

1059   reanalysis data for Southern Siberia (50-65 °N, 60-120 °E) from 1979 to 2010 with a $0.75° \times 0.75°$ grid

1060   resolution showed that the mountain regions of Eastern Siberia have been becoming more arid each month

1061   during the last 30 years (Ryazanova and Voropay, 2017). In Western Siberia, aridity increased in May and

1062   decreased in June, while in the other months positive and negative trends were found. The greatest differences

1063   in the trends of the aridity index (Si), air temperature, and precipitation were observed in July.

1064

1065   *Cloudiness in Arctic*

1066

1067   The climatology and inter-annual variability of Arctic cloudiness remains a wildcard in regional climate

1068   change projections. Both climate models and satellite data products need in situ observations for calibration

1069   and validation. Chernokulsky et al. (2017) and Chernokulsky and Esau (2019) collected and processed manual

1070   cloud observations from meteorological stations in the PEEX area. The cloud records in the Arctic are available

1071   since the end of the 19th century. Since 1936, the cloud observations representatively cover the Eurasian Arctic.

1072   It permits reconstructions of cloud type and cloud cover climatology as well as to study inter-decadal

1073   variability of cloudiness. A problem of a special interest is related to co-variability of the total could cover and

1074   sea ice concentration or extent. Both clouds and sea ice affect the surface heat balance through surface albedo,

1075   but their feedback mechanisms, dynamical impacts and climate sensitivities are different. Chernokulsky et al.

1076   (2017) found that the annual-mean total cloud cover (TCO) decreases during warmer climate periods with a

1077   lower sea ice concentration, but increases over sea ice in the Barents Sea as more moisture is transported into

1078   the Arctic at higher temperatures. Furthermore, the increasing TCO reduces deficit of the surface heat and the

1079   intra- and inter-annual variability of TCO over solid ice is higher than that over open water (Chernokulsky et

1080   al. 2017). Long-term cloud climatological analysis based on meteorological observations of the total and low

1081   cloud cover and of the cloud types from the Barents Sea to the Chukchi Sea showed that significant transitions

1082   between cloud types has been taken place especially the low-level stratus and stratocumulus types has been

1083   transformed to the convective cloud types (Chernokulsky and Esau, 2019). Chernokulsky and Esau (2019)

1084 addressed that their results are relevant for understanding Arctic cloud processes and feedbacks, and that new

1085 knowledge is needed to connect the changes in the Arctic radiation balance with the Arctic cloud cover—cloud

1086 type climatology.

1087

1088 *Boundary layer dynamics and urban heat islands*

1089

1090 On the background of accelerated and amplified Arctic warming, anthropogenic heat release and metabolism

1091 of cities add up to persistent warm temperature anomalies in the urbanized areas (Fig. 4). Indeed, if the climate

1092 change forcing approaches 2 W m^{-2}, the urban heat forcing could be 10-100 W m^{-2} (Konstantinov et al., 2018).

1093 The urban heating trapped in the shallow PBLs is potent to rise the local temperatures by 1ºC to 10ºC and even

1094 more. This local climate phenomenon is known as the urban heat island (UHI) (Esau et al., 2020). A series of

1095 *in situ* and satellite UHI studies in the northern cities revealed strong and persistent warm temperature

1096 anomalies in almost all of 28 northern West Siberian cities (Miles and Esau, 2017), in 5 cities covered by the

1097 UHIARC network (Konstantinov et al., 2019; Varentsov et al., 2018a) and in 57 Scandinavian cities (Miles

1098 and Esau, 2020). The mean wintertime temperature anomalies, the UHI intensity, varied from 0.8 K to1.4 K

1099 and had extreme intensities of up to 7 K during cold anticyclone weather conditions. The complete dataset of

1100 surface UHI intensity derived from MODIS LST data products is freely available and published in Miles

1101 (2020). Such a UHI induced strong mediation of cold temperature spells might cause significant socio-

1102 economic and environmental impacts in the cities (Konstantinov et al. 2018, Fig. 4). A survey of other UHI

1103 studies in 11 Arctic cities and towns confirmed that even relatively small cities at high latitudes may exhibit

1104 intensive UHIs. A recent analysis confirms the important role of the surrounding temperature in explaining

1105 spatial-temporal variation of UHI intensity (Miles and Esau, 2017). The major contribution to the UHI was

1106 revealed for water, sparse vegetation, grassland and scrubland. The mechanisms and pathways of the UHI

1107 maintenance requires involvement of numerical experiments with turbulence-resolving models to advance the

1108 understanding of the local climate features (Urban Heat Islands - UHIARC dataset see

1109 http://urbanreanalysis.ru/uhi_arc.html). We would need a denser meteorological network, especially high

1110 quality temperature data, to better understand the urban climatology and the thawing processes in urban soils

1111 and to better assess climatic trends relevant to Arctic societies and welfare (Konstantinov et al. 2018).

1112

1113 Urban climate anomalies may cause more extreme weather and climate phenomena in densely populated

1114 megacities. The Moscow agglomeration – the largest megacity in the boreal continental climate within the

1115 PEEX domain – demonstrates profound effect of interactions between the UHI and urban winds, known as a

1116 cross-over effect (Varentsov et al. 2018b). The UHI creates an urban heat "dome" with near-surface air inflow

1117 into the urban central districts and air outflow at higher levels in the atmosphere. The air uplift in the urban

1118 dome is connected to the increase in summer rainfall at the lee side and over the central urban districts. Stable

1119 atmospheric stratification over rural area is stregthen by the downwind air motions coming from the urban

1120 region.

1121

1122 Atmospheric boundary layer over the Arctic Ocean has been studied on the basis of tethersonde sounding

1123 observations over sea ice (Palo et al., 2017) and research aircraft observations over the open ocean and sea ice

1124 (Suomi et al., 2016). Palo et al. (2017) found that in spring and summer, the occurrence and properties of

1125 temperature inversions were controlled by the surface melt and warm air advection rather than surface net

1126 radiation. During snow/ice melt, temperature inversions were frequently surface-based, and equally strong as

1127 winter inversions over the Arctic Ocean. To better understand atmospheric boundary layer processes in the

1128 Arctic, Suomi et al. (2016) developed a method to measure wind gusts from a research aircraft. It allows wind

1129 gust observations at altitudes not reached by traditional weather mast observations. The observed gust factors

1130 strongly depended on the surface roughness, which differed for sea ice and the open ocean.

1131

1132   2.3   ARCTIC-BOREAL AQUATIC SYSTEM

1133

1134 We discuss the recent results on the Arctic sea ice dynamics and thermodynamics, snow depth and sea ice

1135 thickness, sea ice research supporting navigation, and rare elements in the snow and the ocean sediments,

1136 especially from the perspective of improvements in the observation and modelling methods (Q7, section 3.3.1).

1137 We introduce new results on the Arctic marine ecosystem and focus on the primary production and carbon

1138 cycle (Q8, section 3.3.2.). In section 3.3.3 for the Artic – boreal lakes and rivers, we discuss the browning of

1139 lakes and lake sediment with a special attention on the Selenga River system of Lake Baikal (Q9).

1140

1141 2.3.1 Changing water systems, snow, sea ice and ocean sediments (Q7)

1142

1143 *Sea ice and thermodynamics with atmospheric and ocean dynamics*

1144

1145 Referring to the earlier discussion in section 2.2.3 on atmospheric circulation, we address here how the sea ice

1146 dynamics closely interacts with atmospheric and ocean dynamics. A rapid decrease in the Arctic Ocean ice

1147 cover, particularly in the Barents and Kara Seas, has occurred since the late 1970s simultaneously with a

1148 cooling of winters in central Eurasia (McCusker et al., 2016). This unexpected winter cooling is related to

1149 increasing northeasterly winds over the southeastern flank of an anomalous high that has developed over the

1150 northwestern coast of Russia (McCusker et al., 2016; Mori et al., 2019, Räisänen 2020). However, the causality

1151 between the atmospheric circulation changes and the Arctic sea ice decrease is debated. Observations suggests

1152 a strong correlation between these two, but climate model simulations forced by reduced ice cover produce a

1153 much weaker circulation change than observed, resulting in only weak cooling in central Eurasia (Mori et al.,

1154 2014, 2019; McCusker et al., 2016). This suggests that either most models are underestimating the sensitivity

1155 of the atmospheric circulation to sea ice decrease, supported by Romanowsky et al. (2019), or that the

1156 circulation change has not been primarily caused by decreasing sea ice. In the latter case, the correlation

1157 between the reduced ice cover and atmospheric circulation would mainly reflect the effect of circulation on

1158 sea ice. In support of this, Blackport et al. (2019) showed that reduced sea ice coincides with anomalous heat

1159 flux from the atmosphere to the ocean, and that on the sub-seasonal time scale, anomalies in atmospheric
1160 circulation tend to precede rather than follow those in sea ice. Thus, while reduced sea ice might partly explain
1161 the observed changes in atmospheric circulation (Mori et al., 2019), the effect of circulation on sea ice appears
1162 to be stronger than the effect of sea ice on circulation.

1163

1164 Considering atmosphere-ice interactions, Jakobson et al. (2019) studied the linkages between sea ice
1165 concentration (SIC), atmospheric stratification, surface roughness and wind speed at the 10-m height (W10)
1166 and 850-hPa level (W850). In all the seasons except summer, a reduction in SIC favored reduced atmospheric
1167 stratification and aerodynamic surface roughness, which resulted in a stronger W10. The effect was the
1168 strongest in autumn, and positive trends in W10 and its ratio to W850 typically occurred in regions with the
1169 strongest negative trends in SIC. The relationships were stronger on inter-annual than sub seasonal time scales.
1170 Large-scale atmospheric circulation, characterized, e.g., by the Dipole Anomaly (DA), has also contributed to
1171 sea ice dynamics. A positive polarity in DA has contributed to the recent rapid loss of summer sea ice in the
1172 Pacific part of the Arctic Ocean by bringing warmer air masses from the south and transporting more ice
1173 towards the north enhancing the ice-albedo feedback (Lei et al., 2016). Another example of ice dynamics
1174 affecting the ice-albedo feedback was the weakened Transpolar Drift Stream in summer 2013. It reduced sea
1175 ice transport out of the Arctic Ocean, and restrained ice melt because of the low air temperatures, weakened
1176 albedo feedback, and a relative small oceanic heat flux in the central Arctic (Lei et al., 2018).

1177 Solar radiation, being the main forcing factor for sea ice melt in summer, is difficult to parameterize in
1178 thermodynamic models. This is due to the large variability of the optical properties of sea ice in space and
1179 time. A two-stream model provides a time-efficient parameterization of the apparent optical properties (AOPs)
1180 for ponded sea ice, accounting for both absorption and scattering, and has a potential for being implemented
1181 into sea-ice thermodynamic models to explain the role of melt ponds in the summer decay of Arctic sea ice
1182 (Lu et al. 2016). This model was used to investigate the role of solar radiation in the Arctic sea ice during the
1183 melting season considering layers of melt ponds, underlying sea ice, and ocean beneath the ice. It was found
1184 that the energy absorption profiles depend strongly on the incident irradiance and ice scattering, but only
1185 weakly on the pond depth. It seems that the incident solar energy is largely absorbed by the melt pond rather
1186 than by the underlying sea ice (Lu et al., 2018a).

1187 The model was further applied to investigate the influence of a surface ice lid on the optical properties of a
1188 melt pond. The thickness of the ice lid determines the amount of solar energy absorbed. Visual inspections on
1189 the color of refreezing melt ponds also help to judge the significance of the influence of the ice lid. This will
1190 allow for an accurate estimation on the role of surface ice lid during field investigations on the optical
1191 properties of melt ponds (Lu et al., 2018a). The modelled pond color agrees with field observations from the
1192 Arctic sea ice in summer. The analysis of pond color is a new potential method to obtain ice thickness in
1193 summer, however, more validation data and improvements to the radiative transfer model would be needed
1194 (Lu et al., 2018b).

1195

Snow depth/mass and sea ice thickness

Snowpack on sea ice has a crucial role in insulating the sea ice from the colder atmosphere, accordingly reducing sea ice growth in winter, effectively reflecting the incoming solar radiation, reducing sea ice melt in spring and summer and contributing to its formation. The replacement of snow fall by rain strongly enhances the ice-albedo feedback in the Arctic Ocean (Dou et al., 2019). Shalina and Sandven (2018) refined the description of snow depth on sea ice in the central Arctic, providing new snow depth data for the Arctic marginal seas. High autumn and winter precipitation and thinning Arctic sea ice make snow-ice formation prevalent in the Atlantic sector of the Arctic (Merkouriadi et al., 2017).

Advance has been made in applying thermistor string based autonomous high-resolution Snow and Ice Mass Balance (IMB) Array (SIMBA) buoys to measure snow depth and ice thickness (Figs. 5, 6.). SIMBA has a lower cost, allowing deployment in large numbers (Lei et al., 2015). The determination of snow depth and ice thickness from SIMBA temperature profiles has so far been largely a manual process. A SIMBA-algorithm was developed to process SIMBA data automatically (Liao et al., 2018), assuming a fixed snow-ice interface. Snow-ice formation results in snow-ice interface moving upward. The SIMBA-algorithm was further developed to tackle the moving interfaces (Cheng et al., 2020). The developed SIMBA-algorithm works well in cold condition for lakes and Polar Oceans. For Polar Oceans, the snow and ice are close to isothermal during summer, which prevents the identification of interfaces on the basis of the temperature gradient. Under such conditions, thermodynamic modelling yields valuable information on snow depth and ice thickness (Tian et al., 2017).

A challenge in sea ice thermodynamic modelling is the uncertainty in the magnitude of the oceanic heat flux at the ice base, especially for land-fast sea ice. Yang et al. (2015) applied a one-dimensional thermodynamic model to investigate impact factors on land-fast sea ice in the East Siberian Sea. The modelled snow cover was less than 10 cm, having a small influence on the ice thickness, but surface albedo and oceanic heat fluxes were critical.

Also in the terrestrial Arctic and boreal zone, there is a need for a better efficiency and coverage of an *in-situ* snow observation network. Snow cover and snow mass are fundamental parameters for global energy and water cycles, and the changes in the regional snowpack have societal impacts like on amount of drinking water or capacity for the hydropower generation (Bormann et al., 2018). Snow depth data in the Arctic region are available from the synoptic weather stations and snow mass data are systematically collected from the snow courses, as demonstrated in Extended Data (fig. 2) by Pulliainen et al. (2020). The use of automatic and cost-effective measurements together with harmonized snow measurement practices is the way forward. A survey on a harmonized snow monitoring in Europe demonstrated that crucial parameters for operational services, such as parameters characterizing precipitating and suspended snow, are measured by 74% of the European snow network contributors (COST Action ES1404), but the parameters characterizing the snow microstructural properties, electromagnetic properties and composition are currently measured by only 41%, 26% and 13%, respectively, of the network contributors (Pirazzini et al., 2018). The observations at the

1234 continental scale, so far, demonstrate a widespread snow-cover retreat since the 1970s across the Northern
1235 Hemisphere, particularly in the Arctic (Derksen et al., 2012; Bormann et al., 2018). On the contrary, the results
1236 from the mountains are mixed and there is no consistent picture of what is happening at the regional scale
1237 (Bormann et al., 2018). Pulliainen et al. (2020) provided new insight into the seasonal snow mass and its trend
1238 by using a bias-corrected GlobSnow 3.0 estimates. Pulliainen et al. (2020) is now able to demonstrate different
1239 continental trends based on the 39-year satellite record: a decrease in North America, a negligible trend in
1240 Eurasia, and a high regional variability in both areas.

1241 *Sea ice research supporting navigation*

1242

1243 Recent research has addressed emerging opportunities for Arctic navigation and the importance of operational
1244 sea ice analysis. Lei et al. (2015) is showing the trends along the Arctic Northeast Passage (NEP) and
1245 demonstrates the increase of the spatially-averaged length of the open period (the ice concentration less than
1246 50%) from 84 days in the 1980s to 114 days in the 2000s. The summer sea ice along the High-Latitude Sea
1247 Route (HSR) north of the eastern Arctic islands has also decreased during the last decade, with the ice-free
1248 period reaching 42 days in 2012. The HSR avoids shallow waters along the coast, which easier the access to
1249 for deeper-draft vessels (Lei et al., 2015). Considering operational sea ice analyses for the Bohai Sea, work
1250 has been done to combine thermodynamic modelling and Earth Observation (EO) data from synthetic aperture
1251 radar (SAR) and microwave radiometers (Karvonen et al., 2017). The SAR-based discrimination between sea
1252 ice and open-water works well, and areas of thinner and thicker ice can be distinguished. However, a larger
1253 comprehensive training dataset is needed to set up an operational algorithm for the estimation of sea ice
1254 concentration and for the weighting scheme for sea ice thickness (Karvonen et al., 2017).

1255

1256 Multi-decadal Arctic sea-ice state estimates are important for the strategic planning of Arctic navigation. These
1257 estimates are usually based on climate models with a thermodynamic-dynamic sea-ice models. An up-to-date
1258 assessment of large-scale sea-ice models was with the aid of sea-ice models as a climate model component, a
1259 comprehensive review was carried out by Leppäranta et al. (2020). Specifically, Uotila et al. (2015) found that
1260 a model with the subgrid-scale sea-ice thickness distribution reproduces more realistic sea ice and upper ocean,
1261 due to better captured spring evolution, than a model with just single sea-ice thickness category. In terms of
1262 validity of initial conditions for multi-decadal predictions, Uotila et al. (2019) analyzed a set of ocean
1263 reanalysis products, including Arctic sea ice, and found that the multi-model set mean is a useful product as a
1264 state estimate. This finding increases confidence toward the use of the combination of ocean reanalysis for
1265 both initialization of multi-decadal predictions and analysis of multi-decadal variability.

1266

1267 *Ocean floor and Sediments: composition and fluxes*

1268

1269 A significant content of illite and muscovite among layer silicates in most of the ice-rafted sediments samples
1270 taken from selected Arctic regions suggests that sources of the sedimentary material are mainly mineralogically
1271 similar to modern bottom sediments of the East Siberian and Chukchi seas, as well as presumably sediments

1272   of the eastern Laptev Sea. A significant kaolinite fraction in the samples from the North Pole area can be

1273   caused by the influx of ice-rafted fine-grained sedimentary material from the Beaufort or Chukchi seas, where

1274   kaolinite is supplied from the Bering Sea. The samples contained variable proportions of erosion products of

1275   both mafic and felsic magmatic rocks and/or sufficiently mature sedimentary rocks (Maslov et al., 2018 a).

1276

1277   Quantification of CH_4 sources is fundamental information for the climate change mitigation (Fletcher and

1278   Schaefer 2019). Methane stored in ocean floor reservoirs can reach the atmosphere in the form of bubbles or

1279   dissolved in water. Methane hydrates could destabilize with rising temperature further increasing greenhouse

1280   gas emissions in a warming climate. Subsea permafrost and hydrates in the East Siberian Arctic Shelf (ESAS)

1281   are acting as a substantial carbon pool, and source of methane to the atmosphere. Annual methane emissions

1282   of the region varies from 0.0 to 4.5 $TgCH_4$ yr^{-1} estimated by Berchet et al. (2016). Yasunaka et al. (2018)

1283   estimated the monthly air-sea CO_2 fluxes in the Arctic Ocean and adjacent seas located north of 60 degrees N

1284   for the period 1997 - 2014 and end up to a net annual Arctic Ocean CO_2 uptake of 180 ± 130 TgC per year.

1285

1286   The Zeppelin Observatory data for 2014 suggest CH_4 fluxes from the Svalbard continental platform below 0.2

1287   Tg yr^{-1}. All estimates are in the lower range of values previously reported (Pisso et al., 2016). Platt et al. (2018)

1288   reported a potential region with ocean-atmosphere CH_4 flux locating north of Svalbard but addressed that at

1289   the time of the measurements the meteorological conditions were unique including a short episode of the highly

1290   sensitive to emissions over an active seep site, without sensitivity to land-based emissions.

1291

1292   *River runoff affecting the hydrological processes at coastal marine environments*

1293

1294   The Arctic Ocean (including the Hudson Bay) receives 55.6 % of its river inflow from Russia, mostly via 19

1295   large rivers (Shiklomanov and Shiklomanov, 2003). This freshwater inflow of approximately 2920 km^3 per

1296   year (Shiklomanov, 2008) is associated with large sediment and heat transports, which together affect the

1297   hydrography, marine climate, and ecosystems across the Siberian shelf seas (Magritsky et al., 2018). A major

1298   part of seasonal and interannual variations in river runoff is anthropogenic, due to regulation in large reservoirs

1299   (Georgiadi et al., 2016). In addition, Magritsky et al. (2018) detected an increased runoff trend of 5-10 %,

1300   compared to a reference period of 1936 to 1975, in most of the major Russian rivers discharging into the Arctic

1301   Ocean. The trend is mostly due to a climate-induced increase since the second half of 1980s (Magritsky et al.,

1302   2018). However, due to gaps in the monitoring programs, these estimates have a large uncertainty: focusing

1303   on river discharge from the six largest Eurasian rivers to the Arctic Ocean, estimates of the increase range from

1304   7% (Peterson et al., 2002) to 1.5 % (Shiklomanov and Lammers, 2009).

1305

1306   Permafrost thawing has resulted in releases of old carbon storages, but so far there is no clear evidence on the

1307   impact of permafrost thawing on the net emissions of CO_2 and CH_4 to the atmosphere (IPCC, 2019). A potential

1308   explanation of no or weak net increase is that part of the methane released has been taken by rivers instead of

1309   emitted to the atmosphere. Increased amounts of organic carbon in rivers impact the regional and global

1310   biochemical and methane cycles (Shakhova et al., 2007; Wild et al., 2019). With the accelerating permafrost

1311   thaw, also the atmospheric emissions are expected to increase, in particular for CO_2 but also for CH_4. Expected

1312   future changes in river ice regime are consistent with the expected changes in the duration of the cold season

1313   and accumulated negative air temperatures. Significant changes are expected for the rivers of the Kola

1314   Peninsula and the lower reaches of the rivers Northern Dvina and Pechora, whereas the lowest changes are

1315   expected for the central parts of Eastern Siberia (Agafonova et al., 2017). Due to anthropogenic activities

1316   (above all industry, municipal services, and filling of reservoirs), water withdrawal from Russian Arctic rivers

1317   and related groundwater systems is approximately 20.6 km^3 per year, and it is expected to increase to 37 km^3

1318   per year by 2025 to 2030 (Magritsky et al., 2018). Features of these changes at the marine margin of the Lena

1319   River delta are different compared to changes in the delta head area.

1320

1321   The hydrological representativeness of a glacier is a new characteristic, and of practical importance for basin-

1322   wide tasks of hydrology and glaciology. For its evaluation, it is proposed to replace the seasonal air

1323   temperatures with the glacier summer mass balance (BS) or to include BS in the multiple regression equations

1324   for calculating the runoff of rivers fed by melting of snow and ice. This method can be recommended for at

1325   least of some glaciers in the existing network of the World Glacier Monitoring Service (WGMS) (Konovalov

1326   et al., 2019).

1327

1328   2.3.2 Marine ecology (Q8)

1329

1330   *Living marine organisms weaken or even subdue CO_2 accumulation*

1331   The important climatological role of the world's oceans is to reduce the CO_2 accumulation into the atmosphere

1332   through its absorption. This mechanism is ordinarily viable as the partial pressure of dissolved CO_2 in marine

1333   surface waters is less than the content of CO_2 in the overlying atmosphere. Due to the organic pump, a net

1334   draw down of atmospheric CO_2 into the ocean is put into effect. It proceeds in the process of sinking of

1335   particulate organic carbon of algal origin: organically bound CO_2 is released through remineralization and

1336   further accumulated in the deep ocean. In contrast, owing to the processes of carbonate counter pump, $CaCO_3$

1337   is exported downward and, at depth, dissolves causing a net release of CO_2 to the atmosphere (Balch et al.,

1338   2016). However, there are living marine organisms that are able to weaken or even subdue CO_2 accumulation,

1339   at least within their habitat. Among this group of marine organisms, the leading role belongs to

1340   coccolithophores. Among marine bio systems, coccolithophores (class Primnesiophycea) are most productive

1341   calcifying algae (Taylor et al., 2017). They both produce particulate inorganic carbon (in the form of calcite)

1342   and promote the increase of CO_2 partial pressure (pCO_2) in the ambient marine surface waters. Thus, the

1343   biological activity of coccolithophores can exercise a direct influence on both the CO_2 flux exchange at the

1344   atmosphere-ocean interface and the marine carbonate chemistry system (CCS). The rain ratio, i.e. the ratio of

1345   particulate inorganic carbon to organic carbon, determines the intensity and direction of CO_2 flux at the

1346   atmosphere-ocean interface. In the case of coccolithophores, the rain ratio is above unity within their habitat

1347   area, which potentially can have climatic consequences but also drive alterations in marine CCSs (Balch 2018).

1348

1349   *Emiliania huxleyi* is the most widespread coccolithophorid algal species in Earth's oceans, which, in light of

1350   the above, naturally explains why this is one of the best-studied marine algae. Of all other coccolithophores,

1351   *E. huxleyi* is probably most successful in forming extensive blooms in world-wide marine waters ranging from

1352   oligotrophic to eutrophic. Unlike diatoms and dinoflagellates, this alga is phenomenally immune to both light-

1353   limitation and very high light intensities. As high levels of incident light/irradiances enhance calcification

1354   (which is predominantly a light-dependent reaction), it is supposed that the calcification machinery enables *E.*

1355   *huxleyi* cells to resist photodamage through dissipating excess energy. This specialty is important in case of

1356   nutrient-depleted waters, especially in combination with the high affinity of *E. huxleyi* for nutrients including

1357   nitrogen but especially phosphorous. The property of both mixothropic nutrition, and resistance, at least partial,

1358   to zooplankton grazing and virus attacks (due to cell's coverage by calcite scales/coccoliths) contribute to this

1359   alga ability to sustain a variety of unfavorable conditions and retain steadfastly its ecological niche (Godrijan

1360   et al, 2020). Thus, the elaborate biology of *E. huxleyi* cells imparts to them the intrinsic and rather rare property

1361   of pursuing growth-maximizing and loss-minimizing life strategies. This property reveals itself through

1362   multiple manifestations, two of which are vastness and sustainability of *E. huxleyi* bloom areas. A typical

1363   bloom surface is not less than thousands of square kilometers, but in many marine environments it is far larger

1364   (Kondrik et al., 2018b). For example, in some years, the value of S in the North and Norwegian Sea can be

1365   well above 100 000 km^2, in the Bering Sea maximum bloom area (S) values were registered at 250 000 km^2,

1366   particularly large *E. huxleyi* bloom areas (up to 380 000 km^2) were observed in the Barents Sea (Kondrik et

1367   al., 2017). Within the subpolar and polar zones of the Northern Hemisphere, in the waters around the Great

1368   Britain, in the North, Norwegian, Labrador, Greenland, Barents, and Bering seas *E. huxleyi* blooms occur

1369   annually although with largely varying intensity (Pozdnyakov et al., 2017). The duration of blooms in the

1370   Northern Atlantic and the Barents Sea is on average about three-four weeks. The moment of onset of the *E.*

1371   *huxleyi* bloom area maximum shifts from June-July to September-October for the seas located at the temperate,

1372   subpolar and polar latitudes of the Northern Hemisphere, respectively. This sequence mimics the flow pattern

1373   of the Golf Stream. In the Bering Sea, the temporal pattern of S variations reveals two periods (1998-2001 and

1374   2018-2020) of extraordinary intense *E. huxleyi* outbursts. It is hypothesized that this phenomenon was driven

1375   by massive advection of Fe-depleted North Pacific waters due to a significant weakening of the Alaskan

1376   Current. The latter is supposed to be a teleconnected aftermath of exceptionally strong El Niño events in 1996-

1377   1997 and 2017, respectively (Pozdnyakov et al., 2020).

1378

1379   Satellite-borne estimations made during 1998-2018 showed that *E. huxleyi* outbursts resulted in the release of

1380   inorganic carbon (PIC) in the form of $CaCO_3$ in surface water in the amounts ranging from ~10 to several

1381   hundreds of kilotons. In the Barents Sea, the released PIC content varied between ~100 kt and 250-300 kt,

1382   whereas in the Bering Sea, during the two periods of exceptional activity, the PIC content was as high as 500

1383   kt (Kondrik et al., 2017). There is ample evidence that the release of PIC was accompanied by a significant

1384   increase in CO_2 partial pressure ($\Delta p CO_2$) within the bloom area: between 1998 and 2016, the mean and

1385   maximum values of the ratio $\Delta p CO_2/(\Delta p CO_2)_{background}$, varied in the range ~ (20-40)%, and ~(30- 60)%. The

1386   highest numbers were registered in the Bering and Barents seas (Kondrik et al., 2018a; 2019). Also, there is

1387   space borne evidence for the atmospheric columnar ΔCO_2 enhancement ($\Delta CO_2)_{atm}$ over *E. huxleyi* blooms:

1388   numerous case studies in the aforementioned North Atlantic seas as well as in the Barents and Black seas

1389   proved that ($\Delta CO_2)_{atm}$ could reach 2-3 ppm (Kondrik et al., 2019; Morozov et al., 2019).

1390

1391   Notwithstanding the remarkable ability of *E. huxleyi* to grow under conditions unfavorable for algae of other

1392   functional groups (e.g. diatoms, flagellates, cyanobacteria), a highly irregular pattern of the registered two-

1393   decadal (1998-present) time series of S, PIC, and $\Delta p CO_2$ are indicative of susceptibility of this alga outbursts

1394   to environmental conditions (Nissen et al., 2018; Kazakov et al., 2019; Silkin et al., 2019). Statistical

1395   prioritization of non-biogenic forcing factors (FFs) shows that the latter are sea- and time-period specific

1396   (Pozdnyakov et al., 2019). Thus, in the Barents Sea, sea water temperature (SWT) is the highest-ranked FF,

1397   followed by PAR (photosynthetic active radiation). In the Bering Sea, beyond the aforementioned periods

1398   (1998-2001 and 2018-present), sea surface salinity (SSS) is the FFs leader, with PAR as a runner up, whereas

1399   SWT is only third in the row. Although these assessments are done without explicitly considered nutrients

1400   concentrations (NCs), implicitly NCs were among the FFs. Indeed, arguably, variations in SWT, SSS, CHL,

1401   MLD, and surface current speed/advection (tested as FFs) indirectly account for the variations in NCs as well

1402   in such CCSs parameters as alkalinity and basicity (Durairaj et al., 2015; Pozdnyakov et al., 2019, and

1403   references therein).

1404

1405   In the long run, under conditions of CO_2 steady accumulation in the atmosphere, this factor should be closely

1406   considered (Rivero-Calle et al., 2015). The action of rising atmospheric CO_2 is expected to proceed through a

1407   number of direct and indirect interactions (Fig. 7), both of which should ultimately cause alterations in the rain

1408   ratio. Increase in atmospheric CO_2 leads to rising of global temperature, and further on to strengthening of

1409   stratification, intensification of irradiance within the euphotic zone, cutting of nutrient fluxes from below.

1410   Although the increase of CO_2 fluxes into the surface ocean causes a reduction of pH and CO_3^{2-} levels in water,

1411   the large pool of HCO_3^- remains to support the calcification machinery. Thus, it will lead to the establishment

1412   of environmental conditions unfavorable for non-calcifying phytoplankton (NCP), but beneficial (or at least

1413   endurable) for coccolithophores in general and *E. huxleyi* specifically. Reduction of NCP and uncontested

1414   growth of *E. huxleyi* drives a further reduction in dissolved CO_2 consumption by other groups of

1415   phytoplankton, increase in $p CO_2$ in the surface ocean and intensification of CO_2 fluxes into the atmosphere.

1416   Concurrently, through a system of feedback interactions, alterations in the rain ratio are bound to affect the

1417   carbon fluxes at the water-atmosphere interface. Therefore, the scenario of further heightening of atmospheric

1418 CO_2 in the future, in all probability, implies more vast proliferation of *E. huxleyi* in the world's oceans.

1419

1420   In combination with statistic-based-mathematical models of *E. huxley* blooms (Pozdnyakov et al., 2019), the

1421   available IPCC climate models permit mid-term projections of the forthcoming changes (Gnatiuk et al., 2020).

1422   However, our knowledge on the reciprocal influence of climate change and both the structure and functioning

1423   of marine ecosystems (even at the level of primary producers!) is still insufficient to confidently prognoses the

1424   future dynamics of the *E. huxleyi* phenomenon. More studies are required even to fully understand the

1425   mechanism of intracellular light-dependent reaction of calcification, its dependency on both seawater

1426   carbonate chemistry and environmental FFs (Vihma et al., 2019). Creation of respective multidecadal

1427   databases (as in Kazakov et al., 2019) as well as further delivery of satellite and *in situ*/shipborne/laboratory

1428   data are necessary to improve our capacity to assess with certainty the climatological and ecological role of *E.*

1429   *huxleyi* blooms on regional and global scales (Fig.7).

1430

1431   2.3.3 Lakes and rivers (Q9)

1432   *Organic carbon in lakes*

1433

1434   Spatial variability, an essential characteristic of lake ecosystems, has often been neglected in field research and

1435   monitoring. The detected spatial "noise" strongly suggests that besides vertical variation also the horizontal

1436   variation should be considered in the ecosystem monitoring and, most importantly when the role of dissolved

1437   organic carbon (DOC) on the CO_2 flux is estimated (Manasypov et al., 2015; Leppäranta et al., 2018). In

1438   natural waters with increasing level of colored dissolved organic matter (CDOM) concentration, the water

1439   color is shifted towards brown. The key "permanent" landscape variables, the coverage by lakes and peatland

1440   in the catchment area can be strongly correlated with lake elevation above the sea level. A high lake coverage

1441   indicates a low CDOM concentration, while a high peat coverage indicates the opposite (Arvola et al., 2016).

1442   For example in Finland, recent results from inland water studies have not shown any overall, consistent large-

1443   scale changes in CDOM concentrations over the last 101-year period (Arvola et al., 2017). Rather, CDOM

1444   changes in individual lakes have been related to changes in land use in the drainage basin. Manasypov et al.

1445   (2015) reported results from Siberian lakes, representing discontinuous permafrost zone, and addressed that

1446   although the concentration of most elements in the lakes are lowest in spring, the maximal water coverage of

1447   land made it as an significant reservoir of DOC. The soluble metals in the water column that can be easily

1448   mobilized to the hydrological network.

1449

1450   In very shallow freezing lakes, the volume liquid water is much reduced due to ice growth, and rejection of

1451   nutrients and pollutants in the ice growth causes major enrichment of the water body. This has major

1452   implications to the ecosystem of these lakes (Yang et al., 2016; Song et al., 2019). Freezing rejects some 80-

1453   90 % of the impurities in freshwater lakes. On the other hand, ice cover accumulates atmospheric deposition

1454   over several months but releases them into the water body within one month's melting phase. Rejection of

1455   nutrients and pollutants in lake ice growth causes major enrichment of the water body in shallow lakes and

1456   notable increases in nutrient concentrations in a shallow lake during seasonal ice growth (Fang et al., 2015).

1457

1458   *Lake carbon balance*

1459

1460   Arctic and boreal lakes are an important natural source of CH_4 to the atmosphere (Bastviken et al, 2011).
1461   Methane is mainly produced in the bottom sediments and/or hypolimnion, where most of anaerobic
1462   decomposition of organic matter take place, and then is either oxidized to CO_2 in the water column or emitted
1463   to the atmosphere. At Kuivajärvi, a typical meso humid lake located in Southern Finland, it was found that
1464   91% of available CH_4 was oxidized in the active CH_4 oxidation zone during hypolimnetic hypoxia (Saarela et
1465   al., 2020). In warm springs, the early onset of thermal stratification with cold and well-oxygenated
1466   hypolimnion delays the period of hypolimnetic hypoxia and thus limiting the production of methane. At
1467   Kuivajärvi measured CO_2 fluxes (F-CO2) showed that the lake acted as net source of carbon during two open-
1468   water periods (Mammarella et al., 2015). During day time, with typically high wind speed, shear-induced water
1469   turbulence controls the water-air gas transfer efficiency, and thus enhancing the vertical diffusive fluxes across
1470   the water-air interface. However, during calm nighttime conditions, buoyancy-driven turbulent mixing,
1471   associated with penetrative cooling of surface water, controls the gas exchange, and simple wind speed-based
1472   transfer velocity models strongly underestimate F- CO_2 (Mammarella et al., 2015). Kiuru et al. (2018)
1473   developed a model simulating CO_2 dynamics of a boreal lake in warming climate. The simulations for 2070-
1474   2099 showed a 20–35% increase in the CO_2 flux from the lake compared to the reference period 1980–2009.
1475
1476   *Lake ice cover*
1477   Wei et al. (2016) studied the Lake Inari (67.14 N, 25.73 E), Finnish Lapland, in winters 1980/1981 - 2012/2013,
1478   and observed an increasing trend of the air temperature during the freezing season, associated with an
1479   increasing trend of water precipitation in winter. Low temperature with less precipitation lead to the formation
1480   of columnar ice, while strong winds together with the heavy snowfall favored of granular ice formation.
1481   Karetnikov et al., (2017) analyzed long-term ice conditions of Lake Ladoga, in Russia, in a period of 1913–
1482   2015 and showed that the mean freezing and breakup dates were November 26 and May 15, respectively, and
1483   that the annual frequency of complete freeze over of the lake was 0.83.The period from 1990 to present was
1484   much milder than the preceding years. The annual increase in ice concentration depended on the accumulated
1485   freezing-degree-days (AFDD) and the hypsographic curve, while the ice thickness increased with the square
1486   root of AFDD.
1487
1488   An analysis of a Siberian thermokarst lake located in the Lena River Delta, characterized as a floating ice lake,
1489   showed that temporal dynamics and magnitude of heat fluxes and surface energy balance closures are
1490   substantially different depending on the lake surface conditions (Franz et al., 2018). Sensible heat and latent
1491   heat fluxes, modelled using available heat bulk transfer models (Woolmay et al, 2015; Verburg and Antenucci,
1492   2010; Andreas et al, 2002) tend to underestimate the measured fluxes and show less variability over freezing
1493   ice cover, melting ice in Spring, as well as over open water in Summer. However, the performance of these
1494   models depends also on the accuracy on meteorological and hydrological input parameters, which should be
1495   carefully measured especially during challenging winter conditions.
1496

1497   The seasonal lake ice cover is a sensitive indicator of climate variations in the Arctic (Kirillin et al., 2012;
1498   Lepäranta, 2015). To work more on this question, Lake Kilpisjärvi (surface 37.1 km2, max depth 57 m), a
1499   tundra lake in northern Finland has been under an intensive ice-related field programs in recent years. The
1500   research covered all year but was focused on the melting period in May–June. The heat budget over the ice
1501   season was dominated by the radiation balance. Turbulent fluxes were significant before the freeze-up in fall,
1502   but in the ice season they were small. The evolution of ice thickness served as a very good approximation for
1503   the total surface heat flux (Leppäranta et al., 2017) (Fig.8). In the melting stage, solar radiation, the strongest
1504   forcing of the water body beneath ice cover, breaks the stability and initiates convective turbulent mixing. This
1505   brings heat from the deeper water to ice enhancing melting at the ice bottom (Kirillin et al., 2018). Thus the
1506   common assumption of the heat flux from the water to ice to be due to molecular conduction does not hold in
1507   the melting stage but it is much higher. The ice–water interaction under lake ice has not been well covered in
1508   earlier studies of ice growth and melting.

1509

1510   Ice melting process was studied in detail in Lake Kilpisjärvi. The melting progressed in the upper and lower
1511   surfaces and in the interior, with proportions depending on the solar flux and optical properties of the ice and
1512   therefore case-dependent. About one-third of the solar flux which penetrated the ice returned to ice bottom
1513   providing heat for melting. This was consistent with the under-ice results in Kirillin et al. (2018). In 2013 a
1514   rapid ice breakage event completed the ice breakup in short time with final breakage at the ice porosity 40-
1515   50%. A lake ice melting model should include the thickness and porosity of ice, with porosity connected to an
1516   ice strength criterion (Leppäranta et al., 2019).

1517

1518   *Lake Baikal and Selenga River delta*
1519   The Selenga River, the main tributary of Lake Baikal, has a catchment area of 450 000 km^2 in the boundary
1520   region between Northern Mongolia and Southern Siberia. This area is well known by its climate, land use and
1521   dynamic socioeconomic changes which might have negative impacts on the ecosystems of Lake Baikal and
1522   thus was selected as PEEX field laboratory within PEEX subprogram Selenga-Baikal Network
1523   (www.atm.helsinki.fi/peex/index.php/baikal-selenga-network-basenet. In the recent past hydroclimatic
1524   development both with land use changes lead to contaminant influx from mining areas and urban settlements
1525   increase. Additional hydrological modifications due to the construction of dams and abstractions/water
1526   diversions from the Selenga's Mongolian tributaries could lead to additional alterations (Karthe et al., 2017b).
1527   In addition to Selenga River, a key issue for improved understanding of regional impacts of the environmental
1528   change is to disentangle the influence of climate change from that of other pressures within the catchment
1529   (Lychagin et al., 2017). The PEEX subprogram Selenga-Baikal Network aims at integrated field-based and
1530   modeling knowledge to develop basin-wide conceptual framework of riverine fluxes (Kasimov et al., 2017a;
1531   Karthe et al., 2019).

1532

1533   As a PEEX field laboratory, the regional large-scale assessments made it possible to predict the comprehensive
1534   nature of hydrological and geochemical changes driven by climatic processes and human impacts. Heavy

1535 metals in water and sediments (Kasimov et al., 2020a, 2020b) and fish communities (Kaus et al., 2017) were
1536 measured since 2011 in over 50 locations around catchment. The mining zones are potential hotspots for
1537 increasing metal loads to downstream river systems. Several metals (Al, Cd, Fe, Mn, Pb and V) are exported
1538 from mining sites to the downstream river system, as shown by net increasing mass flows. Based on novel
1539 partitioning coefficient approach (Fig. 9) contrasting patterns with domination of both particulate and dissolved
1540 phases in different parts of the basin were found. Such heterogeneity of metal partitioning is likely to be found
1541 in many large river systems.

1542

1543 Multiscaling modeling ranged from basin wide (Malsy et al., 2017; Frolova et al., 2017) to specific subregions,
1544 like the particular segments of river system (Kaus et al., 2017; Thorslund et al., 2017; Garmaev et al., 2019)
1545 or its delta (Chalov et al., 2017 a, b; Shinkareva et al., 2019), identified reaction of hydrogeochemical pathways
1546 on climate change. Mean flow reduction in the Selenga River by an average of 3-5% in the 2020s-2030s and
1547 4-25% in the 2080s-2090s is the crucial driver of ongoing and future hydrogeochemical change. Increase in
1548 temperatures with permafrost thaw and the expansion of agricultural, mining and urbanization processes may
1549 induce up to 6% increase in the particulate modes and 3% in the dissolved modes of some metals in the river
1550 system (Chalov et al., 2018). Possible changes in the number or magnitude of high-flow events, caused by
1551 climatic or other anthropogenic factors, could influence total sediment deposition, which was primarily found
1552 to occur during relatively short high-flow events. Such potential changes also have important implications for
1553 the possible spreading of polluted sediments (Pietron et al., 2015) and its storage in the Selenga River Delta,
1554 which is an important wetland region forming the geochemical barrier which mitigate pollution of Lake Baikal
1555 by riverine fluxes (Voropay and Kichigina, 2018, Chalov et al., 2015).. The Selenga delta region sequester
1556 various metals bound to Selenga River sediments (Chalov et al., 2015, Pietroń et al., 2018). Water shortage
1557 decreases processes of suspended sediment retention in the delta. The seasonal hydrogeochemical patterns are
1558 explained by wetland inundation during floods and channel erosion or Baikal wind surge during low flow
1559 periods (Chalov et al., 2017a, 2017b).

1560

1561 *Asian water lakes*

1562

1563 The largest internal drainage basins in the world is located in Central Asia with a limited availability of both
1564 surface and groundwater (Karthe et al., 2017a). Since the twentieth century, water resources of the region have
1565 been over exploited and, for example, from small Mongolian headwater streams to the mighty Aral Sea, surface
1566 waters have been partially desiccated. It seems that the implementation of the Integrated Water Resources
1567 Management and water-food-energy nexus approaches would lead to a more environmental-friendly future
1568 (Karthe et al., 2017). The lake-rich Qinghai-Tibet Plateau (QTP) has recently been identified as the Third Pole
1569 of the Earth. Due to its high elevation and unique climate, QTP affects the global and local climate and played
1570 an important role on the Central and Southern Asian water cycle (Zhang et al., 2018). The lake-atmosphere
1571 interactions have been quantified over open-water periods, yet little is known about the lake ice
1572 thermodynamics and heat and mass balance during the ice-covered season. A modelling study for a

1573 thermokarst lake in the QTP has been performed (Huang et al., 2019a). Strong diurnal cycles were seen for all
1574 surface heat fluxes. The ice mass balance was dominated by growth and melt at base, but surface sublimation
1575 was also crucial for ice loss, accounting for up to 40% of the maximum ice thickness and 41% of the lake water
1576 loss during the ice-covered period. Strong penetration of solar radiative flux is the dominant contributor to
1577 high value of upward sensible heat flux at ice bottom resulting a relatively thin ice cover compared with
1578 equivalent high-latitude climate.

1579

1580   2.4   SOCIETY

1581

1582 The anthropogenic impact has been addressed as one of the PEEX themes for the society system. The
1583 discussion on the mitigation and adaptation including urban infrastructure design and risk assessment are
1584 addressed in this context (Q10, section 3.4.1). The social transformations are discussed in terms how local
1585 reindeer grazing interacts with the environment (Q11 section 3.4.2). The adaptive capacity of the Northern
1586 societies depends on their environment, demographic structure and economic capacity, and the environmental
1587 hazards and environmental health under chancing climate are the key research areas in this context (Q12
1588 section 3.4.3.).

1589

1590 2.4.1. Anthropogenic impact (Q10)

1591

1592 *Mitigation*

1593 Artic climate change generates a need for the long-term planning and development of a new socio-economic
1594 infrastructure, such as dams, bridges, roads, transnational and regional energy networks. For this task, new
1595 climate-based forecasting tools, cost estimates and operational risk and other methods and tools for the
1596 infrastructure and urban design are needed. As an example, engineering calculations for maximal discharges
1597 were provided for the Nadym River in Russia (Shevnina et al., 2017). Badina (2018) introduced a method for
1598 the natural risk assessment by using indices based on the on socioeconomic potential data and spatial
1599 distribution of natural hazards. This method has been tested and used to identify the most vulnerable
1600 municipalities in South Siberia. Another example of new methods is a "Green Factor tool" to increase the share
1601 and effectiveness of green areas in urban environments and cities. An ambitious target set in the tool could
1602 encourage or force urban developers to aim higher with the planning of green areas and construction, but
1603 existing regulations challenge its use (Juhola, 2018).

1604

1605 The energy production is of fundamental importance for the society functions, and new clean energy
1606 technologies are needed for hindering the climate change. The potential of hydropower production under
1607 probabilistic projections of annual runoff rate and future changes in the potential hydropower production need
1608 to be evaluated (Shevnina et al. 2019). All the Nordic countries are vulnerable to various degrees to potential
1609 cross-border impacts, due to their energy sectors being highly globalized and interconnected. However, cross-

1610 border impacts are not yet properly included in Nordic climate assessments or energy strategies. The EU's new

1611 Green Deal is pivotal in this respect, as for the first time emissions along the whole supply chain (oil, gas, coal,

1612 renewables) become under scrutiny and part of normative governance. Therefore, policy makers and energy

1613 planners should be assisted in making comprehensive vulnerability assessments that address both domestic

1614 and international climate risks (Groundstroem and Juhola, 2019).

1615

1616 2.4.2 Environmental impact (Q11)

1617

1618 *Reindeer (Rangifer tarandus L.) grazing and ground vegetation structure and biomass*

1619

1620 Reindeer (*Rangifer tarandus L.*) grazing in the North affects the ground vegetation structure and biomass and

1621 cover of lichens. It seems that reindeers affect GHG fluxes from the forest field layer. Grazing changes affect

1622 the vegetation composition and thereby emissions (Köster et al., 2018). Köster et al. (2017) provided detailed

1623 information on soil CO_2 effluxes, which were mostly affected by the year of measurement, time of

1624 measurement, soil temperature and also by the management, resulting in higher CO_2 emissions on the grazed

1625 areas. Soil moisture content did not affect the soil CO_2 efflux. For example, in the Finnish Lapland the average

1626 soil CO_2 efflux values were significantly higher in the year 2014 compared with 2013, mainly due to

1627 differences in soil temperature at the beginning of the season (Köster et al., 2017). Furthermore, grazing

1628 significantly decreased the biomass and cover of lichens and also the amount of tree regeneration. In a subarctic

1629 mature pine forest, grazing did not affect the soil temperature or soil moisture. No statistically significant effect

1630 of grazing on the soil CO_2 efflux, soil C stock or soil microbial C biomass was found. Soil microbial N biomass

1631 was significantly lower in the grazed areas compared to the non-grazed areas. It seems that in the boreal

1632 subarctic coniferous forests, grazing by reindeer can be considered as "C neutral" (Köster et al., 2015). There

1633 is also indication that reindeer grazing affects the boreal forest soils e.g. their fungal community structure and

1634 litter degradation (Santalahti et al., 2018).

1635

1636 2.4.3 Natural hazards (Q12)

1637

1638 Under this theme, the PEEX research has so far focused on environmental health issues. These include

1639 diseases, the impact of UV radiation, and air pollution in urban environments. The spread of diseases caused

1640 by living pathogens is basically determined by environmental conditions. Medico-geographical assessments

1641 are usually based on identification of the links between the spread of diseases and factors of the geographical

1642 environment.

1643

1644 *Naturally-determined diseases*

1645 The climatic factor is deemed one of the main determinants for the spread of naturally-determined diseases

1646 (Malkhazova et al., 2018). Emerging zoonotic diseases are expected to be particularly vulnerable to climate

1647 and biodiversity disturbances. Anthrax is an archetypal zoonosis that manifests its most significant burden on

1648 vulnerable pastoralist communities. The recent findings highlight the significance of warming temperatures
1649 for anthrax ecology in northern latitudes, and suggest potential mitigating effects of interventions targeting
1650 megafauna biodiversity conservation in grassland ecosystems, and animal health promotion among small to
1651 midsize livestock herds (Walsh, et al., 2018).
1652

1653 *UV variations*
1654 Different geophysical parameters affecting the UV molecular number density show that especially at high
1655 altitudes, the increased surface albedo has a significant effect on the UV growth. The new parameterization of
1656 the on-line UV tool (*momsu.ru/uv/*) for Northern Eurasia allows us to determine the altitude dependence of
1657 UV and to estimate the possible effects of UV on human health considering different skin types and various
1658 open body fraction for January and April conditions in the Alpine region (Chubarova et al., 2016b). Using UV
1659 satellite retrievals, ERA-Interim data and the INM-RSHU chemistry-climate model, the changes in UV
1660 irradiance and UV resources were estimated over Northern Eurasia for the 1979-2015 period, demonstrating a
1661 significant UV increase over vast areas (Chubarova et al., 2020). Referring to long-term UV measurements
1662 and model simulations in Moscow, a statistically significant positive trend of more than 5% per decade since
1663 1979 was evaluated (Chubarova et al., 2018).
1664

1665 *Air pollution and related health effects*
1666

1667 Street-level urban air pollution is one of the key topics of urban environments. In Norway, Bergen, the most
1668 extreme cases of repetitive wintertime air pollution episodes, followed by increased large-scale wind speeds
1669 above the valley, were transported by the local re-circulations to other less polluted areas with only slow
1670 dilution. This observation is underling the need for a better described assumptions e.g. transport paths, weak
1671 dispersion of classical air pollution dispersion models leading to better improved air quality forecasts in urban
1672 areas. (Wolf- Grosse et al., 2017b). A link between the persistence of the flow above the Bergen valley and
1673 the occurrence and severity of the local air pollution episodes was found. Analysis of the large-scale circulation
1674 over the North Atlantic-European region, with respect to air pollution in Bergen, revealed that the persistence
1675 in the meteorological conditions connected to the air pollution episodes is not necessarily caused by large-
1676 scale anomalies of the atmospheric circulation over the Norwegian west coast. It is rather connected to
1677 anomalies further upstream as far away as Greenland. (Wolf-Grosse et al., 2017a).
1678

1679 In Russia, especially intensive atmospheric pollution cases have severely impact the environment and human
1680 health. Popovicheva et al (2019b) analyzed the Tver region, north of Moscow, which was considerably affected
1681 the secondary organic aerosol (SOA) formation originated from long-lasting peat bog fires. Spectral
1682 absorbance characteristics were similar to peat burning and traffic source emissions during fire and non-fire
1683 related days and confirmed the effect of transported peat smoke on air quality in megacity environment
1684 (Popovicheva et al., 2019b). Popovicheva et al. (2019b) also showed that the impact of the long-term transport
1685 from the North-West Russia and Scandinavian on the local populations. Murmansk and Arkhangelsk are

1686 heavily altered by the emission coming from the local Cu Ni smelters. The individual loadings on population
1687 can be up to 120 kg/person/year for the Murmansk region, but clearly less, 15 kg/person/year, in the northern
1688 Norway, and only 5 kg/person/year in the eastern Finland. The largest loadings were observed during winter-
1689 spring in Russia, during spring in Norway, and during autumn in Finland and Sweden.
1690
1691 Local Arctic air pollution alone can seriously affect public health and ecosystems locally, especially in
1692 wintertime when the pollution can accumulate under inversion layers (Schmale et al., 2018a). We need more
1693 research on the contributing emission sources and the relevant atmospheric pollution mechanisms, and more
1694 detailed epidemiological or toxicological health impact studies in the Arctic. Socioeconomic changes
1695 (shipping, tourism, natural resources extraction, increasing number of population) are already taking place in
1696 the Arctic, and they will increase in the future. It is also expected that the emission types and magnitudes will
1697 increase the number of exposed individuals (Arnold et al., 2016). There is still a large variation in the amount
1698 of the location of emissions. Future predictions are even more difficult due to the yet unknown development
1699 of the Arctic economic activities and their emissions (Arnold et al., 2016, Schmale et al., 2018 a,b).
1700
1701 **3. SYNTHESIS AND FUTURE PROSPECTS**
1702
1703 3.1 Future research needs from the system perspectives
1704
1705 For the Land ecosystem, the recent progress towards understanding of the Northern Eurasian Arctic - boreal
1706 land ecosystems (section 3.1) are dealing with the improved methodologies relevant to land processes (Q1),
1707 observations on permafrost thawing (Q2), and observed changes in the Northern ecosystems, especially soil
1708 conditions (Q3).
1709
1710 Improved satellite-based methods and (validation) data together with better quantification and, especially, the
1711 scaling of the gross primary production are enabling a better identification and quantification of Earth surface
1712 characteristics and ecosystem carbon balance compared with the earlier capacity (Gurchenkov et al., 2017,
1713 Rautiainen et al., 2016, Nitzbon et al., 2019, Boike et al., 2019, Terentieva et al., 2016), Zhang et al, 2018,
1714 Pulliainen et al., 2017, Matkala et al., 2020; Bondur and Chimitdorzhiev, 2008 a,b). Intensive research has
1715 been carried out on the quantification of the gross primary production (GPP), a key variable for biological
1716 activity, in different conditions and at different scales (Pulliainen 2017, Kulmala et al., 2019, Matkala et al.,
1717 2020). Further investigations are called for more detailed understanding of the seasonal dynamics of the
1718 biological activity.
1719
1720 The Northern Eurasian ecosystems' tipping points are related to multiple simultaneous stress factors. The key
1721 stress factors here are permafrost thawing and the factors important for ecosystem, such as prolongation of
1722 growing season, increase in mean temperature of growing season and the forest fires (Kukkonen et al. 2020,
1723 Biskaborn et al. 2019, Payne et al., 2016. Köster et al. 2016, Miles and Esau 2016, Miles et al., 2019). New

1724   evidence on the progress of permafrost thawing in Siberia has been introduced by Kukkonen et al. (2020) and

1725   Biskaborn et al. (2019). The permafrost thawing is also triggering yet not clearly-known processes related to

1726   changing fluxes, ecosystem processes and greenhouse gas sink and source dynamics (Schuur et al., 2008,

1727   Thomson et al., 2017, Commane et al., 2017, Euskirchen et al., 2017, Dean et al., 2018, Thonat et al., 2017).

1728   The progress affecting permafrost thawing is not yet analyzed in detail. For example, we need more

1729   information on the dynamics how the thawing processes vary between soil types due to differences in water

1730   movement and, in the winter time, how the snow cover affects the ground surface temperature (Bartsch et al.

1731   2010). In addition to permafrost processes, the recent advances in observed changes in the Northern ecosystem

1732   reveal the significant role of soil processes in biogeochemical cycles, especially the nitrogen cycle (Voigt et

1733   al., 2016, Pärn et al., 2018). Knowledge of the soil microbiological composition and the effect of forest fires

1734   have been improved (Köster et al., 2015, 2016, Zhang-Turpeinen et al., 2020), but further research is called

1735   for vegetation changes influencing the below-ground microbiology, its composition and enzymatic activity

1736   (Payne et al., 2016. Köster et al. 2016). The NDVI methods have made it possible to detect vegetation changes

1737   (Miles and Esau 2016). A range of vegetation cover changes in Siberia have been reported, such as the Arctic

1738   greening and browning processes, but e.g. the greening of Siberian cities remains an issue of intensive research

1739   also in the future (Miles and Esau 2016, Miles et al., 2019).

1740   For the Atmospheric system, the recent progress in understanding the Northern Eurasian Arctic - boreal land

1741   atmospheric system and the aspects of the megacity air quality (section 3.2) are dealing with atmospheric

1742   composition changes (Q4), key feedbacks between climate and air quality (Q5), and synoptic scale weather

1743   (Q6). Recent results demonstrate improved quantification of the carbon balance and CO_2 fluxes and

1744   concentrations due to land use changes (Pulliainen et al., 2017, Karelin et al., 2017, Rakitin et al., 2018,

1745   Skorokhod et al., 2017, Alekseychik et al. 2017), forest fires in Siberia, and new understanding of aerosol

1746   sources and properties in the Arctic environment and across the Northern Eurasia. However, most of the results

1747   deal with atmospheric aerosol chemistry and physics in boreal and Arctic environments originating from

1748   measurements in the few flagship stations in Finland and Russia (Kerminen et al., 2018, Wiedensohler et al.,

1749   2019, Freud et al., 2017, Paasonen et al., 2018, Östrom et al., 2017, Kalogridis et al., 2018, Bondur et al., 2016,

1750   Bondur and Ginzburg 2016, Bondur et al, 2019 c,d, Bondur and Gordo, 2018; Mikhailov et al., 2017, Breider

1751   et al., 2017), indicating the need for a comprehensive station network in the PEEX region. Black carbon emitted

1752   by the Siberian forest fires and some other sources, and its long range transport to the Arctic, are also widely

1753   discussed (Kalogridis et al., 2018, Bondur et al., 2016, Bondur and Ginzburg 2016, Mikhailov et al., 2017,

1754   Breider et al., 2017, Shevchenko et al., 2015, Konovalov et al., 2018, Marelle et al., 2018). In addition,

1755   measurements of ozone in the troposphere and stratosphere have provided insight into atmospheric chemistry

1756   in urban environments (Skorohod et al., 2017), UV radiation and human health (Chubarova et al., 2019).

1757   Environmental health, including the impacts of air quality (black carbon) and UV radiation, is foreseen as a

1758   high momentum research topic in the PEEX domain, and further research is called for in this area.

1759

1760   The impact of air pollution was found to vary from serious effects on population health and ecosystem

1761   processes to large-scale interactions with climate. We reported several new results on the dynamics between

1762   the haze pollution and boundary layer meteorology in enhancing air pollution in megacity environments (Zhao
1763   et al., 2017, Ding et al., 2016a, Wang et al., 2018b, Bai et al., 2018a, Ye et al., 2017). The long-term and
1764   comprehensive measurements carried out especially at the SORPES station in Nanjing provide valuable data
1765   pools for such studies (Ding et al., 2016a). However, the backbone of the recent progress has been based on
1766   improved on-line atmospheric measurements and the use of machine learning methods combined with different
1767   methodologies, such as back trajectories together with the lidar and radiosonde data. In addition, improved
1768   models of emission inventories together with the ECHAM-HAM and GAINS models have led to better
1769   quantification of the aerosol number emissions. New knowledge has enabled introduction of new theoretical
1770   arguments on the feedbacks between high aerosol concentration and the urban boundary layer (Petäjä et al.
1771   2016). New measurements have also been obtained from Siberian cities (Elansky et al., 2016, Chubarova et
1772   al., 2016a, Mahura et al., 2018). However, we are still in the early phase of having a holistic picture of large-
1773   scale feedbacks due to the lack of long-term, comprehensive measurements in these regions.

1775   Changes in the atmospheric dynamics in the North have potential impacts on short-term local/regional and sub
1776   seasonal to seasonal large-scale weather predictions, and on long-term projections on biogeochemical systems.
1777   It is therefore crucial to understand changes in boundary-layer processes as well as synoptic- and large-scale
1778   circulation in the Arctic and Northern Eurasia. Recent results show potential, but causally arguable,
1779   connections between the alarming sea ice decline, evaporation, cloudiness, atmospheric circulation and
1780   moisture transport as well as Arctic and European winter temperatures (Nygård et al., 2019, Rinke et al., 2019,
1781   McCusker et al., 2016, Mori et al, 2014, Blackport et al., 2019; Cohen et al., 2020). Further investigations are
1782   called for atmosphere-ice-ocean interactions, coupling between small-scale processes (such as clouds and
1783   turbulence) and synoptic-scale weather, as well as for polar prediction and extreme events. Furthermore, more
1784   quantitative knowledge is needed on pan-Arctic energy budgets (Spengler et al., 2016). The urban heat island
1785   (UHI) phenomena taking place in Arctic cities has received an increasing attention, and there is a special need
1786   for improved forecasting services for Arctic cities (Miles and Esau 2017, Konstantinov et al., 2018, Varentsov
1787   et al., 2018b).

1789   For the Water system, we discussed the Arctic sea ice dynamics and thermodynamics, snow depth and sea ice
1790   thickness, sea ice research supporting navigation, and rare elements in the snow and the ocean sediments,
1791   especially from the perspective of improvements in the observation and modelling methods (Q7, section
1792   3.3.1.). New evidence on atmosphere – Arctic sea ice interactions have been provided by Lei et al. (2018), and
1793   Jakobson et al. (2019). Lei at al. (2018) analyzed how the climate warming would affect the winter growth
1794   rate of thin and thick ice, and Jakobson et al. (2019) gave new insight into the relation between sea ice
1795   concentration and the wind speed. Furthermore, advance has been made in understanding the thermodynamics
1796   and metamorphosis of the snowpack on sea ice and their interactions with surface albedo changes (Dou et al.,
1797   2019). Operational sea ice analysis is increasingly important for the Arctic shipping and navigation (Lei et al.,
1798   2015, Karvonen et al., 2017). New results on rare elements, mineral composition and CO_2 and methane fluxes
1799   associated with ocean sediments have been attained (Maslov, et al., 2018, Yasunaka et al., 2018). This serves

1800   as important information for mitigation plans, as well as for new estimates on the river runoff and discharge

1801   in Russian rivers into the Arctic seas (Grigoriev and Frolova 2018, Agafonova et al., 2017).

1802

1803   The marine Arctic ecosystems are under a progressive increase of anthropogenic impacts, the main issues

1804   calling for better understanding are the integrated effect of Arctic warming, and ice and snow melt, ocean

1805   freshening, air quality and acidification of the Arctic marine ecosystems, primary production and carbon cycle

1806   (Q8, section 3.3.2). Quantitative information about the CO_2 accumulation into the ocean is having a high

1807   momentum. Marine organisms, such as coccolithoprip algae, are influencing the CO_2 flux exchange (Kondrik,

1808   et al., 2018b, Pozdnyakov et al., 2017). In addition to changing marine environments, the Artic – boreal lakes

1809   and rivers may undergo changes in flooding, increasing the amount of fresh water and allochthonous materials

1810   (Q9, section 3.3.3). In addition to the Arctic Ocean, the ice and snow conditions of Northern lakes are under

1811   pressure. Lake Kilpisjärvi (Finland) (Arvola et al., 2017, Leppäranta et al., 2017) and Lake Ladoga (Russia)

1812   (Karetnikov et al., 2017) have been under intensive research, and the recent results demonstrate changes in

1813   heat fluxes, ice cover periods and stratification. The browning of lakes and lake sediments were discussed, and

1814   new results were attained from the Selenga River of the Baikal Lake. Dramatically changes will be expected

1815   in the water runoff and amount of dissolved modes of metals, also having serious impact on the environmental

1816   health (Chalov et al., 2015, 2016, 2017 a, 2017b , Karthe et al., 2017 a, 2017b). As a comparison to the Northern

1817   high latitudes, we also discussed freezing lakes in Central Asia, where the climate is cold and arid. There the

1818   ice is typically snow-free or possesses only a thin snow cover, allowing penetration of sunlight into the water

1819   body (Huang et al., 2019).

1820

1821   For the Societal system, the anthropogenic impact has been addressed as one of the main themes (Q10). The

1822   discussion on the mitigation and adaptation, including the urban infrastructure design (Juhola 2018) and risk

1823   assessment, were addressed in this context (section 3.4.1). In social transformations, a special attention was

1824   given to one of the most important local livelihoods in Lapland: reindeer grazing and how it interacts with the

1825   environment (Q11 section 3.4.2). The adaptive capacity of the Northern societies rest on their environment,

1826   demographic structure and economic activities (Q12). Referring to the earlier statement about the future

1827   research needs for the Atmospheric system with respect to environmental health, here again we would like to

1828   put an increasing attention to environmental health under changing climate, including the spread of diseases

1829   and air pollution and their combined effects (section 3.4.3.).

1830

1831   3.2 Feedback mechanisms under changing climate, cryosphere conditions and urbanization

1832

1833   During the recent years, Kulmala et al. (2004, 2020) have focused on the quantification of the COntinental

1834   Biosphere-Aerosol-Cloud-Climate (COBACC) feedback loop relevant to Northern Eurasia boreal region.

1835   Previous results on the COBACC feedback loop are addressing the role of BVOC emission dynamics (Arneth

1836   et al., 2016). Both higher temperatures and increased CO_2 concentrations are (separately) expected to increase

1837   emissions of biogenic volatile organic compounds (BVOCs). It also seems that the GPP is controlled by the

1838   BVOC effects on the clouds. Sporre et al. (2019) used an Earth System model to estimate aerosol scattering

1839   due to enhanced BVOC emissions and estimated the associated negative direct radiative effect (-0.06 W m^{-2}).

1840   The total global radiative effect associated with this feedback was estimated to be -0.49 W m^{-2} (Sporre et al.,

1841   2019), indicating that it has the potential to offset about 13 % of the forcing associated with a doubling of CO_2.

1842   The direct effect of aerosol on GPP due to an increase in the fraction of diffuse radiation was estimated between

1843   6 and 14% increase in GPP at maximum observed aerosol loading compared to low aerosol loading in Northern

1844   Eurasia forests (Ezhova et al., 2018b).

1845

1846   The results from the Tibetan plateau demonstrate notable feedbacks between vegetation, BVOC emissions and

1847   aerosols. Historical wetting of the TP region has increased the vegetation cover, allowing for feedback

1848   processes via biogenic aerosol formation and aerosol-cloud-precipitation interactions. A significant wetting

1849   trend since the early 1980s in Tibetan Plateau is most conspicuous in central and eastern Asia. Fang et al.

1850   (2019) hypothesized that the current warming may enhance emissions of biogenic volatile organic compounds

1851   (BVOC), which can increase secondary organic aerosols concentrations, contributing to the precipitation

1852   increase. The wetting trend can increase the vegetation cover and has a positive feedback on the BVOC

1853   emissions. The simulations suggest a significant contribution of increased BVOC emissions to the regional

1854   organic aerosol mass and the simulated increase in BVOC emissions is significantly correlated with the wetting

1855   trend in Tibetan Plateau.

1856

1857   To estimate the net effects of various feedback mechanisms on land cover changes, photosynthetic activity,

1858   GHG exchange, BVOC emissions, formation of aerosols and clouds, and radiative forcing (Q14) calls for

1859   intensive collaboration and integration between the Arctic Ocean sciences and terrestrial sciences across the

1860   Pan-Arctic domain and across the Arctic and high-latitude domain. The Arctic greening and browning (section

1861   3.1.3.) call for a multi-disciplinary scientific approach, improved modelling tools and new data to deeply

1862   understand the biosphere-atmosphere-anthroposphere interactions and feedbacks. Petäjä et al. (2020a, 2020b)

1863   discussed the complexity of feedbacks, especially at the Arctic context, and the interplay between the

1864   temperature, GHG, permafrost, land cover and water bodies and between photosynthetic activity, aerosols,

1865   clouds and radiation budget. The current downturn of the arctic cryosphere (*section 3.1.2*), together with the

1866   changes in sea ice dynamics and glaciers and the permafrost thawing, affects the marine and terrestrial carbon

1867   cycles in interconnected ways (section 3.3.1). Parmentier et al. (2017) discussed the changing arctic cryosphere

1868   and how the processes in the ocean and on land are too often studied as separate systems, although the sea ice

1869   decline connects the rapid warming of the Arctic, Arctic Ocean marine processes and air–sea exchange of CO_2.

1870   Thus, the future priorities would be on the development of our modelling tools towards all-scales modelling

1871   approach to cover the feedbacks, processes and interactions at the land–ocean interface and also in urban

1872   environments in the Arctic region. We also need to support the further development of the ground-based

1873   observation networks.

1874

3.3 Climate scenarios for the Arctic-boreal region

Climate scenarios set the urgency for the mitigation and adaptation actions for the Northern Eurasian region. The Arctic-boreal region combines an area of both amplified climate change (Arctic amplification) and large diversity in the model predictions (Collins et al., 2013, Hoegh-Guldberg et al., 2018). Under the "low-to-medium" RCP4.5 forcing scenario (van Vuuren et al., 2011), the CMIP5 multi-model mean temperature changes during the 21st century indicate the strongest winter-time warming of >5 °C in the Arctic Ocean, whereas the majority of the terrestrial region will warm by 2–4 °C (Fig. 12). Even during summertime, the continental warming over the region will generally exceed 2 °C. It is important to note that the diversity of model projections is accentuated over the Arctic and Northern Eurasian domain: the mechanisms behind the Arctic amplification are implemented in varying details in the distinct models, and the associated interactions and feedback processes provide a diverse picture of the future in the Arctic-boreal regions.

In addition to considerable trends in atmospheric temperatures, the models further indicate prominent changes in precipitation (Collins et al., 2013, Hoegh-Guldberg et al., 2018). For the Arctic boreal region, this is largely depicted as an increasing rainfall during both winter and summer, extending to 15-25% over most of the terrestrial domain over the winter and somewhat less during summer (Fig. 10). Contemporary warm Arctic temperatures and large sea ice deficits (75% volume loss) demonstrate climate states outside our previous experience. The modeled changes in the Arctic cryosphere demonstrate that even limiting the global temperature increase to 2 °C will leave the Arctic a much different environment by mid-century, with less snow and sea ice, melted permafrost, altered ecosystems, and a projected annual mean Arctic temperature increase of +4 °C. Even under ambitious emission reduction scenarios, high-latitude land ice melt, including Greenland, are foreseen to continue due to internal lags, leading to accelerating global sea level rise throughout the century (Overland et al., 2019).

4. CONCLUDING REMARKS

Only the integration of different observing networks and programs into an inter-operable and integrated observation system can provide data needed for understanding the mechanisms of the Arctic-boreal system. There is a fundamental need for an integrated, comprehensive network of the-state-of-the art *in situ* stations measuring Earth surface – atmosphere interactions (Kulmala et al., 2016a, 2018; Uttal et al., 2016; Hari et al., 2016; Alekseychik et al., 2016; Vihma et al. 2019). The results obtained in the Pan Eurasian Experiment (PEEX) programme in Russian and China introduced in this paper are based on a combination of long-term observations and campaign data. In addition, the Arctic marine region require comprehensive observations and subsequent synthesis, as these regions are under a lot of environmental stress. Therefore, we need more *in situ* observations of the Artic system covering the marine atmosphere, sea ice and ocean. However, there are pronounced technological and logistical challenges to setup such continuous, marine *in situ* observations (e.g. Vihma et al. 2019). Furthermore, improved monitoring is needed for river discharge and associated fluxes of

1913   greenhouse gases and other key compounds and more research on the understanding of coastal processes and

1914   atmospheric transport and specific regional socioeconomic issues and their interactions with changing

1915   environment (Vihma et al., 2019; Petäjä et al., 2020).

1916

1917   The international organizations and bodies like the Arctic Council (SAON's Roadmap for Arctic Observing

1918   and Data Systems, ROADS), EU Horizon2020 (Blue Growth INTAROS and APPLICATE projects), GEO-

1919   CRI (high Mountains and cold regions), the Belmont Forum COPERNICUS and WMO are coordinating

1920   development of the Arctic data and services. New data products are expected from the large-scale MOSAiC

1921   campaign and projects like ERA-PLANET iCUPE (Petäjä et al. 2020b) or ArcticFLUX to monitor interface

1922   between the marine Arctic - Eurasian continent. Also, national-based Arctic observations and research

1923   programs like AC^3 by German institutes play a significant role. Russia conducts extensive research in the

1924   Arctic region, notably on the manned drifting ice stations. These Arctic observation activities are coordinated

1925   and carried out by Roshydromet, universities and Russian Academy of Sciences' institutes.

1926

1927   Concerning global energy markets, the Artic region holds 25 % or more of the world's undiscovered oil and

1928   gas (Arctic Oil & Gas, 2008). The plans of China and Russia to build 'Ice Silk Road' along Northern Sea

1929   linking the China and Russia to Europe is highlighting the polar region's growing economic and strategic

1930   importance, and the increasing pressure on the Arctic environment and local communities. In addition, wide

1931   regions of the high latitudes and Arctic regions are under the pressure of the changing economic activities of

1932   the Arctic and are also under a high pressure of the changing environment and climate. A comprehensive

1933   observation network providing in-situ data in close coordination with satellite observations and ground-based

1934   remote sensing is required to monitor the environmental impacts of the envisioned operations.

1935

1936   Over the last few years, Earth system sciences is driven by the need to understand the scientific processes of

1937   climate change and air quality, their interrelations with Earth system and their societal impacts. The interplay

1938   between science, politics and business, and the analysis of the existing policies and strategies help us to

1939   recognize and analyze new and emerging trends of Arctic governance (e.g. protection and resilience vis-a-vis

1940   economic activities), geopolitics (e.g. state sovereignty vis-a-vis internationalization), geo-economics (e.g.

1941   tourism vis-à-vis reindeer herding), and science (e.g. climate change). The intensive work towards the new

1942   Arctic observations and data systems, together with the intensive observations on the land –atmosphere

1943   interactions taking place at the high latitudes, will provide the baseline for cross disciplinary research era.

1944   PEEX is aimed for these directions.

1945

1946   **ACKNOWLEDGEMENTS**

1947

1948   We thank the following funding agencies and projects: Academy of Finland contracts: No 280700, 294600,

1949   296302 (Novel Assessment of Black Carbon in the Eurasian Arctic: From Historical Concentrations and

1950   Sources to Future Climate Impacts (NABCEA), 307331 (FCoE Atmospheric Sciences), 311932, 314798/99,

315203, 317999, 337549 (Atmosphere and Climate Competence Center (ACCC), Jane and Aatos Erkko
Foundation, Russian Foundation for Basic Research (RFBR) projects No. 17-29-05027 (Selenga-Baikal river
system), 17-29-05102, 18-05-00306, 18-05-60037, 18-05-60219 (Arctic river), 18-35-20031, 18-44-860017,
18-45-700015, 18-05-60083 (Storm activity in the Barents Sea), 18-60084 (Dangerous impacts of large - scale
industrial emissions on aerosol pollution and Arctic ecosystem), 19-05-50088, 19-05-00352, 19-55-80021
(MOST and DST studies), the IAO SB RAS supported by RFBR project No. 19-05-50024, Russian Science
Foundation (RSF) projects No.17-17-01117, 18-17-00076 (Long-term measurement of aerosol chemical
composition in Central Siberia, 19-77-20109, 19-77-30004 (Moscow environment), 19-77-300-12
(Measurement networks and field sites in Kola Peninsula), Yugra State University grant No.13-01-20/39,
Ministry of Science and Higher Education of Russia - Agreement No.13.1902.21.0003, State assignment No.
0148-2019-0006, European Research Council (ERC) projects No. 742206 (ATM-GTP), No. 850614
(CHAPAs), EU Horizon 2020 projects No. 727890 (Integrated Arctic Observing System, INTAROS), 689443
(Integrative and Comprehensive Understanding on Polar Environments, iCUPE), 654109 (Aerosol Clouds and
Trace Gases Research Infrastructure, ACTRIS-2), EU7 FP MarcoPolo Grant No. 606953, Erasmus+ 561975-
EPP-1-2015-1-FI-EPPKA2-CBHE-JP, Norwegian Research Council and the Belmont Forum project SERUS,
No. 311986, National Natural Science Foundation of China Grant No. 41275137, ESA-MOST China Dragon
Cooperation projects No. 10663 and 32771 (Dragon 3 and 4).

Our special thanks also to Mrs. Alla Borisova, INAR, University of Helsinki, for the technical editing of the
manuscript.

REFERENCES

Andreae, M. O., Andreae, T. W., and Ditas, F.: How frequent is new particle formation in the boundary layer
over the remote temperate/boreal forest?, AGU Fall Meeting, San Francisco, USA,
doi:10.1002/essoar.10501148.1, 2019.

Aalto, J., Porcar-Castell, A., Atherton, J., Kolari, P., Pohja, T., Hari, P., Nikinmaa, E., Petäjä, T., and Bäck,
J.: Onset of photosynthesis in spring speeds up monoterpene synthesis and leads to emission bursts, Plant,
Cell and Environment., 38, 2299-2312, 2015.

Agafonova, S. A., Frolova, N. L., Surkova, G. V., and Koltermann, K., P.: Modern characteristics of the ice
regime of Russian Arctic rivers and their possible changes in the 21st century, Geogr. Environ. Sustain.,
10(4), 4-15, doi:10.24057/2071-9388-2017-10-4-4-15, 2017.

Alekseychik, P., Lappalainen, H.K., Petäjä, T., Zaitseva, N., Heimann, M., Laurila, T., Lihavainen, H., Asmi,
E., Arshinov, M., Shevchenko, V., Makshtas, A., Dubtsov, S., Mikhailov, E., Lapshina, E., Kirpotin, S.,
Kurbatova, Y., Ding, A., Guo, H., Park, S., Lavric, J.V., Reum, F., Panov, A., Prokushkin, A., and Kulmala,
M.: Ground-based station network in Arctic and Subarctic Eurasia: An overview, Geogr. Environ. Sustain.,
9(2), 75-88, doi:10.24057/2071-9388-2016-9-2-19-35, 2016.

Alekseychik, P., Mammarella, I., Karpov, D., Dengel, S., Terentieva, I., Sabrekov, A., Glagolev, M., and Lapshina, E.: Net ecosystem exchange and energy fluxes measured with the eddy covariance technique in a western Siberian bog, Atmos. Chem. Phys., 17, 9333–9345, doi:10.5194/acp-17-9333-2017, 2017.

AMAP, 2017: Arctic Pollution 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Andreae, M. O.: Emission of trace gases and aerosols from biomass burning – an updated assessment, Atmos. Chem. Phys., 19, 8523-8546, doi:10.5194/acp-19-8523-2019, 2019.

Arneth, A., Harrison, S., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., and Vesala, T.: Terrestrial biogeochemical feedbacks in the climate system. Nature Geosci, 3, 525–532, https://doi.org/10.1038/ngeo905, 2010.

Arneth, A., Makkonen, R., Olin, S., Paasonen, P., Holst, T., Kajos, M. K., Kulmala, M., Maximov, T., Miller, P. A., and Schurgers, G.: Future vegetation–climate interactions in Eastern Siberia: an assessment of the competing effects of CO2 and secondary organic aerosols, Atmos. Chem. Phys., 16, 5243–5262, doi:10.5194/acp-16-5243-2016, 2016.

Arnold, S. R., Law, K. S., Brock, C. A., Thomas, J. L., Starkweather, S. M., von Salzen, K., Stohl, A., Sharma S., Lund, M. T., Flanner, M. G., Petaja, T., Tanimoto, H., Gamble, J., Dibb J. E., Melamed M., Johnson, N., Fidel, M., Tynkkynen, V.-P., Baklanov, A., Eckhardt, S., Monks, S. A., Browse, J., and Bozem, H.: Arctic air pollution: Challenges and opportunities for the next decade, Elementa: Science of the Anthropocene, 4:000104, https://dx.doi.org/10.12952/journal.elementa.00010. 2016.

Arvola, L., Leppäranta, M., and Äijälä, C.: CDOM variations in Finnish lakes and rivers between 1913 and 2014, Sci. Total Environ., 601, 1638-1648, doi:10.1016/j.scitotenv.2017.06.034, 2017.

Arvola, L., Äijälä, C., and Leppäranta, M.: CDOM concentrations of large Finnish lakes relative to their landscape properties, Hydrobiologia, 780(1), 37-46, doi:10.1007/s10750-016-2906-4, 2016.

Asmi, E., Kondratyev, V., Brus, D., Laurila, T., Lihavainen, H., Backman, J., Vakkari, V., Aurela, M., Hatakka, J., Viisanen, Y., Uttal, T., Ivakhov, V., and Makshtas, A.: Aerosol size distribution seasonal characteristics measured in Tiksi, Russian Arctic, Atmos. Chem. Phys., 16, 1271–1287, doi:10.5194/acp-16-1271-2016, 2016.

Backman, J., Schmeisser, L., Virkkula, A., Ogren, J. A., Asmi, E., Starkweather, S., Sharma, S., Eleftheriadis, K., Uttal, T., Jefferson, A., Bergin, M., Makshtas, A., Tunved, P., and Fiebig, M.: On Aethalometer measurement uncertainties and an instrument correction factor for the Arctic, Atmos. Meas. Tech., 10, 5039–5062, doi:10.5194/amt-10-5039-2017, 2017.

Badina, S. V.: Socio-economic potential of municipalities in the context of natural risk (case study – Southern Siberian regions), IOP Conference Series: Earth and Environmental Science, 190, doi:10.1088/1755-1315/190/1/012001, 2018.

2021 Bai, J.H.: Estimation of the isoprene emission from the Inner Mongolia grassland, Atmospheric Pollution
2022 Research, 6, 406-414, doi: 10.5094/APR.2015.045, 2015.

2023 Bai, J. H.: UV extinction in the atmosphere and its spatial variation in North China, Atmos. Environ., 154,
2024 318-330, doi:10.1016/j.atmosenv.2017.02.002, 2017a.

2025 Bai, J. H., Guenther, A., Turnipseed, A., Duhl, T., Greenberg J.: Seasonal and interannual variations in
2026 whole-ecosystem BVOC emissions from a subtropical plantation in China. Atmospheric Environment, 161,
2027 176-190. http://dx.doi.org/10.1016/j.atmosenv.2017.05.002, 2017b.

2028 Bai, J. H., de Leeuw, G., van der Ronald, A., De Smedt, I., Theys, N., Van Roozendael, M., Sogacheva, L.,
2029 and Chai, W. H.: Variations and photochemical transformations of atmospheric constituents in North China,
2030 Atmos. Environ., 189, 213-226, doi:10.1016/j.atmosenv.2018.07.004, 2018a.

2031 Bai, Y., Zhang, J., Zhang, S., Yao, F., and Magliulo, V.: A remote sensing-based two-leaf canopy
2032 conductance model: Global optimization and applications in modeling gross primary productivity and
2033 evapotranspiration of crops, Remote Sensing of Environment, 215, 411-437, doi:10.1016/j.rse.2018.06.005,
2034 2018b.

2035 Bai, J. H.: A calibration method of solar radiometers, Atmos. Pollut. Res., 10(4), 1365-1373,
2036 doi:10.1016/j.apr.2019.03.011, 2019.

2037 Baklanov, A., Mahura, A., Nazarenko, L., Tausnev, N., Kuchin, A., and Rigina, O.: Atmospheric Pollution
2038 and Climate Change in Northern Latitudes, Russ. Acad. Sci., Apatity, Russia, 2012.

2039 Baklanov, A. A., Penenko, V. V., Mahura, A. G., Vinogradova, A. A., Elansky, N. F., Tsvetova, E. A.,
2040 Rigina, O. Y., Maksimenkov, L. O., Nuterman, R. B., Pogarskii, F. A., and Zakey, A.: Aspects of
2041 Atmospheric Pollution in Siberia, in Regional Environmental Changes in Siberia and Their Global
2042 Consequences, edited by: Groismanm P. Y., and Gutman, G., 303–346, Springer, Dordrecht, Netherlands,
2043 2013.

2044 Baklanov, A., Molina, L.T., and Gauss, M.: Megacities, air quality and climate, Atmospheric Environment,
2045 126, 235-249, https://doi.org/10.1016/j.atmosenv.2015.11.059, 2016.

2046 Baklanov, A., Smith Korsholm, U., Nuterman, R., Mahura, A., Nielsen, K. P., Sass, B. H., Rasmussen, A.,
2047 Zakey, A., Kaas, E., Kurganskiy, A., Sørensen, B., and González-Aparicio, I.: Enviro-HIRLAM online
2048 integrated meteorology–chemistry modelling system: strategy, methodology, developments and applications
2049 (v7.2), Geosci. Model Dev., 10, 2971–2999, https://doi.org/10.5194/gmd-10-2971-2017, 2017.

2050 Baklanov, A., Brunner,, D., Carmichael, G., Flemming, J., Freitas, S., Gauss, M., Hov, O., R. Mathur, R.,
2051 Schlünzen, K., Seigneur, C., and Vogel, B.: Key issues for seamless integrated chemistry-meteorology
2052 modeling, Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-15-00166.1., 2018.

Balch, W. M., Bates, N. R., Lam, P. J., Twining, B. S., Rosengard, S. Z., Bowler, B. C., and Rauschenberg, S.: Factors regulating the Great Calcite Belt in the Southern Ocean, and its biogeochemical significance, Global Biogeochem. Cycles, 30(8), 1124-1144, doi:10.1002/2016GB005414, 2016.

Balch, W. M.: The ecology, biogeochemistry, and optical properties of coccolithophores, Ann. Rev. Mar. Sci., 109, 71-98, doi:10.1146/annurev-marine-121916-063319, 2018.

Bartsch, A., Kumpula, T., Forbes, B.C. and Stammler F.: Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding, Ecol Appl., 20, 2346-58., doi: 10.1890/09-1927.1., 2010.

Barreira, L. M. F., Duporté, G., Rönkkö, T., Parshintsev, J., Hartonen, K., Hyrsky, L., Heikkinen, E., Kulmala, M., and Riekkola, M.-L.: Field measurements of biogenic volatile organic compounds in the atmosphere using solid-phase microextraction Arrow, Atmos. Meas. Tech., 11, 881–893, 2018.

Bashmachnikov, I.L., Yurova, A.Y., Bobylev, L.P., and Vesman, A. V.: Seasonal and Interannual Variations of Heat Fluxes in the Barents Sea Region, Izv., Atmos. Ocean. Phys., 54, 213–222, doi:10.1134/S0001433818020032, 2018a.

Bashmachnikov, I. L., Yurova, A.Y., Bobylev, L. P., Vesman, A.V.: Seasonal and interannual variations of the heat fluxes in the Barents Sea region, Izv. Atmos. Ocean. Phys., 54(2), 239-249, doi:10.7868/S0003351518020149, 2018b.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Altaf Arain, A., Baldocchi, D., Bonan, G.B., Bondeau, A.., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., F Ian Woodward, F.,I., and Papale, D.:Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science, 329, 834–838, doi: 10.1126/science.1184984, 2010.

Belikov, D., Arshinov, M., Belan, B., Davydov, D., Fofonov, A., Sasakawa, M., Machida, T.: Analysis of the Diurnal, Weekly, and Seasonal Cycles and Annual Trends in Atmospheric CO2 and CH4 at Tower Network in Siberia from 2005 to 2016, Atmosphere, 10 (11), 689, doi: 10.3390/atmos10110689, 2019.

Berchet, A., Bousquet, P., Pison, I., Locatelli, R., Chevallier, F., Paris, J.-D., Dlugokencky, E. J., Laurila, T., Hatakka, J., Viisanen, Y., Worthy, D. E. J., Nisbet, E., Fisher, R., France, J., Lowry, D., Ivakhov, V., and Hermansen, O.: Atmospheric constraints on the methane emissions from the East Siberian Shelf, Atmos. Chem. Phys., 16, 4147–4157, doi:10.5194/acp-16-4147-2016, 2016.

Berezina, E., Moiseenko, K., Skorokhod, A., Elansky, N., Belikov, I., and Pankratova, N.: Isoprene and monoterpenes over Russia and their impacts in tropospheric ozone formation, Geogr., Environ., Sustain., 12(1), 63-74, doi:10.24057/2071-9388-2017-24, 2019.

Bezuglaya, E. Y., Ed.: Air quality in largest cities of Russia for 10 years (1988-1997), Hydrometeoizdat, St. Petersburg, Russia, 1999.

2087 Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P.,

2088 Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H.

2089 H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., … and Lantuit, H.: Permafrost is

2090 warming at a global scale, Nat. Commun., 10(1), 264, doi: 10.1038/s41467-018-08240-4, 2019.

2091 Blackport, R., Screen, J. A., van der Wiel, K., and Bintanja, R.: Minimal influence of reduced Arctic sea ice

2092 on coincident cold winters in mid-latitudes, Nat. Clim. Change, 9, 697–704, doi: 10.1038/s41558-019-0551-

2093 4, 2019.

2094 Bobylev, S.N., Chereshnya, O.Y., Kulmala, M., Lappalainen, H. K., Petäjä, T., Solov'eva, S.V., Tikunov,

2095 V.S., and Tynkkynen, V.-P.: Indicators for digitalization of sustainable development goals in PEEX

2096 program, J. Geogr. Sust., 11, 145-156, 2018.

2097 Boike, J., Nitzbon, J., Anders, K., Grigoriev, M., Bolshiyanov, D., Langer, M., Lange, S., Bornemann, N.,

2098 Morgenstern, A., Schreiber, P., Wille, C., Chadburn, S., Gouttevin, I., Burke, E., and Kutzbach, L.: A 16-

2099 year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island

2100 Arctic permafrost research site, Lena River delta, northern Siberia: an opportunity to validate remote-sensing

2101 data and land surface, snow, and permafrost models, Earth Syst. Sci. Data, 11, 261–299,

2102 https://doi.org/10.5194/essd-11-261-2019, 2019.

2103

2104 Bondur, G., and Vorobev, V. E.: Satellite Monitoring of Impact Arctic Regions, Izv. Atmos. Ocean. Phys.,

2105 51, 949–968, doi: 10.1134/S0001433815090054, 2015.

2106 Bondur, V. G., and Ginzburg, A. S.: Emission of carbon-bearing gases and aerosols from natural fires on the

2107 territory of Russia based on space monitoring, Dokl. Earth Sci., 466(2), 148-152,

2108 doi:10.1134/s1028334x16020045, 2016.

2109 Bondur, V. G.: Satellite monitoring of trace gas and aerosol emissions during wildfires in Russia. Izv.

2110 Atmos. Ocean. Phys., 52(9), 1078-1091, doi:10.1134/s0001433816090103, 2016.

2111 Bondur, V. G., Gordo, K. A., and Kladov, V. L.: Spacetime distributions of wildfire areas and emissions of

2112 carbon-containing gases and aerosols in northern eurasia according to satellite-Monitoring Data, Izv. Atmos.

2113 Ocean. Phys., 53(9), 859-874, doi:10.1134/s0001433817090055, 2017.

2114 Bondur, V. G. and Gordo, K. A.: Satellite Monitoring of Burned out Areas and Emissions of Harmful

2115 Contaminants due to Forest and other Wildfires in Russia, Izv., Atmos. Ocean. Phys., 54 (9),955–965, doi:

2116 10.1134/S0001433818090104, 2018.

2117 Bondur V. G., Chimitdorzhiev T. N., Dmitriev A. V., and Dagurov P. N.: Otsenka prostranstvennoy

2118 anizotropii neodnorodnostey lesnoy rastitelnosti pri razlichnykh azimutalnykh uglakh radarnogo

2119 polyarimetricheskogo zondirovaniya (Spatial anisotropy assessment of the forest vegetation heterogeneity at

2120   various azimuth angles of the radar polarimetric sensing), Issledovanie Zemli iz kosmosa, Russia, 3, 92-103,

2121   doi:10.31857/S0205-96142019392-103, 2019a.

2122   Bondur, V. G., Chimitdorzhiev, T. N., Dmitriev, A. V., Dagurov, P. N., Zakharov, A. I., and Zakharova, L.

2123   N.: Metody radarnoj polyarimetrii dlya issledovaniya izmenenij mekhanizmov obratnogo rasseyaniya v

2124   zonah opolznej na primere obrusheniya sklona berega reki Bureya (Using radar polarimetry to monitor

2125   changes in backscattering mechanisms in landslide zones for the case study of the Bureya river bank

2126   collapse), Issledovanie Zemli iz kosmosa., Russia, 4, 3-17, doi:10.31857/S0205-9614201943-17, 2019b.

2127   Bondur, V. G., Tsidilina, M. N., and Cherepanova, E.V.: Satellite Monitoring of Wildfire Impacts on The

2128   Conditions of Various Types of Vegetation Cover in The Federal Districts of the Russian Federation, Izv.

2129   Atmos. Ocean. Phys., 55 (9), 1238–1253, doi:10.1134/s000143381909010X, 2019 (c).

2130   Bondur, V. G., Tsidilina, M. N., Kladov, V. L., and Gordo, K. A.: Irregular Variability of Spatiotemporal

2131   Distributions of Wildfires and Emissions of Harmful Trace Gases in Europe Based on Satellite Monitoring

2132   Data // Doklady Earth Sciences, Vol. 485, Part 2, pp. 461–464, doi: 10.1134/S1028334X19040202, 2019(d).

2133   Bondur, V. G., Zakharova, L. N., and Zakharov, A. I.: Monitoring of the landslide area state on Bureya river

2134   in 2018-2019 according to radar and optical satellite images, Issledovanie Zemli iz kosmosa, Russia, No. 6,

2135   26-35, doi:10.31857/S0205-96142019626-35, 2019(e).

2136   Bondur, V. G., Zakharova, L. N., Zakharov, A. I., Chimitdorzhiev, T. N., Dmitriev, A. V., and Dagurov,

2137   P.N.: Monitoring of landslide processes by means of L-band radar interferometric observations: Bureya river

2138   bank caving case // Issledovanie Zemli iz kosmosa, Russia, No. 5, 3-14, DOI:

2139   https://doi.org/10.31857/S0205-9614201953-14. 2019 (f).

2140   Bondur, V. G., Tsidilina, M. N., and Kladov, V. L.: Irregular Variability of Spatiotemporal Distributions of

2141   Wildfires and Emissions of Harmful Trace Gases in Europe Based on Satellite Monitoring Data, Dokl. Earth

2142   Sc., 485, 461–464, https://doi.org/10.1134/S1028334X19040202, 2019.

2143   Bondur, V. G., Mokhov, I. I., Voronova, O. S., and Sitnov, S. A.: Satellite Monitoring of Siberian Wildfires

2144   and Their Effects: Features of 2019 Anomalies and Trends of 20-Year Changes, Doklady Earth Sciences,

2145   492, 1, 370–375. doi: 10.1134/S1028334X20050049, 2020.

2146   Bormann, K. J., Brown, R. D., Derksen, C., and Painter, T. H.: Estimating snow-cover trends from space,

2147   Nat. Clim. Chang., 8, 924-928, 2018.

2148   Boy, M., Thomson, E. S., Acosta Navarro, J.-C., Arnalds, O., Batchvarova, E., Bäck, J., Berninger, F., Bilde,

2149   M., Brasseur, Z., Dagsson-Waldhauserova, P., Castarède, D., Dalirian, M., de Leeuw, G., Dragosics, M.,

2150   Duplissy, E.-M., Duplissy, J., Ekman, A. M. L., Fang, K., Gallet, J.-C., Glasius, M., Gryning, S.-E., Grythe,

2151   H., Hansson, H.-C., Hansson, M., Isaksson, E., Iversen, T., Jonsdottir, I., Kasurinen, V., Kirkevåg, A.,

2152   Korhola, A., Krejci, R., Kristjansson, J. E., Lappalainen, H. K., Lauri, A., Leppäranta, M., Lihavainen, H.,

2153   Makkonen, R., Massling, A., Meinander, O., Nilsson, E. D., Olafsson, H., Pettersson, J. B. C., Prisle, N. L.,

2154   Riipinen, I., Roldin, P., Ruppel, M., Salter, M., Sand, M., Seland, Ø., Seppä, H., Skov, H., Soares, J., Stohl,

2155   A., Ström, J., Svensson, J., Swietlicki, E., Tabakova, K., Thorsteinsson, T., Virkkula, A., Weyhenmeyer, G.

2156   A., Wu, Y., Zieger, P., and Kulmala, M.: Interactions between the atmosphere, cryosphere, and ecosystems

2157   at northern high latitudes, Atmos. Chem. Phys., 19, 2015–2061, https://doi.org/10.5194/acp-19-2015-2019,

2158   2019.

2159   Breider, T.J., Mickley, L.J., Jacob, D.J., Ge, C., Wang, J., Sulprizio, M.P., Croft, B., Ridley, D.A.,

2160   McConnell, J.R., Sharma, S., Husain, L., Dutkiewicz, V. A., Eleftheriadis, K., Skov, H., and Hopke, P. K.:

2161   Multidecadal trends in aerosol radiative forcing over the Arctic: Contribution of changes in anthropogenic

2162   aerosol to Arctic warming since 1980, J. Geophys. Res.: Atmos., 122, 3573-3594,

2163   https://doi.org/10.1002/2016JD025321, 2017.

2164   Burkhard, B., Kroll, F., Müller, F., and Windhorst, W. F., Landscapes' Capacities to Provide Ecosystem

2165   Services – a Concept for Land-Cover Based Assessments, Landscape Online 15(1), 1-12, DOI:

2166   10.3097/LO.200915, 2009.

2167   Chalov, S. R., Jarsjo, J., Kasimov, N. S., Romanchenko, A. O., Pietron, J., Thorslund, J., and Promakhova,

2168   E. V.: Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia,

2169   Environ. Earth Sci., 73(2), 663-680, doi:10.1007/s12665-014-3106-z, 2015.

2170   Chalov, S. R., Bazilova, V. O., and Tarasov, M. K.: Modelling suspended sediment distribution in the

2171   Selenga River Delta using LandSat data, in Integrating Monitoring and Modelling for Understanding,

2172   Predicting and Managing Sediment Dynamics, edited by: Collins, A., Stone, M., Horowitz, A., and Foster, I.,

2173   Copernicus Gesellschaft, Gottingen, Germany, 375, 19-22, 2017a.

2174   Chalov, S., Thorslund, J., Kasimov, N., Aybullatov, D., Ilyicheva, E., Karthe, D., Kositsky, A., Lychagin,

2175   M., Nittrouer, J., Pavlov, M., Pietron, J., Shinkareva, G., Tarasov, M., Garmaev, E., Akhtman, Y., and Jarsjö,

2176   J.: The Selenga River delta: a geochemical barrier protecting Lake Baikal waters, Regional Environ. Change,

2177   17, 2039-2053, doi: 10.1007/s10113-016-0996-1, 2017b.

2178   Chalov, S. R., Millionshchikova, T. D., and Moreido, V. M.: Multi-Model Approach to Quantify Future

2179   Sediment and Pollutant Loads and Ecosystem Change in Selenga River System, Water Resour., 45, S22-S34,

2180   doi:10.1134/s0097807818060210, 2018.

2181   Che, Y., Xue, Y., Mei, L., Guang, J., She, L., Guo, J., Hu, Y., Xu, H., He, X., Di, A., and Fan, C.: Technical

2182   note: Intercomparison of three AATSR Level 2 (L2) AOD products over China, Atmos. Chem. Phys., 16,

2183   9655–9674, https://doi.org/10.5194/acp-16-9655-2016, 2016.

2184   Cheng, Y., Cheng, B., Zheng, F., Vihma, T., Kontu, A., Yang, Q. and Liao, Z.: Air/snow, snow/ice and

2185   ice/water interfaces detection from high-resolution vertical temperature profiles measured by ice mass-

2186   balance buoys on an Arctic lake. Annals of Glaciology, accepted (2020).

2187   Chernokulsky, A. V., Esau, I., Bulygina, O. N., Davy, R., Mokhov, II, Outten, S., and Semenov, V. A.:

2188   Climatology and interannual variability of cloudiness in the Atlantic Arctic from surface observations since

2189   the late nineteenth century, J. Clim., 30(6), 2103-2120, doi:10.1175/jcli-d-16-0329.1, 2017.

2190   Chernokulsky, A., and Esau, I.: Cloud cover and cloud types in the Eurasian Arctic in 1936–2012. *Int. J.*

2191   *Climatol.*, **39**(15), 5771–5790, https://doi.org/10.1002/joc.6187, 2019

2192   Chu, B., Kerminen, V.-M., Bianchi, F., Yan, C., Petäjä, T. and Kulmala, M.: Atmospheric new particle

2193   formation in China, Atmos. Chem. Phys., 19, 115-138, 2019.

2194   Chubarova, N. Y., Poliukhov, A. A., and Gorlova, I. D.: Long-term variability of aerosol optical thickness in

2195   Eastern Europe over 2001–2014 according to the measurements at the Moscow MSU MO AERONET site

2196   with additional cloud and NO2 correction, Atmos. Meas. Tech., 9, 313–334, https://doi.org/10.5194/amt-9-

2197   313-2016, 2016a.

2198   Chubarova, N., Zhdanova, Y., and Nezval, Y.: A new parameterization of the UV irradiance altitude

2199   dependence for clear-sky conditions and its application in the on-line UV tool over Northern Eurasia, Atmos.

2200   Chem. Phys., 16, 11867–11881, https://doi.org/10.5194/acp-16-11867-2016, 2016b.

2201   Chubarova, N. E., Pastukhova, A. S., and Galin, V. Y.: Long-Term Variability of UV Irradiance in the

2202   Moscow Region according to Measurement and Modeling Data, Izv. Atmos. Ocean. Phys., 54, 139–146,

2203   https://doi.org/10.1134/S0001433818020056, 2018.

2204   Chubarova, N. E., Androsova, E. E., Kirsanov, A. A., Vogel, B., Vogel, H., Popovicheva, O. B., and Rivin,

2205   G. S.: Aerosol and Its Radiative Effects during the Aeroradcity 2018 Moscow Experiment, Geography,

2206   Environment, Sustainability, 12, 114-131, https://doi.org/10.24057/2071-9388-2019-72 2019a.

2207   Chubarova, N. E., Timofeev, Y. M., Virolainen, Y. A., and Polyakov, A. V.: Estimates of UV indices during

2208   the periods of reduced ozone content over Siberia in Winter-Spring 2016, Atmos. Oceanic Opt., 32, 177-179,

2209   doi:10.1134/s1024856019020040, 2019b.

2210   Chubarova, N. E., Pastukhova, A.S., Zhdanova, E.Y., Volpert, E.V., Smyshlyaev and S.P., and Galin, V.Y.:

2211   Effects of Ozone and Clouds on Temporal Variability of Surface UV Radiation and UV Resources over

2212   Northern Eurasia Derived from Measurements and Modeling., Atmosphere, 11, 59, 2020.

2213   Cohen, J., X. Zhang, T., Jung, R. Kwok, J., Overland, T., Ballinger, U.S., Bhatt, H. W., Chen, D., Coumou,

2214   S., Feldstein, H., Gu, D., Handorf, G., Henderson, M,. Ionita, M., Kretschmer, F., Laliberte, S., Lee, H. W.,

2215   Linderholm, W., Maslowski, Y., Peings, K., Pfeiffer, I., Rigor, T., Semmler, J., Stroeve, P.C., Taylor, S.,

2216   Vavrus, T., Vihma, S., Wang, M., Wendisch, Y., Wu, and Yoon, J.: Divergent consensuses on Arctic

2217   amplification influence on midlatitude severe winter weather. Nature Climate Change, 10, 20-29,

2218   doi:10.1038/s41558-019-0662-y, 2020.

2219   Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski,

2220   W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., and Wehner, M.: Long-term climate

change: Projections, commitments and irreversibility, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T.F., Quin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Doschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., Cambridge University Press, Cambridge, United-Kingdom, 1029-1136, doi:10.1017/CBO9781107415324.024, 2013.

Commane, R., Lindaas, J., Benmergui, J., Luus K. A., Chang, R. Y.-W., Daube, B. C., Euskirchen, E. S., Henderson, J. M., Karion, A., Miller, J. B., Miller, S. M., Parazoo, N. C., Randerson, J. T., Sweeney, C., Tans, P., Thoning, K., Veraverbeke, S., Miller, C. E., and Wofsy, S. C.: Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra, PNAS, 114(21), 5361-5366, 2017.

Coumou, C., Petoukhov, V., Rahmstorf, S., Petri, S., and Schellnhuber, H.-J.: Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer, Proc. Natl. Acad. Sci., 111, 12 331–12336, https://doi.org/10.1073/pnas.1412797111, 2014.

Dada, L., Paasonen, P., Nieminen, T., Buenrostro Mazon, S., Kontkanen, J., Peräkylä, O., Lehtipalo, K., Hussein, T., Petäjä, T., Kerminen, V.-M., Bäck, J. and Kulmala, M.: Long-term analysis of clear-sky new particle formation events and nonevents in Hyytiälä, Atmos. Chem. Phys., 17, 6227-6241, 2017.

Dada, L., Chellapermal, R., Buenrostro Mazon, S., Paasonen, P., Lampilahti, J., Manninen, H. E., Junninen, H., Petäjä, T., Kerminen, V.-M., and Kulmala, M.: Refined classification and characterization of atmospheric new-particle formation events using air ions, Atmos. Chem. Phys., 18, 17883–17893, https://doi.org/10.5194/acp-18-17883-2018, 2018.

Dagsson-Waldhauserova, P., Meinander, O.: Atmosphere-cryosphere interaction in the Arctic, at high latitudes and mountains with focus on transport, deposition and effects of dust, black carbon, and other aerosols., Front. Earth Sci., 7, 337, https://www.frontiersin.org/articles/10.3389/feart.2019.00337/full, 2019.

Davy, R., and Esau, I.: Differences in the efficacy of climate forcings explained by variations in atmospheric boundary layer depth, Nat. Commun., 7, 8, doi:10.1038/ncomms11690, 2016.

Davy, R., Esau, I., Chernokulsky, A., Outten, S., and Zilitinkevich, S.: Diurnal asymmetry to the observed global warming, Int. J. Climatol., 37, 79-93, doi:10.1002/joc.4688, 2017.

Dean, J. F., Middelburg, J. J., Röckmann, T., Aerts, R., Blaauw, L. G., Egger, M., Jetten, M. S. M., de Jong, A. E. E., Meisel, O. H., Rasigraf, O., Slomp, C. P., in't Zandt, M. H., and Dolman, A. J.: Methane feedbacks to the global climate system in a warmer world, Rev. Geophys., 56(1), 207-250, https://doi.org/10.1002/2017RG00055, 2018.

Derksen, C., and Brown, R.: Spring snow cover extent reductions in the 2008-2012 period exceeding climate model predictions, Geophys. Res. Lett., 39, L19504, 2012.

https://doi.org/10.5194/acp-2021-341
Preprint. Discussion started: 19 May 2021

Derome, J., and Lukina, N.: Interaction between environmental pollution and land-cover/land-use change in Arctic areas, in: Eurasian Arctic Land Cover and Land Use in a Changing Climate, edited by: Gutman, G., and Reissell, A., 6, 269–290, Springer, Amsterdam, Netherlands, 2011.

Ding, A. J., Huang, X., Nie, W., Sun, J. N., Kerminen, V.-M., Petäjä, T., Su, H., Chen, Y. F., Yang, X.-Q., Wang, M. H., Chi, X. G., Wang, J. P., Virkkula, A., Guo, W. D., Yuan, J., Wang, S. Y., Zhang, R. J., Wu, Y. F., Song, Y. Zhu, T., Zilitinkevich, S., Kulmala, M., and Fu, C. B.: Enhanced haze pollution by black carbon in megacities in China, Geophys. Res. Lett., 43, 2873-2879, doi:10.1002/2016GL067745, 2016a.

Ding, A. J., Nie, W., Huang, X., Chi, X., Sun, J., Kerminen, V.-M., Xu, Z., Guo, W., Petäjä, T., Yang, X., Kulmala, M., and Fu, G.: Long-term observation of pollution-weather/climate interactions at the SORPES station: a review and outlook, Front. Environ. Sci. Eng., 10, doi:10.1007/s11783-016-0877-3, 2016b.

Dou, T., Xiao, C., Liu, J., Han, W., Du, Z., Mahoney, A. R., Jones, J., and Eicken, H.: A key factor initiating surface ablation of Arctic sea ice: earlier and increasing liquid precipitation, The Cryosphere, 13, 1233–1246, https://doi.org/10.5194/tc-13-1233-2019, 2019.

Dragosics, M., Meinander, O., Jonsdottir, T., Durig, T., De Leeuw, G., Palsson, F., Dagsson-Waldhauserová, P., and Thorsteinsson, T.: Insulation effects of Icelandic dust and volcanic ash on snow and ice, Arab. J. Geosci., 9, 126, DOI:10.1007/s12517-015-2224-6, 2016.

Duporte, G., Parshintsev, J., Barreira, L. M. F., Hartonen, K., Kulmala, M., and Riekkola, M. L.: Nitrogen-containing low volatile compounds from pinonaldehyde-dimethylamine reaction in the atmosphere: a laboratory and field study, Environ. Sci. Technol., 50(9), 4693-4700, doi:10.1021/acs.est.6b00270, 2016.

Durairaj, P., Sarangi., R., Ramalingam, S., Thirunavukarassu, T., and Chauhan, P.: Seasonal nitrate algorithms for nitrate retrieval using OCEANSAT-2 and MODIS-AQUA satellite data, Environ. Monit. Assess., 187, 176-189, doi: 10.1007/s10661-015-4340-x, 2015.

Dyukarev, E.A., Godovnikov, E.A., Karpov, D.V., Kurakov, S.A., Lapshina, E.D., Filippov, I.V., Filippova, N.V., and Zarov, E.A.: Net ecosystem exchange, gross primary production and ecosystem respiration in ridge-hollow complex at Mukhrino Bog, Geography, Environment, Sustainability,12(2), 227-244, doi.10.24057/2071-9388-2018-77, 2019.

Elansky, N. F., Lavrova, O. V., Skorokhod, A. I., and Belikov, I. B.: Trace gases in the atmophere over Russian cities, Atmos. Environ., 143, 108-119, doi:10.1016/j.atmosenv.2016.08.046, 2016.

Esau, I., Miles, V. V., Davy, R., Miles, M. W., and Kurchatova, A.: Trends in normalized difference vegetation index (NDVI) associated with urban development in northern West Siberia, Atmos. Chem. Phys., 16, 9563–9577, https://doi.org/10.5194/acp-16-9563-2016, 2016.

Esau, I., Varentsov, M., Laruelle, M., Miles, M. W., Konstantinov, P., Soromotin, A., Baklanov, A. A., and Miles, V. V.: Warmer Climate of Arctic Cities, Chapter 3 in the monography "The Arctic: Current Issues and

Challenges", Edited by: Pokrovsky, O., NOVA Publishers, ISBN: 978-1-53617-306-2, https://novapublishers.com/shop/the-arctic-current-issues-and-challenges/, 2020.

Euskirchen, E. S., Bret-Harte, M. S., Shaver, G. R., Edgar, C. W., and Romanovsky, V. E.: Long-term release of carbon dioxide from arctic tundra ecosystems in northern Alaska, Ecosystems, 1–15, 2017.

Evangeliou, N., Shevchenko, V. P., Yttri, K. E., Eckhardt, S., Sollum, E., Pokrovsky, O. S., Kobelev, V. O., Korobov, V. B., Lobanov, A. A., Starodymova, D. P., Vorobiev, S. N., Thompson, R. L., and Stohl, A.: Origin of elemental carbon in snow from western Siberia and northwestern European Russia during winter–spring 2014, 2015 and 2016, Atmos. Chem. Phys., 18, 963–977, https://doi.org/10.5194/acp-18-963-2018, 2018.

Ezhova, E., Kerminen, V.-M., Lehtinen, K. E. J., and Kulmala, M.: A simple model for the time evolution of the condensation sink in the atmosphere for intermediate Knudsen numbers, Atmos. Chem. Phys., 18, 2431–2442, https://doi.org/10.5194/acp-18-2431-2018, 2018a.

Ezhova, E., Ylivinkka, I., Kuusk, J., Komsaare, K., Vana, M., Krasnova, A., Noe, S., Arshinov, M., Belan, B., Park, S.-B., Lavrič, J. V., Heimann, M., Petäjä, T., Vesala, T., Mammarella, I., Kolari, P., Bäck, J., Rannik, Ü., Kerminen, V.-M., and Kulmala, M.: Direct effect of aerosols on solar radiation and gross primary production in boreal and hemiboreal forests, Atmos. Chem. Phys., 18, 17863–17881, https://doi.org/10.5194/acp-18-17863-2018, 2018b.

Fang, K., Makkonen, R., Guo, Z., and Seppa, H.: An increase in the biogenic aerosol concentration as a contributing factor to the recent wetting trend in Tibetan Plateau. Sci Rep 5, 14628, https://doi.org/10.1038/srep14628, 2015.

Fang, Y., Changyou, L., Leppäranta, M., Xiaonghong, S., Shengnan, Z., and Chengfu, Z.: Notable increases in nutrient concentrations in a shallow lake during seasonal ice growth, Water Science and Technology, 74(12), 2773-2783, 2016.

Fang, K. , Makkonen, R. , Guo, Z , Zhao , Y., and Seppä, H.: An increase in the biogenic aerosol concentration as a contributing factor to the recent wetting trend in Tibetan Plateau, Scientific Reports , 5 , 14628, DOI: 10.1038/srep14628, 2015.

Fletcher, S. E. M., and Schaefer, H.: Rising methane: a new climate challenge, Science, 364, 932-933, 2019.

Franz, D., Mammarella, I., Boike, J., Kirillin, G., Vesala, T., Bornemann, N., Larmanou, E., Langer, M., and Sachs, T.: Lake-Atmosphere Heat Flux Dynamics of a Thermokarst Lake in Arctic Siberia, J. Geophys. Res.: Atmos., 123(10), 5222-5239, doi:10.1029/2017jd027751, 2018.

Freud, E., Krejci, R., Tunved, P., Leaitch, R., Nguyen, Q. T., Massling, A., Skov, H., and Barrie, L.: Pan-Arctic aerosol number size distributions: seasonality and transport patterns, Atmos. Chem. Phys., 17, 8101–8128, https://doi.org/10.5194/acp-17-8101-2017, 2017.

2319   Frolova, N.L., Belyakova, P.A., Grigoriev, V.Y. *et al.* : Runoff fluctuations in the Selenga River Basin, Reg

2320   Environ Change, 17**,** 1965–1976, doi.org/10.1007/s10113-017-1199-0, 2017.

2321

2322   Fu, B. J., and Forsius, M.: Ecosystem services modeling in contrasting landscapes, Landscape Ecol., 30(3),

2323   375-379, doi:10.1007/s10980-015-0176-6, 2015.

2324   Garmaev, E. Z., Kulikov, A. I., Tsydypov, B. Z., Sodnomov, B. V., and Ayurzhanaev, A. A.: Environmental

2325   Conditions Of Zakamensk Town (Dzhida River Basin Hotspot), Geography, Environment,

2326   Sustainability,12(3), 224-239, https://doi.org/10.24057/2071-9388-2019-32, 2019.

2327   Georgiadi, A. G., Koronkevich, N. I., Milyukova, I. P., and Barabanova, E. A.: Integrated projection for

2328   runoff changes in large Russian river basins in the XXI Century, Geography, Environment, Sustainability,

2329   9(2), 38-46, 2016.

2330   GGO: Air quality in cities of Russia during the year 2015, St. Petersburg, Voeikov Main Geophysical

2331   Observatory, RosHydroMet, 2016.

2332   Giamarelou, M., Eleftheriadis, K., Nyeki, S., Tunved, P., Torseth, K., and Biskos, G.: Indirect evidence of

2333   the composition of nucleation mode atmospheric particles in the high Arctic, J. Geophys. Res.: Atmos.,

2334   121(2), 965-975, doi:10.1002/2015jd023646, 2016.

2335   Gil, J., Pérez, T., Boering, K., Martikainen, P. J., and Biasi, C.: Mechanisms responsible for high N2O

2336   emissions from subarctic permafrost peatlands studied via stable isotope techniques, Global Biogeochem.

2337   Cycles, 31(1), 172, doi:10.1002/2015GB005370, 2017.

2338   Glagolev, M.V., Ilyasov, D. V. I., Terentieva, E., Sabrekov, A. F., Yu Mochenov, S., and Maksutov, S. S.:

2339   Methane and carbon dioxide fluxes in the waterlogged forests of south and middle taiga of Western Siberia,

2340   IOP Conf. Ser.: Earth Environ. Sci., 138 012005, 2018.

2341   Gnatiuk, N., Radchenko, I., Davy, R., Morozov E., and Bobylev, L.: Simulation of factors affecting

2342   Emiliania huxleyi blooms in Arctic and sub-Arctic seas by CMIP5 climate models: model validation and

2343   selection, Biogeosciences, 17, 1199–1212. doi: 10.5194/bg-17-1199-2020, 2020.

2344   Godrijan, J., Drapeau, D., and Balch, W. M.: Mixotrophic uptake of organic compounds by coccolithphores,

2345   Limnol. Ocean., Early bird publication, https://doi.org/10.1002/lno.11396, 2020.

2346   Gordov, E.P., Okladnikov, I.G., Titov, A.G., Voropay N.N., Ryazanova A.A., and Lykosov V.N.:

2347   Development of Information-computational Infrastructure for Modern Climatology, Russ. Meteorol. Hydrol.,

2348   43, 722–728, https://doi.org/10.3103/S106837391811002X, 2018.

2349   Granath, G., Rydin, H., Baltzer, J. L., Bengtsson, F., Boncek, N., Bragazza, L., Bu, Z.-J., Caporn, S. J. M.,

2350   Dorrepaal, E., Galanina, O., Gałka, M., Ganeva, A., Gillikin, D. P., Goia, I., Goncharova, N., Hájek, M.,

2351   Haraguchi, A., Harris, L. I., Humphreys, E., Jiroušek, M., Kajukało, K., Karofeld, E., Koronatova, N. G.,

2352 Kosykh, N. P., Lamentowicz, M., Lapshina, E., Limpens, J., Linkosalmi, M., Ma, J.-Z., Mauritz, M., Munir,

2353 T. M., Natali, S. M., Natcheva, R., Noskova, M., Payne, R. J., Pilkington, K., Robinson, S., Robroek, B. J.

2354 M., Rochefort, L., Singer, D., Stenøien, H. K., Tuittila, E.-S., Vellak, K., Verheyden, A., Waddington, J. M.,

2355 and Rice, S. K.: Environmental and taxonomic controls of carbon and oxygen stable isotope composition in

2356 Sphagnum across broad climatic and geographic ranges, Biogeosciences, 15, 5189–5202,

2357 https://doi.org/10.5194/bg-15-5189-2018, 2018.

2358 Grigoriev, V.Y., and Frolova, N.L.: Terrestrial water storage change of European Russia and its impact on

2359 water balance, Geography, Environment, Sustainability, 11(1), 38-50. https://doi.org/10.24057/2071-9388-

2360 2018-11-1-38-50, 2018.

2361 Groundstroem, F., and Juhola, S.: A framework for identifying cross-border impacts of climate change on

2362 the energy sector, Environment Systems and Decisions, 39(1), 3-15, doi:10.1007/s10669-018-9697-2, 2019.

2363 Gunchin, G., Manousakas, M., Osan, J., Karydas, A. G., Eleftheriadis, K., Lodoysamba, S., Shagjjamba, D.,

2364 Migliori, A., Padilla-Alvarez, R., Streli, C., and Darby, I.: Three-year long source apportionment study of

2365 airborne particles in Ulaanbaatar using x-ray fluorescence and positive matrix factorization, Aerosol and Air

2366 Quality Research, 19(5), 1056-1067, doi:10.4209/aaqr.2018.09.0351, 2019.

2367 Guo, Y., Yan, C., Li, C., Feng, Z., Zhou, Y., Lin, Z., Dada, L., Stolzenburg, D., Yin, R., Kontkanen, J.,

2368 Daellenbach, K. R., Kangasluoma, J., Yao, L., Chu, B., Wang, Y., Cai, R., Bianchi, F., Liu, Y., and Kulmala,

2369 M.: Formation of Nighttime Sulfuric Acid from the Ozonolysis of Alkenes in Beijing, Atmos. Chem. Phys.

2370 Discuss., https://doi.org/10.5194/acp-2019-1111, in review, 2020.

2371 Gurchenkov, A. A., Murynin, A. B., Trekin, A. N., and Ignatyev, V. Y.: Object-oriented classification of

2372 substrate surface objects in Arctic impact regions aerospace monitoring, Herald of the Bauman Moscow

2373 State Technical University, 135-146. doi:10.18698/1812-3368-2017-3-135-146, 2017.

2374 Göckede, M., Kittler, F., Kwon, M. J., Burjack, I., Heimann, M., Kolle, O., Zimov, N., and Zimov, S.:

2375 Shifted energy fluxes, increased Bowen ratios, and reduced thaw depths linked with drainage-induced

2376 changes in permafrost ecosystem structure, The Cryosphere, 11, 2975–2996, https://doi.org/10.5194/tc-11-

2377 2975-2017, 2017.

2378 Göckede, M., Kwon, M. J., Kittler, F., Heimann, M., Zimov, N., and Zimov, S.: Negative feedback processes

2379 following drainage slow down permafrost degradation, Glob. Change Biol., 25, 3254– 3266,

2380 https://doi.org/10.1111/gcb.14744, 2019.

2381 Hao, L., Garmash, O., Ehn, M., Miettinen, P., Massoli, P., Mikkonen, S., Jokinen, T., Roldin, P., Aalto, P.,

2382 Yli-Juuti, T., Joutsensaari, J., Petäjä, T., Kulmala, M., Lehtinen, K. E. J., Worsnop, D. R., and Virtanen, A.:

2383 Combined effects of boundary layer dynamics and atmospheric chemistry on aerosol composition during

2384 new particle formation periods, Atmospheric Chemistry and Physics, 18(23), 17705-17716. doi:10.5194/acp-

2385 18-17705-2018, 2018.

2386   Hari, P. & Kulmala, M.: Station for Measuring Ecosystem–Atmosphere Relations (SMEAR II). Boreal Env.
2387   Res. 10: 315–322, 2005.

2388

2389   Hari, P., Andreae M., Kabat P., and Kulmala M.: A comprehensive network of measuring stations to monitor
2390   climate change. Boreal Env. Res. 14: 442-446, 2009.

2391

2392   Hari, P., Petäjä, T., Bäck, J., Kerminen, V.-M., Lappalainen, H. K., Vihma, T., Laurila, T., Viisanen, Y.,
2393   Vesala, T., and Kulmala, M..: Conceptual design of a measurement network of the global change, Atmos.
2394   Chem. Phys., 16, 1017-1028, doi:10.5194/acp-16-1017-2016, 2016.

2395   Hari, P., Kerminen, V.-M., Kulmala, L., Kulmala, M., Noe, S., Petäjä, T., Vanhatalo, A., and Bäck, J.:
2396   Annual cycle of Scots pine photosynthesis, Atmos. Chem. Phys., 17, 15045–15053, doi:10.5194/acp-17-
2397   15045-2017, 2017.

2398   Heikkilä, A., Makelä, J. S., Lakkala, K., Meinander, O., Kaurola, J., Koskela, T., Karhu, J. M., Karppinen,
2399   T., Kyro, E., and De Leeuw, G.: In search of traceability: two decades of calibrated Brewer UV
2400   measurements in Sodankyla and Jokioinen, Geoscientific Instrumentation, Methods and Data Systems, 5(2),
2401   531-540, doi:10.5194/gi-5-531-2016, 2016.

2402   Heintzenberg, J., Tunved, P., Galí, M., and Leck, C.: New particle formation in the Svalbard region 2006–
2403   2015, Atmos. Chem. Phys., 17, 6153–6175, doi:10.5194/acp-17-6153-2017, 2017.

2404   Helin, A., Sietiö, O.-M., Heinonsalo, J., Bäck, J., Riekkola, M.-L., and Parshintsev, J.: Characterization of
2405   free amino acids, bacteria and fungi in size-segregated atmospheric aerosols in boreal forest: seasonal
2406   patterns, abundances and size distributions, Atmos. Chem. Phys., 17, 13089–13101, doi.org/10.5194/acp-17-
2407   13089-2017, 2017.

2408   Hellén, H., Praplan, A. P., Tykkä, T., Ylivinkka, I., Vakkari, V., Bäck, J., Petäjä, T., Kulmala, M., and
2409   Hakola, H.: Long-term measurements of volatile organic compounds highlight the importance of
2410   sesquiterpenes for the atmospheric chemistry of a boreal forest, Atmos. Chem. Phys., 18, 13839–13863,
2411   https://doi.org/10.5194/acp-18-13839-2018, 2018.

2412   Hinzman, L.D., Bettez, N.D., Bolton, W.R. et al. :Evidence and Implications of Recent Climate Change in
2413   Northern Alaska and Other Arctic Regions, Climatic Change, 72, 251–298, doi.org/10.1007/s10584-005-
2414   5352-2, 2005.

2415   Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A.,
2416   Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I.,
2417   Thomas, A., Warren, R., and Zhou, G.: Impacts of 1.5℃ Global Warming on Natural and Human Systems,
2418   in: Global Warming of 1.5℃: An IPCC Special Report on the impacts of global warming of 1.5℃ above
2419   pre-industrial levels and related global greenhouse gas emission pathways, in the context of
2420   strengthening the global response to the threat of climate change, sustainable development, and efforts to

2421   eradicate poverty, edited by: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.

2422   R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou,

2423   X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T., WMO, Geneva, Switzerland,

2424   2018.

2425   Hong, J., Kim, J., Nieminen, T., Duplissy, J., Ehn, M., Äijälä, M., Hao, L. Q., Nie, W., Sarnela, N., Prisle, N.

2426   L., Kulmala, M., Virtanen, A., Petäjä, T., and Kerminen, V.-M.: Relating the hygroscopic properties of

2427   submicron aerosol to both gas- and particle-phase chemical composition in a boreal forest environment,

2428   Atmos. Chem. Phys., 15, 11999–12009, https://doi.org/10.5194/acp-15-11999-2015, 2015.

2429   Huang, W., Cheng, B., Zhang, J., Zhang, Z., Vihma, T., Li, Z., and Niu, F.: Modeling experiments on

2430   seasonal lake ice mass and energy balance in the Qinghai–Tibet Plateau: a case study, Hydrol. Earth Syst.

2431   Sci., 23, 2173-2186, 2019a.

2432   Huang, W., Zhang, J., Leppäranta, M., Li, Z., Cheng, B. and Lin, Z. 2019b. Thermal structure and water-ice

2433   heat transfer in a shallow ice–covered thermokarst lake in central Qinghai-Tibet Plateau, Journal of

2434   Hydrology, 578, [124122], 2019b.

2435   Hölttä, T., Lintunen, A., Chan, T., Mäkelä, A., and Nikinmaa, E.: A steady state stomatal model of balanced

2436   leaf gas exchange, hydraulics and maximal source-sink flux, Tree Physiology, 37, 851-868, doi:

2437   10.1093/treephys/tpx011, 2017.

2438   IPCC: Special Report on the Ocean and Cryosphere in a Changing Climate, edited by Pörtner, H.-O.,

2439   Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A.,

2440   Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., 2019.

2441   Ivakhov, V. M., Paramonova, N. N., Privalov, V. I., Zinchenko, A. V., Loskutova, M. A., Makshtas, A. P.,

2442   Kustov, V. Y., Laurila, T., Aurela, M., and Asmi, E.: Atmospheric Concentration of Carbon Dioxide at Tiksi

2443   and Cape Baranov Stations in 2010-2017, Russ. Meteorol. Hydrol., 44, 291–299,

2444   doi:10.3103/s1068373919040095, 2019.

2445   Jaffe, D., Bertschi, I., Jaegle, L., Novelli, P., Reid, J. S., Tanimoto, H., Vingarzan, R. and Westphal, D. L.:

2446   Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North

2447   America, Geophys. Res. Lett., 31(16), L16106, doi:10.1029/2004GL020093, 2004.

2448   Jakobson, L., T. Vihma, and E. Jakobson,: Relationships between Sea Ice Concentration and Wind Speed

2449   over the Arctic Ocean during 1979–2015., J. Climate, 32, 7783–7796, https://doi.org/10.1175/JCLI-D-19-

2450   0271.1, 2019.

2451   Juhola, S.: Planning for a green city: The Green Factor tool, Urban Forestry and Urban Greening, 34, 254-

2452   258, doi:10.1016/j.ufug.2018.07.019, 2018.

2453   Juutinen, S., Virtanen, T., Kondratyev, V., Laurila, T., Linkosalmi, M., Mikola, J., Nyman, J., Räsänen, A.,

2454   Tuovinen, J.-P., and Aurela, M.: Spatial variation and seasonal dynamics of leaf-area index in the arctic

2455   tundra-implications for linking ground observations and satellite images, Environ. Res. Lett., 12(9), 10,
2456   doi:10.1088/1748-9326/aa7f85, 2017.

2457   Kalogridis, A.C., Popovicheva, O.B., Engling, G., Diapouli, E., Kawamura, K., Tachibana, E., Ono, K.,
2458   Kozlov, V.S., and Eleftheriadis, K.: Smoke aerosol chemistry and aging of Siberian biomass burning
2459   emissions in a large aerosol chamber, Atmos. Environ., 185,15-28, 2018.

2460   Kangasluoma, J., Ahonen, L. R., Laurila, T., Cai, R., Enroth, J., Mazon, S., Korhonen, F., Aalto, P.,
2461   Kulmala, M., Attoui, M. and Petäjä, T.: Laboratory verification of a new high flow differential mobility
2462   particle sizer, and field measurements in Hyytiälä, J Aerosol Sci, 124, 1-9, 2018.

2463   Karelin, D. V., Goryachkin, S. V., Zamolodchikov, D. G., Dolgikh, A. V., Zazovskaya, E. P., Shishkov, V.
2464   A., and Kraev, G. N.: Human footprints on greenhouse gas fluxes in cryogenic ecosystems, Dokl. Earth Sc.,
2465   477, 1467–1469, doi:10.1134/S1028334X17120133, 2017.

2466   Karetnikov, S., Leppäranta, M., and Montonen, A.: A time series of over 100 years of ice seasons on Lake
2467   Ladoga, Journal of Great Lakes Research, 43(6), 979-988, doi:10.1016/j.jglr.2017.08.010, 2017.

2468   Karthe, D., Abdullaev, I., Boldgiv, B., Borchardt, D., Chalov, S., Jarsjö, J., Li, L., and Nittrouer, J.A.: Water
2469   in Central Asia: an integrated assessment for science-based management, Environmental Earth Sciences,
2470   76(20), 15, doi:10.1007/s12665-017-6994-x, 2017a.

2471   Karthe, D., Chalov, S., Moreido, V., Pashkina, M., Romanchenko, A., Batbayar, G., Kalugin, A., Westphal,
2472   K., Malsy, M., and Flörke, M.: Assessment of runoff, water and sediment quality in the Selenga River basin
2473   aided by a web-based geoservice, Water Resources, 44(3), 399-416, 2017b.

2474   Karthe D., Chalov S., Gradel A., and Kusbach A.: Special issue: Environment change on the Mongolian
2475   plateau: atmosphere, forests, soils and water, Geography, Environment, Sustainability, 12(3), 60-65,
2476   doi:10.24057/2071-9388-2019-1411, 2019.

2477   Karvonen, J., Shi, L., Cheng, B., Similä, M., Mäkynen, M., and Vihma, T.: Bohai Sea ice parameter
2478   estimation based on thermodynamic ice model and Earth observation data, Remote Sensing, 9, 234,
2479   doi:10.3390/rs9030234, 2017.

2480   Kasimov, N., Karthe, D., and Chalov, S.: Environmental change in the Selenga River—Lake Baikal Basin,
2481   Reg. Environ. Chang., 17, 1945–1949, 2017a.

2482   Kasimov, N. S., Kosheleva, N. E., Nikiforova, E. M., and Vlasov, D. V.: Benzo a pyrene in urban
2483   environments of eastern Moscow: pollution levels and critical loads, Atmos. Chem. Phys., 17(3), 2217-2227,
2484   doi:10.5194/acp-17-2217-2017, 2017b.

2485   Kasimov, N., Shinkareva, G., Lychagin, M., Kosheleva, N., Chalov, S., Pashkina, M., Thorslund, J., and
2486   Jarsjö, J.:River water quality of the selenga-baikal basin: Part i—spatio-temporal patterns of dissolved and
2487   suspended metals, Water, 12(8), 2137, 2020a.

2488

2489 Kasimov, N., Shinkareva, G., Lychagin, M., Chalov, S., Pashkina, M., Thorslund, J., and Jarsjö, J.: River water
2490 quality of the selenga-baikal basin: part ii — metal partitioning under different hydroclimatic conditions,
2491 Water, 12(9), 2392, 2020b.

2492

2493 Kaus, A., Schäffer, M., Karthe, D., Büttner, O., von Tümpling, W., and Borchardt, D.: Regional patterns of
2494 heavy metal exposure and contamination in the fish fauna of the Kharaa River basin, Mongolia, Reg.
2495 Environ. Change, 17, 2023–2037, doi: 10.1007/s10113-016-0969-4, 2017.

2496 Kazakov, E., Kondrik, D., and Pozdnyakov, D.: A synthetic satellite dataset of the spatio-temporal
2497 distributions of Emiliania huxleyi blooms and their impacts on Arctic and sub-Arctic marine environments
2498 (1998–2016), Earth Systems Science Data, 11, 119–128, doi: 10.5194/essd-11-119-2019, 2019.

2499 Kecorius, S., Vogl, T., Paasonen, P., Lampilahti, J., Rothenberg, D., Wex, H., Zeppenfeld, S., van Pinxteren,
2500 M., Hartmann, M., Henning, S., Gong, X., Welti, A., Kulmala, M., Stratmann, F., Herrmann, H., and
2501 Wiedensohler, A.: New particle formation and its effect on cloud condensation nuclei abundance in the
2502 summer Arctic: a case study in the Fram Strait and Barents Sea, Atmos. Chem. Phys., 19, 14339–14364, doi:
2503 10.5194/acp-19-14339-2019, 2019.

2504 Kerminen, V.-M., Chen, X., Vakkari, V., Petäjä, T., Kulmala, M., and Bianchi, F.: Atmospheric new particle
2505 formation and growth: review of field observations, Environ. Res. Lett., 13, 103003, doi: 10.1088/1748-
2506 9326/aadf3c, 2018.

2507 Kim, J., Kim, H. M., Cho, C.-H., Boo, K.-O., Jacobson, A. R., Sasakawa, M., Machida, T., Arshinov, M.,
2508 and Fedoseev, N.: Impact of Siberian observations on the optimization of surface CO2 flux, Atmos. Chem.
2509 Phys., 17, 2881–2899, https://doi.org/10.5194/acp-17-2881-2017, 2017.

2510 Kirillin, G., Leppäranta, M., Terzhevik, A., Bernhardt, J., Engelhardt, C., Granin, N., Golosov, S., Efremova,
2511 T., Palshin, N., Sherstyankin, P., Zdorovennova, G., and Zdorovennov, R.: Physics of seasonally ice-covered
2512 lakes: major drivers and temporal/spatial scales, Aquatic Ecol., 74, 659–682, 2012.

2513 Kirillin, G., Aslamov, I., Leppäranta, M., and Lindgren, E.: Turbulent mixing and heat fluxes under lake ice:
2514 the role of seiche oscillations, Hydrology of Earth System Sciences, 22(12), 6493-6504, doi:10.5194/hess-
2515 22-6493-2018, 2018.

2516 Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P.
2517 Bergmann, D, Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser,
2518 A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J.-F.,
2519 Langenfelds, R. L., Le Quere, C., Naik, V., O'Doherty, S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B.,
2520 Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R.,
2521 Steele, L. P., Strode, S. A., Sudo, K., Szopa, S., van der Werf, G.R., Voulgarakis, A., van Weele, M., Weiss,
2522 R. F., Williams, J. E., and Zeng, G.: Three decades of global methane sources and sinks, Nature Geoscience,
2523 6(10), 813-823, doi: 10.1038/ngeo1955, 2013.

Kiselev, M. V., Voropay, N. N., and Cherkashina, A. A.: influence of anthropogenic activities on the temperature regime of soils of the South-Western Baikal region, IOP Conf. Ser.: Earth Environ. Sci., 381, 012043, doi: 10.1088/1755-1315/381/1/012043, 2019.

Kittler, F., Heimann, M., Kolle, O., Zimov, N., Zimov, S., and Göckede, M.: Long-term drainage reduces CO_2 uptake and CH_4 emissions in a Siberian permafrost ecosystem, Global Biogeochemical Cycles, 31, 1704– 1717. doi: 10.1002/2017GB005774, 2017.

Kiuru, P., Ojala, A., Mammarella, I., Heiskanen, J., Kämäräinen, M., Vesala, T. and Huttula, T.: Effects of Climate Change on CO_2 Concentration and Efflux in a Humic Boreal Lake: A Modeling Study, Journal of Geophysical Research, Biogeosciences, 123, 7, 2212-2233, 2018.

Kondrik, D., Pozdnyakov, D., and Pettersson, L.: Particulate inorganic carbon production within E. huxleyi blooms in subpolar and polar seas: a satellite time series study (1998–2013), International Journal of Remote Sensing, 38:22, 6179-6205, doi: 10.1080/01431161.2017.1350304, 2017.

Kondrik, D. V., Pozdnyakov, D. V., and Johannessen, O. M.: Satellite evidence that E. huxleyi phytoplankton blooms weaken marine carbon sinks, Geophys. Res. Lett., 5, 846–854. doi: 10.1002/2017GL076240, 2018a.

Kondrik, D. V., Pozdnyakov, D. V., and Pettersson, L. H.: Tendencies in Coccolithophorid Blooms in Some Marine Environments of the Northern Hemisphere according to the Data of Satellite Observations in 1998–2013. Izv. Atmos. Ocean. Phys., 53, 955-964, doi: 10.1134/S000143381709016X, 2018b.

Kondrik, D. V., Kazakov, E. E., Pozdnyakov, D. V., and Johannessen, O. M.: Satellite evidence for enhancement of the column mixing ratio of atmospheric CO_2 over E. huxleyi blooms, Transactions of the Karelian Research Centre of the Russian Academy of Sciences, Limnologoia i Oceanologia series, 9, 1-11, doi: 10/17076/lim1107, 2019.

Konovalov, I. B., Lvova, D. A., Beekmann, M., Jethva, H., Mikhailov, E. F., Paris, J.-D., Belan, B. D., Kozlov, V. S., Ciais, P., and Andreae, M. O.: Estimation of black carbon emissions from Siberian fires using satellite observations of absorption and extinction optical depths, Atmos. Chem. Phys., 18, 14889–14924, doi: 10.5194/acp-18-14889-2018, 2018.

Konovalov V., Rets E., and Pimankina N.: Interrelation between glacier summer mass balance and runoff in mountain river basins, Geography, Environment, Sustainability, 12(1), 23-33, doi: 10.24057/2071-9388-2018-26, 2019.

Konstantinov, P. I., Grishchenko, M. Y., and Varentsov, M. I.: Mapping urban heat islands of arctic cities using combined data on field measurements and satellite images based on the example of the city of Apatity (Murmansk Oblast), Izv. Atmos. Ocean. Phys., 51(9), 992-998, doi:10.1134/s000143381509011x, 2015.

Konstantinov, P., Varentsov, M., and Esau, I.: A high density urban temperature network deployed in several cities of Eurasian Arctic, Environ. Res. Lett., 13(7), 12, doi:10.1088/1748-9326/aacb84, 2018.

2558   Kontkanen, J., Paasonen, P., Aalto, J., Back, J., Rantala, P., Petäjä, T., and Kulmala, M.: Simple proxies for

2559   estimating the concentrations of monoterpenes and their oxidation products at a boreal forest site, Atmos.

2560   Chem. Phy., 16(20), 13291-13307, doi:10.5194/acp-16-13291-2016, 2016.

2561   Kooijmans, L. M. J., Sun, W., Aalto, J., Erkkilä, K.M., Maseyk, K., Seibt, U., Vesala, T., Mammarella, I.,

2562   and Chen, H.: Influences of light and humidity on carbonyl sulfide-based estimates of photosynthesis,

2563   Proceedings of the National Academy of Sciences, 116 (7), 2470-2475, doi:10.1073/pnas.1807600116, 2019.

2564   Korneykova, M. V., and Evdokimova, G. A.: Microbiota of the ground air layers in natural and industrial

2565   zones of the Kola Arctic, J Environ. Sci. Health A, 53(3), 271-277, doi:10.1080/10934529.2017.1397444,

2566   2018a.

2567   Korneikova, M. V., Redkina, V. V., and Shalygina, R. R.: Algological and mycological characterization of

2568   soils under pine and birch forests in the Pasvik Reserve, Eurasian Soil Science, 51(2), 211-220,

2569   doi:10.1134/s1064229318020047, 2018b.

2570   Koronatova, N. G., & Milyaeva, E. V.:Plant community succession in post-mined quarries in the northern-

2571   taiga zone of West Siberia. Contemporary Problems of Ecology, 4(5), 513–518, 2011.

2572   Kukkonen, I., Ezhova, E., Suhonen, E. A. J., Lappalainen, H. K., Gennadinik, V., Ponomareva, O., Gravis,

2573   A., Miles, V., Kulmala, M., Melnikov, V., and Drozdov, D.: Observations and modelling of ground

2574   temperature evolution in the discontinuous permafrost zone in Nadym, North-West Siberia, Permafrost and

2575   Periglacial Processes, 1– 17, doi:10.1002/ppp.2040, 2020.

2576   Kulmala, M., Vehkamäki, H., Petäjä, T., .Dal Maso, M., Lauri, A., Kerminen, V-M., Birmili, W., and

2577   McMurry, P.H.: Formation and growth rates of ultrafine atmospheric particles: a review of observations,

2578   Journal of Aerosol Science, 35, 143-176, doi:10.1134/S1995425511050, 2004.

2579   Kulmala, M.: Atmospheric chemistry: China's choking cocktail, Nature, 526, 497-499,

2580   doi:10.1038/526497a, 2015a.

2581   Kulmala, M., Lappalainen, H. K., Petäjä, T., Kurten, T., Kerminen, V.-M., Viisanen, Y., Hari, P., Sorvari, S.,

2582   Bäck, J., Bondur, V., Kasimov, N., Kotlyakov, V., Matvienko, G., Baklanov, A., Guo, H. D., Ding, A.,

2583   Hansson, H.-C., and Zilitinkevich, S.: Introduction: The Pan-Eurasian Experiment (PEEX) –

2584   multidisciplinary, multiscale and multicomponent research and capacity-building initiative, Atmos. Chem.

2585   Phys., 15, 13085-13096, doi:10.5194/acp-15-13085-2015, 2015b.

2586   Kulmala, M., Lappalainen, H. K., Petäjä, T., Kerminen, V.-M., Viisanen, Y., Matvienko, G., Melnikov, V.,

2587   Baklanov, A., Bondur, V., Kasimov, N., and Zilitinkevich, S.: Pan-Eurasian Experiment (PEEX) Program:

2588   Grant Challenges in the Arctic-boreal context, J. Geography Environment Sustainability, 2, 5–18, 2016a.

2589   Kulmala, M., Petäjä, T., Kerminen, V. M., Kujansuu, J., Ruuskanen, T., Ding, A., Nie, W., Hu, M., Wang,

2590   Z., Wu, Z., and Wang, L.: On secondary new particle formation in China, Front. Environ. Sci. Eng., 10, 8,

2591   doi:10.1007/s11783-016-0850-1, 2016b.

2592   Kulmala, M., Kerminen, V.-M., Petäjä, T., Ding, A. J., and Wang L.: Atmospheric gas-to-particle
2593   conversion: why NPF events are observed in megacities?, Faraday Discuss., 200, 271-288,
2594   doi:10.1039/c6fd00257a, 2017.

2595   Kulmala, M.: Build a global Earth observatory, Nature, 553, 21-23, doi: 10.1038/d41586-017-08967-y, 2018.

2596   Kulmala, L., Pumpanen, J., Kolari, P., Dengel, S., Berninger, F., Köster, K., Matkala, L., Vanhatalo, A.,
2597   Vesala, T., and Bäck, J.: Inter- and intra-annual dynamics of photosynthesis differ between forest floor
2598   vegetation and tree canopy in a subarctic Scots pine stand, Agricultural and Forest Meteorology, 271, 1-11,
2599   doi: 10.1016/j.agrformet.2019.02.029, 2019.

2600   Kulmala, M., Dada, L., Daellenbach, K. R., Yan, C., Stolzenburg, D., Kontkanen, J., Ezhova, E., Hakala, S.,
2601   Tuovinen, S., Kokkonen, T. V., Kurppa, M., Cai, R., Zhou, Y., Yin, R., Baalbaki, R., Chan, T., Chu, B.,
2602   Deng, C., Fu, Y., Ge, M., He, H., Heikkinen, L., Junninen, H., Liu, Y., Lu, Y., Nie, W., Rusanen, A.,
2603   Vakkari, V., Wang, V., Yang, G., Yao, L., Zheng, J., Kujansuu, J., Kangasluoma, J., Petäjä, T., Paasonen, P.,
2604   Järvi, L., Worsnop, D., Ding, A., Liu, Y., Wang, L., Jiang, J., Bianchi, F., and Kerminen, V.-M.: Is reducing
2605   new particle formation a plausible solution to mitigate particulate air pollution in Beijing and other Chinese
2606   megacities?, Faraday Discussions, doi: 10.1039/D0FD00078G.2021.

2607   Kwon, M. J., Beulig, F., Ilie, I., Wildner, M., Küsel, K., Merbold, L., Mahecha, M. D., Zimov, N., Zimov, S.
2608   A., Heimann, M., Schuur, E. A. G., Kostka, J. E., Kolle, O., Hilke, I. and Göckede, M.: Plants,
2609   microorganisms, and soil temperatures contribute to a decrease in methane fluxes on a drained Arctic
2610   floodplain, Glob. Change Biol., 23, 2396-2412, doi:10.1111/gcb.13558, 2017.

2611   Kwon, M. J., Natali, S. M., Hicks Pries, C. E., Schuur, E. A., Steinhof, A., Crummer, K .G., Zimov, N.,
2612   Zimov, S. A., Heimann, M., Kolle, O., and Göckede, M.: Drainage enhances modern soil carbon contribution
2613   but reduces old soil carbon contribution to ecosystem respiration in tundra ecosystems, Glob. Change Biol.,
2614   25, 1315– 1325, doi: 10.1111/gcb.14578, 2019.

2615   Kühn, T., Kupiainen, K., Miinalainen, T., Kokkola, H., Paunu, V.-V., Laakso, A., Tonttila, J., Van
2616   Dingenen, R., Kulovesi, K., Karvosenoja, N., and Lehtinen, K. E. J.: Effects of black carbon mitigation on
2617   Arctic climate, Atmos. Chem. Phys., 20, 5527–5546, doi: 10.5194/acp-20-5527-2020, 2020.

2618   Köster, E., Köster, K., Berninger, F., and Pumpanen, J.: Carbon dioxide, methane and nitrous oxide fluxes
2619   from podzols of a fire chronosequence in the boreal forests in Värriö, Finnish Lapland, Geoderma Regional,
2620   5, 181-187, doi:10.1016/j.geodrs.2015.07.001, 2015.

2621   Köster, E., Köster, K., Berninger, F., Prokushkin, A., Aaltonen, H., Zhou, X., and Pumpanen, J.: Changes in
2622   fluxes of carbon dioxide and methane caused by fire in Siberian boreal forest with continuous permafrost,
2623   Journal of Environmental Management, 228, 405-415, doi:10.1016/j.jenvman.2018.09.051, 2018.

Köster, K., Berninger, F., Koster, E., and Pumpanen, J.: Influences of reindeer grazing on above- and belowground biomass and soil carbon dynamics, Arctic Antarctic and Alpine Res., 47(3), 495-503, doi:10.1657/aaar0014-062, 2015.

Köster, K., Berninger, F., Heinonsalo, J., Lindén, A., Köster, E., Ilvesniemi, H., and Pumpanen J.: The long-term impact of low-intensity surface fires on litter decomposition and enzyme activities in boreal coniferous forests, Int. J Wildland Fire, 25(2), 213-223, doi:10.1071/wf14217_co, 2016.

Köster, K., Koster, E., Berninger, F., Heinonsalo, J., and Pumpanen, J.: Contrasting effects of reindeer grazing on CO2, CH4, and N2O fluxes originating from the northern boreal forest floor. Land Degradation and Development, 29(2), 374-381, doi:10.1002/ldr.2868, 2018.

Köster, K., Koster, E., Kulmala, L., Berninger, F., and Pumpanen, J.: Are the climatic factors combined with reindeer grazing affecting the soil CO2 emissions in subarctic boreal pine forest? Catena, 149, 616-622, doi:10.1016/j.catena.2016.06.011, 2017.

Lan, H., Holopainen, J., Hartonen, K., Jussila, M., Ritala, M. and Riekkola, M.-L.: Fully automated online dynamic in-tube extraction for continuous sampling of volatile organic compounds in air, Anal. Chem., 91, 8507, 2019.

Lappalainen, H.K., Kulmala, M. and Zilitinkevich, S. (Eds.): Pan Eurasian Experiment (PEEX) Science Plan, web: www.atm.helsinki.fi/peex, ISBN 978-951-51-0587-5 (printed), ISBN 978-951-51-0588-2 (online), 2015.

Lappalainen H.K., Petäjä T., Kujansuu J., Kerminen V., Shvidenko A., Bäck J., Vesala T., Vihma T., De Leeuw G., Lauri A., Ruuskanen T., Lapshin V.B., Zaitseva N., Glezer O., Arshinov M., Spracklen D.V., Arnold S.R., Juhola S., Lihavainen H., Viisanen Y., Chubarova N., Chalov S., Filatov N., Skorokhod A., Elansky N., Dyukarev E., Esau I., Hari P., Kotlyakov V., Kasimov N., Bondur V., Matvienko G., Baklanov A., Mareev E., Troitskaya Y., Ding A., Guo H., Zilitinkevich S., and Kulmala M.: Pan-Eurasian Experiment (PEEX) –a research initiative meeting the grand challenges of the changing environment of the northern Pan-Eurasian arctic-boreal areas, J. Geography Environment Sustainability, 2(7), 13-48, doi:10.24057/2071-9388-2014-7-2-13-48, 2014.

Lappalainen, H. K., Kerminen, V.-M., Petäjä, T., Kurten, T., Baklanov, A., Shvidenko, A., Bäck, J., Vihma, T., Alekseychik, P., Andreae, M. O., Arnold, S. R., Arshinov, M., Asmi, E., Belan, B., Bobylev, L., Chalov, S., Cheng, Y., Chubarova, N., de Leeuw, G., Ding, A., Dobrolyubov, S., Dubtsov, S., Dyukarev, E., Elansky, N., Eleftheriadis, K., Esau, I., Filatov, N., Flint, M., Fu, C., Glezer, O., Gliko, A., Heimann, M., Holtslag, A. A. M., Hõrrak, U., Janhunen, J., Juhola, S., Järvi, L., Järvinen, H., Kanukhina, A., Konstantinov, P., Kotlyakov, V., Kieloaho, A.-J., Komarov, A. S., Kujansuu, J., Kukkonen, I., Duplissy, E.-M., Laaksonen, A., Laurila, T., Lihavainen, H., Lisitzin, A., Mahura, A., Makshtas, A., Mareev, E., Mazon, S., Matishov, D., Melnikov, V., Mikhailov, E., Moisseev, D., Nigmatulin, R., Noe, S. M., Ojala, A., Pihlatie, M., Popovicheva, O., Pumpanen, J., Regerand, T., Repina, I., Shcherbinin, A., Shevchenko, V., Sipilä, M., Skorokhod, A.,

2659   Spracklen, D. V., Su, H., Subetto, D. A., Sun, J., Terzhevik, A. Y., Timofeyev, Y., Troitskaya, Y.,

2660   Tynkkynen, V.-P., Kharuk, V. I., Zaytseva, N., Zhang, J., Viisanen, Y., Vesala, T., Hari, P., Hansson, H. C.,

2661   Matvienko, G. G., Kasimov, N. S., Guo, H., Bondur, V., Zilitinkevich, S., and Kulmala, M.: Pan-Eurasian

2662   Experiment (PEEX): towards a holistic understanding of the feedbacks and interactions in the land–

2663   atmosphere–ocean–society continuum in the northern Eurasian region, Atmos. Chem. Phys., 16, 14421–

2664   14461, https://doi.org/10.5194/acp-16-14421-2016, 2016.

2665   Lappalainen, H.K., Kulmala, M., Kujansuu, J., Petäjä, T., Mahura, A., de Leeuw, G., Zilitinkevich, S.,

2666   Juustila, M., Kerminen, V.M., Bornstein, B. and Jiahua, Z.: The Silk Road agenda of the Pan-Eurasian

2667   Experiment (PEEX) program, Big Earth Data, 2(1), 8-35, doi:10.1080/20964471.2018.1437704, 2018.

2668   Lei, R. B., Xie, H. J., Wang, J., Leppäranta, M., Jonsdottir, I., and Zhang, Z. H.: Changes in sea ice

2669   conditions along the Arctic Northeast Passage from 1979 to 2012, Cold Regions Science and Technology,

2670   119, 132-144. doi:10.1016/j.coldregions.2015.08.004, 2015.

2671   Lei, R., Tian-Kunze, X., Leppäranta, M., Wang, J., Kaleschke, L., and Zhang, Z.: Changes in summer sea

2672   ice, albedo, and portioning of surface solar radiation in the Pacific sector of Arctic Ocean during 1982-2009,

2673   J. Geophys. Res.: Oceans, 121(8), 5470-5486, doi:10.1002/2016jc011831, 2016.

2674   Lei, R. B., Cheng, B., Heil, P., Vihma, T., Wang, J., Ji, Q., and Zhang, Z. H.: Seasonal and interannual

2675   variations of sea ice mass balance from the Central Arctic to the Greenland Sea, J. Geophys. Res.: Oceans,

2676   123(4), 2422-2439, doi:10.1002/2017jc013548, 2018.

2677   Leino, K., Nieminen, T., Manninen, H. E., Petäjä, T., Kerminen, V.-M., and Kulmala, M.: Intermediate ions

2678   as a strong indicator of new particle formation bursts in a boreal forest, Boreal Environ. Res., 21(3-4), 274-

2679   286, 2016.

2680   Leppäranta, M.: Structure and properties of lake ice. Freezing of Lakes and the Evolution of their Ice Cover,

2681   Springer, Berlin/Heidelberg, Germany, 51–90. doi: 10.1007/978-3-642-29081-7_3, 2015.

2682   Leppäranta, M., Lindgren, E., and Shirasawa, K.: The heat budget of Lake Kilpisjarvi in the Arctic tundra,

2683   Hydrol. Res., 48(4), 969-980, doi:10.2166/nh.2016.171, 2017.

2684   Leppäranta, M., Lewis, J. E., Heini, A., and Arvola, L.: Spatial statistics of hydrography and water chemistry

2685   in a eutrophic boreal lake based on sounding and water samples, Environ. Monit. Assess., 190(7), 378,

2686   doi:10.1007/s10661-018-6742-z, 2018.

2687   Leppäranta, M., Lindgren, E., Wen, L. and Kirillin, G.: Ice cover decay and heat balance in Lake Kilpisjärvi

2688   in Arctic tundra, Journal of Limnology, 78(2). doi: 10.4081/jlimnol.2019.1879, 2019.

2689   Leppäranta, M., Meleshko, V., Uotila, P., and Pavlova, T.: Sea ice modelling, 315-387, Sea Ice in the Arctic
2690   (Springer, Cham), 2020.

Li, H., Väliranta, M., Mäki, M., Kohl, L., Sannel, B., Pumpanen, J., Koskinen, M., Bäck, J. and Bianchi, F.: Overlooked organic vapor emissions from thawing Arctic permafrost, Environmental Research Letters 15, Issue 10, id.104097, 12 pp., 2020a.

Li, M., Wang, L., Liu, J., Gao, W., Song, T., Sun, Y., Li, L., Li, X., Wang, Y., Liu, L. and Daellenbach, K.R., Paasonen, P.J., Kerminen, V.-M., Kulmala, M., and Wang Y.: Exploring the regional pollution characteristics and meteorological formation mechanism of PM2. 5 in North China during 2013–2017, Environment international, 134, 105283, 2020b.

Liao, Z., Cheng, B., Zhao, J., Vihma, T., Jackson, K., Yang, Q., Yang, Y., Zhang, L., Li, Z., Qiu, Y., and Cheng, X.: Snow depth and ice thickness derived from SIMBA ice mass balance buoy data using an automated algorithm, Int. J. Digital Earth, 12(8), 962-979, doi:10.1080/17538947.2018.1545877, 2018.

Lin, X., Rogers, B. M., Sweeney, C., Chevallier, F., Arshinov, M., Dlugokencky, E., Machida, T., Motoki Sasakawa, Tans, P., Keppel-Aleks, G.: Siberian and temperate ecosystems shape Northern Hemisphere atmospheric CO_2 seasonal amplification, PNAS, 117 (35), 21079-21087, doi:10.1073/pnas.1914135117 , 2020.

Lintunen, A., Paljakka, T., Salmon, Y., Dewar, R., Riikonen, A, and Hölttä, T.: The influence of soil temperature and water content on belowground hydraulic conductance and leaf gas exchange in mature trees of three boreal species, Plant, Cell and Environment, 43, 532-547, doi: 10.1111/pce.13709, 2020.

Liu, J., Wang, L., Li, M., Liao, Z., Sun, Y., Song, T., Gao, W., Wang, Y., Li, Y., Ji, D., Hu, B., Kerminen, V.-M., Wang, Y., and Kulmala, M.: Quantifying the impact of synoptic circulation patterns on ozone variability in northern China from April to October 2013–2017, Atmos. Chem. Phys., 19, 14477–14492, doi:10.5194/acp-19-14477-2019, 2019 a.

Liu, W., Atherton, J., Mõttus, M., Gastellu-Etchegorry, J.P., Malenovský, Z., Raumonen, P., Åkerblom, M., Mäkipää, R. and Porcar-Castell, A.: Simulating solar-induced chlorophyll fluorescence in a boreal forest stand reconstructed from terrestrial laser scanning measurements, Remote Sensing of Environment, 232, 111274, 2019b.

Liu, Y., de Leeuw, G., Kerminen, V.-M., Zhang, J., Zhou, P., Nie, W., Qi, X., Hong, J., Wang, Y., Ding, A., Guo, H., Krüger, O., Kulmala, M., and Petäjä, T.: Analysis of aerosol effects on warm clouds over the Yangtze River Delta from multi-sensor satellite observations, Atmos. Chem. Phys., 17, 5623–5641, doi:10.5194/acp-17-5623-2017, 2017.

Liu, Y., Zhang, J., Zhou, P., Lin, T., Hong, J., Shi, L., Yao, F., Wu, J., Guo, H., and de Leeuw, G.: Satellite-based estimate of the variability of warm cloud properties associated with aerosol and meteorological conditions, Atmos. Chem. Phys., 18, 18187–18202, doi:10.5194/acp-18-18187-2018, 2018.

López-Blanco, E., Exbrayat, J.-F., Lund, M., Christensen, T. R., Tamstorf, M. P., Slevin, D., Hugelius, G., Bloom, A. A., and Williams, M.: Evaluation of terrestrial pan-Arctic carbon cycling using a data-assimilation system, Earth Syst. Dynam., 10, 233–255, doi:10.5194/esd-10-233-2019, 2019.

Lu, P., Leppäranta, M., Cheng, B., and Li, Z.: Influence of melt-pond depth and ice thickness on Arctic sea-ice albedo and light transmittance, Cold Regions Science and Technology, 124, 1-10, doi:10.1016/j.coldregions.2015.12.010, 2016.

Lu, P., Cheng, B., Leppäranta, M., and Li, Z. J.: Partitioning of solar radiation in Arctic sea ice during melt season, Oceanologia, 60(4), 464-477, doi:10.1016/j.oceano.2018.03.002, 2018a.

Lu, P., Leppäranta, M., Cheng, B., Li, Z., Istomina, L., and Heygster, G.: The color of melt ponds on Arctic sea ice, The Cryosphere, 12, 1331–1345, doi:10.5194/tc-12-1331-2018, 2018b.

Luoma, K., Virkkula, A., Aalto, P.P, Petäjä, T., and Kulmala, M.: Over a 10-year record of aerosol optical properties at SMEAR II, Atmos. Chem. Phys., 19, 11363–11382, doi:10.5194/acp-19-11363-2019, 2019.

Lychagin, M., Chalov, S., Kasimov, N., Shinkareva, G., Jarsjo, J., and Thorslund, J.: Surface water pathways and fluxes of metals under changing environmental conditions and human interventions in the Selenga River system, Environ. Earth Sci., 76(1), 14, doi:10.1007/s12665-016-6304-z, 2017.

Ma,J., Yan, X., Dong, W. et al.: Gross primary production of global forest ecosystems has been overestimated, Sci Rep 5, 10820, doi:10.1038/srep10820, 2015.

Magritsky, D. V., Frolova, N. L. , Evstigneev, V. M. , Povalishnikova, E. S. , Kireeva, M. B., and Pakhomova, O. M.: Long-term changes of river water inflow into the seas of the Russian Arctic sector, Polarforschung, 87(2),177-194, doi: 10.2312/polarforschung.87.2.177, 2018.

Mahura A., Baklanov A., Sørensen, J. H., Svetlov, A., and Koshkin, V.: Assessment of Long-Range Transport and Deposition from Cu-Ni Smelters of Russian North. In ”Air, Water and Soil Quality Modelling for Risk and Impact Assessment", Security Through Science, Series C - Environmental Security. Eds. A. Ebel, T. Davitashvili, Springer Elsevier Publishers, pp. 115-124, 2007.

Mahura, A., Gonzalez-Aparacio, I., Nuterman, R., and Baklanov, A.: Seasonal Impact Analysis on Population due to Continuous Sulphur Emissions from Severonikel Smelters of the Kola Peninsula. Geography, Environment, Sustainability, 11(1), 130-144, doi:10.24057/2071-9388-2018-11-1-130-144, 2018.

Malkhazova, S. M., Mironova, V. A., Orlov, D. S., and Adishcheva, O. S.: Influence of climatic factor on naturally determined diseases in a regional context, Geography, Environment, Sustainability, 11(1), 157-170, doi:10.24057/2071-9388-2018-11-1-157-170, 2018.

Malsy, M., Flörke, M., and Borchardt, D.:What drives the water quality changes in the Selenga basin: climate change or socio-economic development?, Reg Environ Chang., 17, 1977–1989 doi:10.1007/s10113-016-1005-4, 2017.

2757   Mammarella, I., Nordbo, A., Rannik, Ü., Haapanala, S., Levula, J., Laakso, H., Ojala, A., Peltola, O.,

2758   Heiskanen, J., Pumpanen, J. and Vesala, T.: Carbon dioxide and energy fluxes over a small boreal lake in

2759   Southern Finland, J. Geophys. Res.: Biogeosciences, 120(7), 1296-1314, doi:10.1002/2014jg002873, 2015.

2760   Manasypov, R. M., Vorobyev, S. N., Loiko, S. V., Krivtzov, I. V., Shirokova, L. S., Shevchenko, V. P.,

2761   Kirpotin, S. N., Kulizhsky, S. P., Kolesnichenko, L. G., Zemtsov, V. A. and Sinkinov, V. V.: Seasonal

2762   dynamics of thermokarst lake chemical composition in discontinuous permafrost zone of Western Siberia,

2763   Biogeosciences, 12, 3009-3028, 2015.

2764   Marelle, L., Raut, J. C., Law, K. S., and Duclaux, O.: Current and future arctic aerosols and ozone from

2765   remote emissions and emerging local sources-modeled source contributions and radiative effects, J.

2766   Geophys. Res.: Atmos., 123(22), 12942-12963, doi:10.1029/2018jd028863, 2018.

2767   Maslov, A. V., Shevchenko, V. P., Bobrov, V. A., Belogub, E. V., Ershova, V. B., Vereshchagin, O. S., and

2768   Khvorov, P. V.: Mineralogical-geochemical features of ice-rafted sediments in some arctic regions,

2769   Lithology and Mineral Resources, 53(2), 110-129, doi:10.1134/s0024490218020037, 2018a.

2770   Maslov, A. V., Shevchenko, V. P., Kuznetsov, A. B., and Stein, R.: Geochemical and Sr-Nd-Pb-isotope

2771   characteristics of ice-rafted sediments of the Arctic Ocean, Geochem. Int., 56(8), 751-765,

2772   doi:10.1134/s0016702918080050, 2018b.

2773   Matkala, L., Kulmala, L., Kolari, P., Aurela, M., and Bäck, J.: Resilience of carbon dioxide and water

2774   exchange to extreme weather events in subarctic Scots pine and Norway spruce stands, Agricultural and

2775   Forest Meteorology, 296, 108239, 2020.

2776   McCusker, K., Fyfe, J., and Sigmond, M.: Twenty-five winters of unexpected Eurasian cooling unlikely due

2777   to Arctic sea-ice loss, Nature Geoscience 9, 838–842, doi:10.1038/ngeo2820, 2016.

2778   Meinander, O., Heikkinen, E., Aurela, M., and Hyvärinen, A.: Sampling, Filtering, and Analysis Protocols to

2779   Detect Black Carbon, Organic Carbon, and Total Carbon in Seasonal Surface Snow in an Urban Background

2780   and Arctic Finland (>60° N), Atmosphere, 11, 923. doi:10.3390/atmos11090923, 2020a.

2781   Meinander, O., Kontu, A., Kouznetsov, R., Sofiev, M.: Snow Samples Combined with Long-Range

2782   Transport Modeling to Reveal the Origin and Temporal Variability of Black Carbon in Seasonal Snow in

2783   Sodankylä (67° N), Front. Earth Sci., 8, 13,

2784   https://www.frontiersin.org/articles/10.3389/feart.2020.00153/full, 2020b.

2785   Merkouriadi, I., Cheng, B., Graham, R. M., Rösel, A., and Granskog, M. A.: Critical role of snow on sea ice

2786   growth in the Atlantic sector of the Arctic Ocean. Geophysical Research Letters, 44.

2787   doi:10.1002/2017GL075494, 2017

2788   Merkouriadi, I., Cheng, B., Graham, R. M., Rösel, A., and Granskog, M. A.: Critical role of snow on sea ice

2789   growth in the Atlantic sector of the Arctic Ocean, Geophys. Res. Lett., 44, doi: 10.1002/2017GL075494,

2790   2018.

2791   Mikhailov, E. F., Mironova, S. Y., Makarova, M. V., Vlasenko, S. S., Ryshkevich, T. I., Panov, A. V., and

2792   Andreae, M. O.: Studying seasonal variations in carbonaceous aerosol particles in the atmosphere over

2793   central Siberia, Izv. Atmos. Oceanic Phys., 51(4), 423-430, doi:10.1134/s000143381504009x, 2015a.

2794   Mikhailov, E. F., Mironov, G. N., Pöhlker, C., Chi, X., Krüger, M. L., Shiraiwa, M., Förster, J.-D., Pöschl,

2795   U., Vlasenko, S. S., Ryshkevich, T. I., Weigand, M., Kilcoyne, A. L. D., and Andreae, M. O.: Chemical

2796   composition, microstructure, and hygroscopic properties of aerosol particles at the Zotino Tall Tower

2797   Observatory (ZOTTO), Siberia, during a summer campaign, Atmos. Chem. Phys., 15, 8847–8869,

2798   doi:10.5194/acp-15-8847-2015, 2015b.

2799   Mikhailov, E. F., Mironova, S., Mironov, G., Vlasenko, S., Panov, A., Chi, X., Walter, D., Carbone, S.,

2800   Artaxo, P., Heimann, M., Lavric, J., Pöschl, U., and Andreae, M. O.: Long-term measurements (2010–2014)

2801   of carbonaceous aerosol and carbon monoxide at the Zotino Tall Tower Observatory (ZOTTO) in central

2802   Siberia, Atmos. Chem. Phys., 17, 14365–14392, doi:10.5194/acp-17-14365-2017, 2017.

2803   Mikola, J., Virtanen, T., Linkosalmi, M., Vähä, E., Nyman, J., Postanogova, O., Räsänen, A., Kotze, D. J.,

2804   Laurila, T., Juutinen, S., Kondratyev, V., and Aurela, M.: Spatial variation and linkages of soil and

2805   vegetation in the Siberian Arctic tundra – coupling field observations with remote sensing data,

2806   Biogeosciences, 15, 2781–2801, doi:10.5194/bg-15-2781-2018, 2018.

2807   Miles, V. V., and Esau, I.: Spatial heterogeneity of greening and browning between and within bioclimatic

2808   zones in northern West Siberia, Environ. Res. Lett., 11(11), 12, doi:10.1088/1748-9326/11/11/115002, 2016.

2809   Miles, V., and Esau, I.: Seasonal and Spatial Characteristics of Urban Heat Islands (UHIs) in Northern West

2810   Siberian Cities., Remote Sens., 9, 989, 2017.

2811   Miles, M. W., Miles, V, and Esau, I.: Varying climate response across the tundra, forest–tundra and boreal

2812   forest biomes in northern West Siberia, Environ. Res. Lett., 14, 075008, doi:10.1088/1748-9326/ab2364,

2813   2019.

2814   Miles, V., and Esau, I.: Surface urban heat islands in 57 cities across different climates in northern

2815   Fennoscandia, Urban Climate, 31, 10.1016/j.uclim.2019.100575, 2020.

2816   Miles, V.: Arctic surface Urban Heat Island (UHI), MODIS Land Surface Temperature (LST) data, 2000-

2817   2016. Arctic Data Center. doi:10.18739/A2TB0XW4T, 2020.

2818   Mori, M., Watanabe, M., Shiogama, H., Inoue, J., and Kimoton, M.: Robust Arctic sea-ice influence on the

2819   frequent Eurasian cold winters in past decades, Nat. Geosci., 7, 869–873, doi:10.1038/ngeo2277, 2014.

2820   Mori, M., Kosaka, Y., Watanabe, M., Nakamura, H., and Kimoto, M.: A reconciled estimate of the influence

2821   of Arctic sea-ice loss on recent Eurasian cooling, Nat. Clim. Change, 9, 123–129, doi: 10.1038/s41558-018-

2822   0379-3, 2019.

2823   Morozov, E. A., Kondrik, D. V., Chepikova, S. S., and Pozdnyakov, D. V.: Atmospheric columnar CO_2

2824   enhancement over E. huxleyi blooms: case studies in the North Atlantic and Arctic waters. Transactions of

2825   the Karelian Research Centre of the Russian Academy of Sciences, Limnologoia i Oceanologia series, 3, 1-6.

2826   doi:10.17076/lim989, 2019.

2827   Myslenkov S., Medvedeva A., Arkhipkin V., Markina M., Surkova G., Krylov A., Dobrolyubov S.,

2828   Zilitinkevich S., and Koltermann P.: Long-term statistics of storms in the Baltic, Barents and White Seas and

2829   their future climate projections,. Geography, environment, sustainability, 11, 93-112, doi:10.24057/2071-

2830   9388-2018-11-1-93-112, 2018.

2831   Mäki, M., Krasnov, D., Hellén, H., Noe, S. M., and Bäck, J.: Stand type affects fluxes of volatile organic

2832   compounds from the forest floor in hemiboreal and boreal climates, Plant Soil, 441, 363–381,

2833   doi:10.1007/s11104-019-04129-3, 2019.

2834   Naakka, T., Nygård, T., Vihma, T., Graversen, R., and Sedlar, J.: Atmospheric moisture transport between

2835   mid-latitudes and the Arctic: regional, seasonal and vertical distributions, Int. J. Climatol., 32, 1–18,

2836   doi:10.1002/joc.5988, 2019.

2837   Natali, S.M., Watts, J.D., Rogers, B.M., Potter, S., Ludwig, S. M., Selbmann, A. K., Sullivan, P.F. Abbott, B.

2838   W., Arndt, K. A., Birch, L., Björkman, M.P., Bloom, A., Celis, G., Christensen, T. R., Christiansen, C. T.,

2839   Commane, R., Cooper, E. J., Crill, P., Czimczik, C., Davydov, S., Du, J., Egan, J.E., Elberling, B.,

2840   Euskirchen, B.S., Friborg, T., Genet, H., Göckede, M., Goodrich, J.P., Grogan, P., Helbig, M., Jafarov, E.E.,

2841   Jastrow, J. D., Kalhori, A.A.M., Kim, Y Kimball, J. S., Kutzbach, L., Lara, M. J, Larsen, K., S., Lee, B.-Y.,

2842   Liu, Z., Loranty, M. M., Lund, M., Lupascu, M., Madani, N., Malhotra, A., Matamala, R., McFarland, J.,

2843   McGuire, A. D., Michelsen, A., Minions, C., Oechel, W., Olefeldt, D., Parmentier, F.-J., Pirk, N., Poulter,

2844   B., Quinton, W., Rezanezhad, F., Risk, D., Sachs, T., Schaefer, K., Schmidt, N. M., Schuur, E., Semenchuk,

2845   P. R., Shaver, G., Sonnentag, O., Starr, G., Treat, C. C., Waldrop, M. P., Wang, Y., Welker, J., Wille, C., Xu,

2846   X., Zhang, Z., Zhuang, Q., and Zona, D.: Large loss of CO2 in winter observed across the northern

2847   permafrost region, Nat. Clim. Chang., 9, 852–857, doi:10.1038/s41558-019-0592-8, 2019.

2848   Nikandrova, A., Tabakova, K., Manninen, A., Väänänen, R., Petäjä, T., Kulmala, M., Kerminen, V.-M., and

2849   O'Connor, E.: Combining airborne in situ and ground-based lidar measurements for attribution of aerosol

2850   layers, Atmos. Chem. Phys., 18, 10575–10591, doi:10.5194/acp-18-10575-2018, 2018.

2851   NILU, 2013: Sandanger, T.M., Anda, E., Berglen, T.F., Evenset, A., Christensen, G., and Heimstad, E.S.:

2852   Health and environmental impacts in the Norwegian border area related to local Russian industrial emissions.

2853   Knowledge status, 40/2013, 2013.

2854   Nissen, C., Munnich, M., Grube, M., and Haumann, N.: Factors controlling coccolithophore biogeography in

2855   the Southern Ocean, Biogeosciences, 15(22), 6997-7024, doi:10.5194/bg-15-6997-2018, 2018.

2856   Nitzbon, J., Langer, M., Westermann, S., Martina, L., Aas, K. S., and Boike, J.: Pathways of ice-wedge

2857   degradation in polygonal tundra under different hydrological conditions, Cryosphere, 13(4), 1089-1123,

2858   doi:10.5194/tc-13-1089-2019, 2019.

Nygård, T., Graversen, R. G., Uotila, P., Naakka, T., and Vihma, T.: Strong dependence of wintertime Arctic moisture and cloud distributions on atmospheric large-scale circulation, J. Climate, 32, 8771-8790, doi: 10.1175/JCLI-D-19-0242.1, 2019.

Overland, J., Dunlea, E., Box, J. E., Corell, R., Forsius, M., Kattsov, V., Olsen, M. S., Pawlak, J., Reiersen, L. O., and Wang, M.: The urgency of Arctic change, Polar Science, 21, 6-13, doi:10.1016/j.polar.2018.11.008, 2019.

Paasonen, P., Peltola, M., Kontkanen, J., Junninen, H., Kerminen, V.-M., and Kulmala, M.: Comprehensive analysis of particle growth rates from nucleation mode to cloud condensation nuclei in boreal forest, Atmos. Chem. Phys., 18, 12085–12103, doi:10.5194/acp-18-12085-2018, 2018.

Palo, T., Vihma, T., Jaagus, J., and Jakobson, E.: Observations on temperature inversion over central Arctic sea ice in summer, Q. J. R. Meteorol. Soc., 143(708), 2741-2754, doi:10.1002/qj.3123, 2017.

Panov, A. V., Prokushkin, A. S., Bryukhanov, A. V., Korets, M. A., Ponomarev, E. I., Sidenko, N. V., Zrazhevskaya, G. K., Timokhina, A. V., and Andreae, M. O.: A complex approach for the estimation of carbonaceous emissions from wildfires in Siberia, Russian Meteorol, Hydrol., 43(5), 295-301, 2018.

Parmentier, F. W., Christensen, T. R., Rysgaard, S. Bendtsen, J., Glud, R. N., Else, B., van Huissteden, J., Sachs, T., Vonk, J. E., and Sejr, M. K.: A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere, Ambio, 46, 53–69, doi:10.1007/s13280-016-0872-8, 2017.

Parshintsev, J., Vaikkinen, A., Lipponen, K., Vrkoslav, V., Cvačka, J., et al. : Desorption atmospheric pressure photoionization high-resolution mass spectrometry: a complementary approach for the chemical analysis of atmospheric aerosols, Rapid Commun. Mass Spectrom., 29, 1233–1241, 2015.

Passananti, M., Zapadinsky, E., Zanca, T., Kangasluoma, J., Myllys, N., Rissanen, M.P., Kurtén, T., Ehn, M., Attoui, M., and Vehkamäki, H.: How well can we predict cluster fragmentation inside a mass spectrometer? Chem. Commun., 55, 5946-5949, 2019.

Payne, R. J., Creevy, A., Malysheva, E., Ratcliffe, J., Andersen, R., Tsyganov, A. N., Rowson, J., Marcisz, K., Zielinska, M., Lamentowicz, M., Lapshina, E. D., and Mazei, Y.: Tree encroachment may lead to functionally-significant changes in peatland testate amoeba communities. Soil Biology & Biochemistry, 98, 18-21. doi:10.1016/j.soilbio.2016.04.002, 2016.

Peltola, O., Vesala,T., Gao, Y.; Räty, O. et al. : Monthly gridded data product of northern wetland methane emissions based on upscaling eddy covariance observations, Earth System Science Data, 11, 1263-1289, doi:10.5194/essd-11-1263-2019, 2019.

Peltoniemi, J. I., Gritsevich, M., Hakala, T., Dagsson-Waldhauserová, P., Arnalds, Ó., Anttila, K., Hannula, H.-R., Kivekäs, N., Lihavainen, H., Meinander, O., Svensson, J., Virkkula, A., and de Leeuw, G.: Soot on

Snow experiment: bidirectional reflectance factor measurements of contaminated snow, The Cryosphere, 9, 2323–2337, doi:10.5194/tc-9-2323-2015, 2015.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., and Rahmstorf, S.: Increasing river discharge to the Arctic Ocean, Science, 80, 298, 2171–2173, doi: 10.1126/science.1077445, 2002.

Petäjä, T., Järvi, L., Kerminen, V.-M., Ding, A. J., Sun, J. N., Nie, W., Kujansuu, J., Virkkula, A., Yang, X.-Q., Fu, C. B., Zilitinkevich, S., and Kulmala M.: Enhanced air pollution via aerosol-boundary layer feedback in China, Scientific Reports, 6, 18998, doi:10.1038/srep18998, 2016.

Petäjä, T., Duplissy, E.-M., Tabakova, K., Schmale, J., Altstädter, B., Ancellet, G., Arshinov, M., Balin, Y., Baltensperger, U., Bange, J., Beamish, A., Belan, B., Berchet, A., Bossi, R., Cairns, W. R. L., Ebinghaus, R., El Haddad, I., Ferreira-Araujo, B., Franck, A., Huang, L., Hyvärinen, A., Humbert, A., Kalogridis, A.-C., Konstantinov, P., Lampert, A., MacLeod, M., Magand, O., Mahura, A., Marelle, L., Masloboev, V., Moisseev, D., Moschos, V., Neckel, N., Onishi, T., Osterwalder, S., Ovaska, A., Paasonen, P., Panchenko, M., Pankratov, F., Pernov, J. B., Platis, A., Popovicheva, O., Raut, J.-C., Riandet, A., Sachs, T., Salvatori, R., Salzano, R., Schröder, L., Schön, M., Shevchenko, V., Skov, H., Sonke, J. E., Spolaor, A., Stathopoulos, V., K., Strahlendorff, M., Thomas, J. L., Vitale, V., Vratolis, S., Barbante, C., Chabrillat, S., Dommergue, A., Eleftheriadis, K., Heilimo, J., Law, K. S., Massling, A., Noe, S. M., Paris, J.-D., Prévôt, A. S. H., Riipinen, I., Wehner, B., Xie, Z., and Lappalainen, H. K.: Overview: Integrative and Comprehensive Understanding on Polar Environments (iCUPE) – concept and initial results, Atmos. Chem. Phys., 20, 8551–8592, doi:10.5194/acp-20-8551-2020, 2020a.

Petäjä, T., Ganzei, K. S., Lappalainen, H. K., Tabakova, K., Makkonen, R., Räisänen, J., Chalov, S., Kulmala, M., Zilitinkevich, S. S., Baklanov, P., Shakirov, R. B., Mishina, N.V., Egidarev, E.G., and Kondrat'ev, I. I.: Research agenda for the Russian Far East and utilization of multi-platform compherensive environmental observations, J. Big Data, submitted, 2020b.

Pietron, J., Jarsjo, J., Romanchenko, A. O., and Chalov, S. R.: Model analyses of the contribution of in-channel processes to sediment concentration hysteresis loops, Journal of Hydrology, 527, 576-589. doi:10.1016/j.jhydrol.2015.05.009, 2015.

Pietroń, J., Nittrouer, J. A., Chalov, S. R., Dong, T. Y., Kasimov, N., Shinkareva, G., and Jarsjö, J.: Sedimentation patterns in the Selenga River delta under changing hydroclimatic conditions, Hydrological Processes, 32(2), 278-292, doi:10.1002/hyp.11414, 2018.

Pirazzini, R., Leppanen, L., Picard, G., Lopez-Moreno, J. I., Marty, C., Macelloni, G., Kontu, A., Von Lerber, A., Tanis, C.M., Schneebeli, M., De Rosnay, P., Arslan, A. N.: European in-situ snow measurements: practices and purposes, Sensors, 18(7), 51, doi:10.3390/s18072016, 2018.

Pisso, I., Myhre, C. L., Platt, S. M., Eckhardt, S., Hermansen, O., Schmidbauer, N., Mienert, J., Vadakkepuliyambatta, S., Bauguitte, S., Pitt, J., Allen, G., Bower, K. N., O'Shea, S., Gallagher, M. W.,

Percival, C. J., Pyle, J., Cain, M., and Stohl, A.: Constraints on oceanic methane emissions west of Svalbard from atmospheric in situ measurements and Lagrangian transport modeling, J. Geophys. Res. Atmos., 121(23), 14188-14200, doi:10.1002/2016jd025590, 2016.

Platt, S. M., Eckhardt, S., Ferré, B., Fisher, R. E., Hermansen, O., Jansson, P., Lowry, D., Nisbet, E. G., Pisso, I., Schmidbauer, N., Silyakova, A., Stohl, A., Svendby, T. M., Vadakkepuliyambatta, S., Mienert, J., and Lund Myhre, C.: Methane at Svalbard and over the European Arctic Ocean, Atmos. Chem. Phys., 18, 17207–17224, doi:10.5194/acp-18-17207-2018, 2018.

Ponomarev, Evgenii I., Kharuk, Viacheslav I., and Ranson, Kenneth J.:Wildfires Dynamics in Siberian Larch Forests, Forests, 7(6), 125, 2016.

Popovicheva O., Evangeliou N., Eleftheriadis K., Kalogridis A. C., Sitnikov V. N., Eckhardt S., Stohl A.: Black carbon sources constrained by observations and modeling in the Russian high Arctic, Environmental Science Technology, 51(7), 3871-3879, 2017.

Popovicheva, O., Diapouli, E., Makshtas, A., Shonija, N., Manousakas, M., Saraga, D., Uttal, T., and Eleftheriadis, K.: East Siberian Arctic background and black carbon polluted aerosols at HMO Tiksi, Science of the Total Environment, 655, 924-938, doi:10.1016/j.scitotenv.2018.11.165, 2019a.

Popovicheva, O. B., Engling, G., Ku, I. T., Timofeev, M. A., and Shonija, N. K.: Aerosol emissions from long-lasting smoldering of boreal peatlands: chemical composition, markers, and microstructure, Aerosol and Air Quality Research, 19(3), 484-503, doi:10.4209/aaqr.2018.08.0302, 2019b.

Popovicheva, O. B., Padoan, S., Schnelle- Kreis, J., Nguyen, D. L., Adam, T.W., Kistler, M., Steinkogler, T., Kasper-Giebl, A., Zimmermann, R., and Chubarova, N. E.: Spring aerosol in urban atmosphere of megacity: analytical and statistical assessment for source impacts, Aerosol and Air Quality Research, 20, 702–719, 2020a.

Popovicheva O., Ivanov A., and Vojtisek M.: Functional Factors of Biomass Burning Contribution to Spring Aerosol Composition in a Megacity: Combined FTIR-PCA Analyses, Atmosphere, 11, 319-339, 2019b.

Popovicheva, O., Volpert, E., Sitnikov, N., Chichaeva, M., and Padoan, S.: Black carbon in spring aerosols of Moscow urban background, Geography, Environment, Sustainability, 13, 1, 233-243, 2020c

Pozdnyakov D. V., Pettersson L. H., and Korosov A. A.: Exploring the Marine Ecology from Space. Springer, Switzerland, 2017.

Pozdnyakov, D. V., Kondrik, D.V., Kazakov, E. E., and Chepikova, S.: Environmental conditions favoring coccolithophore blooms in subarctic and arctic seas: a 20-year satellite and multi-dimensional statistical study, Proc. SPIE 11150, Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions, 111501W, 14 October 2019, doi: 10.1117/12.2547868, 2019.

2958 Pozdnyakov D., Kondrik D., and Chepikova S.: Origination of E. huxleyi extraordinary bloom outbursts in

2959 the Bering Sea between the late 1990s and early 2000s, and in 2018-2019: A hypothesis, Fisheries

2960 Oceanography, submitted, 2020.

2961 Preis, Y. I., Simonova, G. V., Voropay, N. N., and Dyukarev, E. A.: Estimation of the influence of

2962 hydrothermal conditions on the carbon isotope composition in Sphagnum mosses of bogs of Western Siberia,

2963 IOP Conf. Series: Earth Environ. Sci., 211, doi:10.1088/1755-1315/211/1/012031, 2018.

2964 Pugac,h S. P., Pipko I. I., Shakhova, N. E., Shirshin, E. A., Perminova, I. V., Gustafsson, O., Bondur, V. G.,

2965 Ruban, A. S., and Semiletov, I. P.: Dissolved organic matter and its optical characteristics in the Laptev and

2966 East Siberian seas: spatial distribution and interannual variability (2003–2011), Ocean Sci., 14, 87–103,

2967 doi:10.5194/os-14-87-2018, 2018.

2968 Pulliainen, J., Aurela, M., Laurila, T., Aalto, T., Takala, M., Salminen, M., Kulmala, M., Barr, A., Heimann,

2969 M., Lindroth, A., Laaksonen, A., Derksen, C., Mäkelä, A., Markkanen, T., Lemmetyinen, J., Susiluoto, J.,

2970 Dengel, S., Mammarella, I., Tuovinen, J.-P., and Vesala, T.: Early snowmelt significantly enhances boreal

2971 springtime carbon uptake, PNAS, 114(42), 11081-11086, doi:10.1073/pnas.1707889114, 2017.

2972 Pulliainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., Ikonen, J., Takala, M.,

2973 Cohen, J., Smolander, T., and Norberg, J.: Patterns and trends of Northern Hemisphere snow mass from

2974 1980 to 2018, Nature 581, 294–298, doi:10.1038/s41586-020-2258-0, 2020.

2975 Pärn, J., Verhoeven, J.T., Butterbach-Bahl, K., Dise, N.B., Ullah, S., Aasa, A., Egorov, S., Espenberg, M.,

2976 Järveoja, J., Jauhiainen, J. and Kasak, K.: Nitrogen-rich organic soils under warm well-drained conditions

2977 are global nitrous oxide emission hotspots, Nat. Commun., 9, 1135, doi:10.1038/s41467-018-03540-1, 2018.

2978 Qi, X. M., Ding, A. J., Nie, W., Petäjä, T., Kerminen, V.-M., Herrmann, E., Xie, Y. N., Zheng, L. F.,

2979 Manninen, H., Aalto, P., Sun, J. N., Xu, Z. N., Chi, X. G., Huang, X., Boy, M., Virkkula, A., Yang, X.-Q.,

2980 Fu, C. B., and Kulmala, M.: Aerosol size distribution and new particle formation in the western Yangtze

2981 River Delta of China: 2 years of measurements at the SORPES station, Atmos. Chem. Phys., 15, 12445–

2982 12464, doi:10.5194/acp-15-12445-2015, 2015.

2983 Rakitin, V. S., Elansky, N. F., Wang, P., Wang, G., Pankratova, N. V., Shtabkin, Y. A., Skorokhod A.I.,

2984 Safronov A.N., Makarova M.V., and Grechko E.I.: Changes in trends of atmospheric composition over urban

2985 and background regions of Eurasia: estimates based on spectroscopic observations, Geography,

2986 Environment, Sustainability, 11(2), 84-96, doi:10.24057/2071-9388-2018-11-2-84-96, 2018.

2987 Rautiainen, K., Parkkinen, T., Lemmetyinen, J., Schwank, M., Wiesmann, A., Ikonen, J., Derksen, C.,

2988 Davydov, S., Davydova, A., Boike, J., Langer, M., Druschg, M., and Pulliainen, J.: SMOS prototype

2989 algorithm for detecting autumn soil freezing, Remote Sensing of Environment, 180, 346-360,

2990 doi:10.1016/j.rse.2016.01.012, 2016.

2991 Rinke, A., Segger, B., Crewell, S., Maturilli, M., Naakka, T., Nygård, T., Vihma, T., Alshawaf, F., Dick, G.,

2992 Wickert, J., and Keller, J.: Trends of vertically integrated water vapor over the Arctic during 1979-2016:

2993 Consistent moistening all over?, J. Climate, 32, 6097–6116, doi:10.1175/JCLI-D-19-0092.1, 2019.

2994 Ripple, W. J., Wolf, C., Newsome, T. M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M. I., Laurance, W.

2995 F., and 15,364 scientist signatories from 184 countries. World scientists' warning to humanity: A second

2996 notice, BioScience, 67(12), 1026-1028, 2017.

2997 Rivero-Calle, S., Gnanadesikan, A., Del Castilo, C., Balch, W., and Guikema, S.: Multidecadal increase in

2998 North Atlantic coccolithophores and the potential role of rising CO_2, Science, 350 (6267), 1533-1537, doi:

2999 10.1126/science.aaa8026, 2015.

3000 Romanowsky, E., Handorf, D., Jaiser, R., Wohltmann, I., Dorn, W., Ukita, J., Cohen, J., Dethloff, K., and

3001 Rex, M.: The role of stratospheric ozone for Arctic-midlatitude linkages, Sci. Rep. 9, 7962,

3002 doi:10.1038/s41598-019-43823-1, 2019.

3003 Romanovsky, V. E., and Osterkamp, T. E.: Effects of unfrozen water on heat and mass transport processes in

3004 the active layer and permafrost, Permafrost Periglac. Process, 11, 219–39, 2000.

3005 Rost, B., and Riebesell, U.: Coccolithophores and the biological pump: responses to environmental changes,

3006 in: Coccolithophores, from molecular processes to global impact, edited by: Thierstein, H. R., Young, J. R.,

3007 99–125, Springer, Heidelberg, Germany, 2004.

3008 Ryazanova, A., and Voropay, N. N.: Droughts and Excessive Moisture Events in Southern Siberia in the

3009 Late XXth - Early XXIst Centuries, IOP Conf. Ser.: Earth Environ. Sci., 96, 012015, 2017.

3010 Räisänen, J.: Effect of atmospheric circulation on recent temperature changes in Finland, Clim. Dyn., 53,

3011 5675–5687, doi:10.1007/s00382-019-04890-2, 2019.

3012 Räisänen, J.: Effect of atmospheric circulation on surface air temperature trends in years 1979-2018, Clim.

3013 Dyn., Clim. Dyn., in press, 2020.

3014 Saarela, T., Rissanen, A. J., Ojala, A. et al.: CH4 oxidation in a boreal lake during the development of

3015 hypolimnetic hypoxia, Aquat Sci, 82, 19, /doi.org/10.1007/s00027-019-0690-8, 2020.

3016 Salmon, Y., Lintunen, A., Dayet, A., Chan, T., Dewar, R., Vesala, T. and Hölttä, T.: Leaf carbon and water

3017 status control stomatal and non-stomatal limitations of photosynthesis in trees, New Phytologist 226, 690-

3018 703. doi: 10.1111/nph.16436, 2020.

3019 Santalahti, M., Sun, H., Sietiö, O.M., Köster, K., Berninger, F., Laurila, T., Pumpanen, J., and Heinonsalo,

3020 J.: Reindeer grazing alter soil fungal community structure and litter decomposition related enzyme activities

3021 in boreal coniferous forests in Finnish Lapland, App. Soil Ecol., 132, 74-82,

3022 doi:10.1016/j.apsoil.2018.08.013, 2018.

Schallhart, S., Rantala, P., Kajos, M. K., Aalto, J., Mammarella, I., Ruuskanen, T. M., and Kulmala, M.:
Temporal variation of VOC fluxes measured with PTR-TOF above a boreal forest, Atmospheric Chemistry
and Physics, 18(2), 815-832. doi:10.5194/acp-18-815-2018, 2018.

Schmale, J., Arnold, S. R., Law, K. S., Thorp, T., Anenberg, S., Simpson, W. R., Mao, J. and Pratt, K. A.:
Local Arctic air pollution: a neglected but serious problem, Earths Future, 6(10), 1385-1412,
doi:10.1029/2018ef000952, 2018a.

Schmale, J., Henning, S., Decesari, S., Henzing, B., Keskinen, H., Sellegri, K., Ovadnevaite, J., Pöhlker, M.
L., Brito, J., Bougiatioti, A., Kristensson, A., Kalivitis, N., Stavroulas, I., Carbone, S., Jefferson, A., Park,
M., Schlag, P., Iwamoto, Y., Aalto, P., Äijälä, M., Bukowiecki, N., Ehn, M., Frank, G., Fröhlich, R.,
Frumau, A., Herrmann, E., Herrmann, H., Holzinger, R., Kos, G., Kulmala, M., Mihalopoulos, N., Nenes,
A., O'Dowd, C., Petäjä, T., Picard, D., Pöhlker, C., Pöschl, U., Poulain, L., Prévôt, A. S. H., Swietlicki, E.,
Andreae, M. O., Artaxo, P., Wiedensohler, A., Ogren, J., Matsuki, A., Yum, S. S., Stratmann, F.,
Baltensperger, U., and Gysel, M.: Long-term cloud condensation nuclei number concentration, particle
number size distribution and chemical composition measurements at regionally representative observatories,
Atmos. Chem. Phys., 18, 2853–2881, doi:10.5194/acp-18-2853-2018, 2018b.

Schmeisser, L., Backman, J., Ogren, J. A., Andrews, E., Asmi, E., Starkweather, S., Uttal, T., Fiebig, M.,
Sharma, S., Eleftheriadis, K., Vratolis, S., Bergin, M., Tunved, P., and Jefferson, A.: Seasonality of aerosol
optical properties in the Arctic, Atmos. Chem. Phys., 18, 11599–11622, doi:10.5194/acp-18-11599-2018,
2018.

Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., Hagemann,
S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F. E., Rinke, A.,. Romanovsky, V. E.,
Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J. G., and Zimov, S. A.: Vulnerability of permafrost
carbon to climate change: implications for the global carbon cycle, BioScience, 58(8), 701–714,
doi:10.1641/B580807, 2008.

Schuur, E. A. G., McGuire, A. D., Romanovsky, V., Schädel, C., and Mack, M.: Chapter 11: Arctic and
boreal carbon, in: Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report,
edited by: Cavallaro, N., Shrestha, G., Birdsey, R., Mayes, M. A., Najjar, R. G., Reed, S. C., Romero-
Lankao, P., and Zhu, Z., U.S. Global Change Research Program, Washington, DC, USA, 428-468,
doi:10.7930/SOCCR2.2018.Ch11, 2018.

Scott, C. E., Monks, S. A., Spracklen, D. V., Arnold, S. R., Forster, P. M., Rap, A., Äijälä, M., Artaxo, P.,
Carslaw, K. S., Chipperfield, M. P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T.,
Reddington, C. L. S., Rizzo, L. V., Swietlicki, E., Vignati, E., and Wilson, C.: Impact on short-lived climate
forcers increases projected warming due to deforestation, Nat. Commun., 9, 9, doi:10.1038/s41467-017-
02412-4, 2018.

3057   Shakhova, N., Semiletov, I., and Belcheva, N.: The great Siberian rivers as a source of methane on the
3058   Russian Arctic shelf, Dokl. Earth Sci., 415, 734–736, doi: 10.1134/S1028334X07050169, 2007.

3059   Shalina, E. V., and Sandven, S.: Snow depth on Arctic sea ice from historical in situ data, Cryosphere, 12(6),
3060   1867-1886, doi:10.5194/tc-12-1867-2018, 2018.

3061   Shen, Y., Virkkula, A., Ding, A., Wang, J., Chi, X., Nie, W., Qi, X., Huang, X., Liu, Q., Zheng, L., Xu, Z.,
3062   Petäjä, T., Aalto, P. P., Fu, C., and Kulmala, M.: Aerosol optical properties at SORPES in Nanjing, east
3063   China, Atmos. Chem. Phys., 18, 5265–5292, doi: 10.5194/acp-18-5265-2018, 2018.

3064   Shen, Y., Virkkula, A., Ding, A., Luoma, K., Keskinen, H., Aalto, P. P., Chi, X., Qi, X., Nie, W., Huang, X.,
3065   Petäjä, T., Kulmala, M., and Kerminen, V.-M.: Estimating cloud condensation nuclei number concentrations
3066   using aerosol optical properties: role of particle number size distribution and parameterization, Atmos.
3067   Chem. Phys., 19, 15483–15502, doi:10.5194/acp-19-15483-2019, 2019.

3068   Shestakova, T. A., Gutierrez, E., Valeriano, C., Lapshina, E., and Voltas, J.: Recent loss of sensitivity to
3069   summer temperature constrains tree growth synchrony among boreal Eurasian forests, Agr. Forest Meteorol.,
3070   268, 318-330, doi:10.1016/j.agrformet.2019.01.039, 2019.

3071   Shevchenko, V. P., Starodymova, D. P., Vinogradova, A. A., Lisitzin, A. P., Makarov, V. I, Popova, S. A.,
3072   Sivonen, V. V., and Sivonen, V. P.: Elemental and organic carbon in atmospheric aerosols over the
3073   northwestern coast of Kandalaksha Bay of the White Sea, Dokl. Earth Sci., 461(1), 242-246,
3074   doi:10.1134/s1028334x1503006x, 2015.

3075   Shevchenko, V. P., Maslov, A. V., and Stein, R.: Distribution of some rare and trace elements in ice-rafted
3076   sediments in the Yermak Plateau area, the Arctic Ocean, Oceanol., 57(6), 855-863,
3077   doi:10.1134/s0001437017060157, 2017a.

3078   Shevchenko, V. P., Pokrovsky, O. S., Vorobyev, S. N., Krickov, I. V., Manasypov, R. M., Politova, N. V.,
3079   Kopysov, S. G., Dara, O. M., Auda, Y., Shirokova, L. S., Kolesnichenko, L. G., Zemtsov, V. A., and
3080   Kirpotin, S. N.: Impact of snow deposition on major and trace element concentrations and elementary fluxes
3081   in surface waters of the Western Siberian Lowland across a 1700 km latitudinal gradient, Hydrol. Earth Syst.
3082   Sci., 21, 5725–5746, doi:10.5194/hess-21-5725-2017, 2017b.

3083   Shevchenko, V. P., Kopeikin, V. M., Novigatsky, A. N., and Malafeev, G. V.: Black carbon in the
3084   atmospheric boundary layer over the North Atlantic and the Russian Arctic seas in June–September 2017,
3085   Oceanol., 59(5), doi:10.1134/S0001437019050199, 692–696, 2019.

3086   Shevnina, E., Kourzeneva, E., Kovalenko, V., and Vihma, T.: Assessment of extreme flood events in a
3087   changing climate for a long-term planning of socio-economic infrastructure in the Russian Arctic, Hydrol.
3088   Earth Syst. Sci., 21(5), 2559-2578, doi:10.5194/hess-21-2559-2017, 2017.

3089   Shevnina, E., Silaev, A., and Vihma, T.: Probabilistic projections of annual runoff and potential hydropower
3090   production in Finland, Universal Journal of Geoscience, 7(2), 43-55, doi:10.13189/ujg.2019.070201, 2019.

3091   Shiklomanov, A.I., and Lammers, R.B.: Record Russian river discharge in 2007 and the limits of analysis,

3092   Environ. Res. Lett., 4, doi: 10.1088/1748-9326/4/4/045015, 2009.

3093   Shinkareva G. L., Lychagin M. Y., Tarasov M. K., Pietroń J., Chichaeva M. A., and Chalov S. R.:

3094   Biogeochemical specialization of macrophytes and their role as a biofilter in the Selenga delta, Geography,

3095   Environment, Sustainability,12(3), 240-263, 2019.

3096   Silkin, V. A., Pautova, L., Giordano, M., Chasovnikov, V., Vostokov, S., Podymov, O., Parkhomova, S., and

3097   Moskalenko, L.: Drivers of phytoplankton blooms in the northeastern Black Sea, Mar. Pollution Bull., 138,

3098   274-284, doi:10.1016/j.marpolbul.2018.11.042, 2018.

3099   Sizov O. S., and Lobotrosova S. A.: Features of revegetation of drift sand sites in the northern taiga subzone

3100   of Western Siberia. Earth Cryosphere, (3), 3–13, doi:10.21782/kz1560-7496-2016-3(3-13), 2016.

3101   Skorokhod, A. I., Berezina, E. V., Moiseenko, K. B., Elansky, N. F., and Belikov, I. B.: Benzene and toluene

3102   in the surface air of northern Eurasia from TROICA-12 campaign along the Trans-Siberian Railway, Atmos.

3103   Chem. Phys., 17(8), 5501-5514, doi:10.5194/acp-17-5501-2017, 2017.

3104   Slukovskaya, M. V., Vasenev, V. I., Ivashchenko, K. V., Morev, D. V., Drogobuzhskaya, S. V., Ivanova, L.

3105   A., and Kremenetskaya, I. P.: Technosols on mining wastes in the subarctic: Efficiency of remediation under

3106   Cu-Ni atmospheric pollution, Int. Soil Water Conserv. Res., 7(3), 297-307, doi:10.1016/j.iswcr.2019.04.002,

3107   2019.

3108   Smith, L.: The new north: The world in 2050, Profile Books, London, UK, 2011.

3109   Song, S., Li, C., Shi , X., Zhao, S., Li, Z., Bai, Y., Cao, X., Wang, Q., Huotari, J., Tulonen, T., Uusheimo, S.,

3110   Leppäranta, M., and Arvola, L.: Under-ice metabolism in a shallow lake (Wuliangsuhai) in Inner Mongolia,

3111   in cold and arid climate zone, Freshw. Biol., 1–11, 2019.

3112   Spengler, T., Renfrew, I. A., Terpstra, A., Tjernström, M., Screen, J., Brooks, I. M., Andrew Carleton, A.,

3113   Chechin, D., Chen, L., Doyle, J., Esau, I., Hezel, P. J., Jung, T., Kohyama, T., Lüpkes, C., McCusker, C. E.,

3114   Nygård, T., Sergeev, D., Shupe, M. D., Sodemann, H., and Vihma, T.: High-latitude dynamics of

3115   atmosphere–ice–ocean interactions, Bull. Am. Meteorol. Soc., 97(9), ES179-ES182, doi:10.1175/bams-d-15-

3116   00302.1, 2016.

3117   Sporre, M. K., Blichner, S. M., Karset, I. H. H., Makkonen, R., and Berntsen, T. K.: BVOC–aerosol–climate

3118   feedbacks investigated using NorESM, Atmos. Chem. Phys., 19, 4763–4782, doi:10.5194/acp-19-4763-

3119   2019, 2019.

3120   Starodymova, D. P., Shevchenko, V. P., Sivonen, V. P., and Sivonen, V. V.: Material and elemental

3121   composition of surface aerosols on the north-western coast of the Kandalaksha Bay of the White Sea, Atmos.

3122   Oceanic Opt., 29(6), 507-511, doi:10.1134/s1024856016060154, 2016.

low1H

Detectability of Arctic methane sources at six sites performing continuous atmospheric measurements, Atmos. Chem. Phys., 17, 8371–8394, doi:10.5194/acp-17-8371-2017, 2017.

Thorslund, J., Jarsjo, J., Wallstedt, T., Morth, C. M., Lychagin, M. Y., and Chalov, S. R.: Speciation and hydrological transport of metals in non-acidic river systems of the Lake Baikal basin: Field data and model predictions, Reg. Environ. Chang., 17(7), 2007-2021, doi:10.1007/s10113-016-0982-7, 2017.

Tian, Z. X., Cheng, B., Zhao, J. C., Vihma, T., Zhang, W. L., Li, Z. J., and Zhang, Z. H.: Observed and modelled snow and ice thickness in the Arctic Ocean with CHINARE buoy data, Acta Oceanologica Sinica, 36(8), 66-75, doi:10.1007/s13131-017-1020-4, 2017.

Tillman, H., Yang, J. and Nielsson, E.: The Polar Silk Road: China's New Frontier of International Cooperation, China Quarterly of International Stragegic Studies, 4. 10.1142/S2377740018500215, 2018.

Timokhina, A. V., Prokushkin, A. S., Onuchin, A. A., Panov, A. V., Kofman, G. B., and Heimann, M.: Variability of ground CO2 concentration in the middle taiga subzone of the Yenisei region of Siberia, Russ. J. Ecol., 46, 143-151, doi:10.1134/s1067413615020125, 2015a.

Timokhina, A. V., Prokushkin, A. S., Onuchin, A. A., Panov, A. V., Kofman, G. B., Verkhovets, S. V., and Heimann, M., Long-term trend in CO2 concentration in the surface atmosphere over Central Siberia, Russ. Meteorol. Hydrol., 40, 186-190, 2015b.

Tsuruta, A., Aalto, T., Backman, L., Hakkarainen, J., … and Peters, W.: Global methane emission estimates for 2000–2012 from CarbonTracker Europe-CH4 v1.0. Geosci. Model Dev., 10, 1261–1289, 2017.

Tuovinen, J-P., Aurela, M., Hatakka, J., Räsänen, A., … Laurila, T.: Interpreting eddy covariance data from heterogeneous Siberian tundra: land-cover-specific methane fluxes and spatial representativeness, Biogeosciences, 16, 255–274, 2019.

Uotila, P., Vihma, T., and Haapala, J.: Atmospheric and oceanic conditions and the extremely low Bothnian Bay sea ice extent in 2014/2015, 42, 7740-7749, Geophysical Research and Letters, 2015.

Uotila, P., Iovino, D., Vancoppenolle, M., Lensu, M., and Rousset, C., Comparing sea ice, hydrography and circulation between NEMO3.6 LIM3 and LIM2, Geosci. Model Dev., 10, 1009–1031, doi:10.5194/gmd-10-1009-2017, 2017.

Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthélemy, A., Bricaud, C., Carton, J., Fučkar, N., Garric, G., Iovino, D., Kauker, F., Korhonen, M., Lien, V. S., Marnela, M., Massonnet, F., Mignac, D., Peterson, K. A., Sadikni, R., Shi, L., Tietsche, S., Toyoda, T., Xie, J., and Zhang, A.: An assessment of ten ocean reanalyses in the polar regions, Clim Dyn 52, 1613–1650, doi:10.1007/s00382-018-4242-z, 2019.

Uttal, T., Starkweather, S., Drummond, J. R., Vihma, T., Makshtas, A. P., Darby, L. S., Burkhart, J. F., Cox, C. J., Schmeisser, L. N., Haiden, T., Maturilli, M., Shupe, M. D., De Boer, G., Saha, A., Grachev, A. A., Crepinsek, S. M., Bruhwiler, L., Goodison, B., McArthur, B., Walden, V. P., Dlugokencky, E. J., P. Persson, O., Lesins, G., Laurila, T., Ogren, J. A., Stone, R., Long, C. N., Sharma, S., Massling, A., Turner, D. D.,

Stanitski, D. M., Asmi, E., Aurela, M., Skov, H., Eleftheriadis, K., Virkkula, A., Platt, A., Førland, E. J., Iijima, Y., Nielsen, I. E., Bergin, M. H., Candlish, L., Zimov, N. S., Zimov, S. A., O'Neill, N. T., Fogal, P. F., Kivi, R., Konopleva-Akish, E. A., Verlinde, J., Kustov, V. Y., Vasel, B., Ivakhov, V. M., Viisanen Y., and Intrieri, J. M.: International Arctic Systems for Observing the Atmosphere: An International Polar Year Legacy Consortium, Bull. Amer. Meteor. Soc., 97, 1033–1056, doi:10.1175/BAMS-D-14-00145.1, 2016.

Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Ebert, C., Goetz, S., Johnstone, J. F., Potter, S., Rogers, B. M., Schuur, E. A. G., Turetsky, M. R., and Mack, M. C., Increasing wildfires threaten historic carbon sink of boreal forest soils, Nature, 572, 520-523, doi:10.1038/s41586-019-1474-y, 2019.

Walsh, M. G., de Smalen, A. W., and Mor, S. M.: Climatic influence on anthrax suitability in warming northern latitudes, Sci Rep, 8(1), 9269, doi:10.1038/s41598-018-27604-w, 2018.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, Clim. Chang., 109, 5-31, doi:10.1007/s10584-011-0148-z, 2011.

Wang, J., Ge, X., Chen, Y., Shen, Y., Zhang, Q., Sun, Y., Xu, J., Ge, S., Yu, H., and Chen, M.: Highly time-resolved urban aerosol characteristics during springtime in Yangtze River Delta, China: insights from soot particle aerosol mass spectrometry, Atmos. Chem. Phys., 16, 9109–9127, doi:10.5194/acp-16-9109-2016, 2016.

Wang, J., Zhao, B., Wang, S., Yang, F., Xing, J., Morawska, L., Ding, A., Kulmala, M., Kerminen, V.-M., Kujansuu, J., Wang, Z., Ding, D., Zhang, X., Wang, H., Tian, M., Petäjä, T., Jiang, J., and Hao J.: Particulate matter pollution over China and the effects of control policies, Sci. Total Environ., 584-585, 426-447, 2017a.

Wang, Z. B., Wu, Z. J., Yue, D. L., Shang, D. J., Guo, S., Sun, J. Y., Ding, A. J., Wang, L., Jiang, J. K., Guo, H., Gao, J., Cheung, H. C., Morawska, L., Keywood, M., and Hu, M.: New particle formation in China: Current knowledge and further directions, Sci. Total Environ., 577, 258–266, doi:10.1016/j.scitotenv.2016.10.177, 2017b.

Wang, P. C., Elansky, N. F., Timofeev, Y. M., Wang, G. C., Golitsyn, G. S., Makarova, M. V., Rakitin, V. S., Shtabkin, Yu., Skorokhod, A. I., Grechko, E. I., Fokeeva, E. V., Safronov, A. N., Ran, L., and Wang, T.: Long-term trends of carbon monoxide total columnar amount in urban areas and background regions: ground- and satellite-based spectroscopic measurements, Adv. Atmos. Sci., 35(7), 785-795, doi:10.1007/s00376-017-6327-8, 2018a.

Wang, Y., Wang, Y., Wang, L., Petäjä, T., Zha, Q., Gong, C., Li, S., Pan, Y., Hu, B., Xin, J., and Kulmala, M.: Increased inorganic aerosol fraction contributes to air pollution and haze in China, Atmos. Chem. Phys., 19, 5881–5888, doi:10.5194/acp-19-5881-2019, 2019.

3224 Wang, Y.H., Yu, M., Wang, Y., Tang, G., Song, T., Zhou, P., Liu, Z., Hu, B., Ji, D.S., Wang, L., Zhu, X.,

3225 Yan, C., Ehn, M., Gao, W.K., Pan, Y.P., Xin, J.Y., Sung, Y., Kerminen, V.-M., Kulmala, M. and Petäjä, T.:

3226 Rapid formation of intense haze episode via aerosol-boundary layer feedback in Beijing, Atmos. Chem.

3227 Phys., 10, 45-53, 2020.

3228 Wang, Z., Huang, X., and Ding, A.: Dome effect of black carbon and its key influencing factors, Atmos.

3229 Chem. Phys., 18, 2821-2834, 2018b.

3230 Vanhatalo, A., Ghirardo, A., Juurola, E., Schnitzler, J.-P., Zimmer, I., Hellén, H., Hakola, H., and Bäck, J.:

3231 Long-term dynamics of monoterpene synthase activities, monoterpene storage pools and emissions in boreal

3232 Scots pine, Biogeosciences, 15, 5047–5060, doi:10.5194/bg-15-5047-2018, 2018.

3233 Varentsov, M., Konstantinov, P., Baklanov, A., Esau, I., Miles, V., and Davy, R.: Anthropogenic and natural

3234 drivers of a strong winter urban heat island in a typical Arctic city, Atmos. Chem. Phys., 18(23), 17573-

3235 17587, doi:10.5194/acp-18-17573-2018, 2018a.

3236 Varentsov, M., Wouters, H., Platonov, V., and Konstantinov, P.: Megacity-induced mesoclimatic effects in

3237 the lower atmosphere: a modeling study for multiple summers over Moscow, Russia, Atmos., 9(2), 24,

3238 doi:10.3390/atmos9020050, 2018b.

3239 Vasileva, A., Moiseenko, K., Skorokhod, A., Belikov, I., Kopeikin, V., and Lavrova, O.: Emission ratios of

3240 trace gases and particles for Siberian forest fires on the basis of mobile ground observations, Atmos. Chem.

3241 Phys., 17(20), 12303-12325, doi:10.5194/acp-17-12303-2017, 2017.

3242 Wei, L. X., Deng, X. H., Cheng, B., Vihma, T., Hannula, H. R., Qin, T., and Pulliainen, J.: The impact of

3243 meteorological conditions on snow and ice thickness in an Arctic lake, Tellus A: Dyn. Meteorol. Oceanogr.,

3244 68, 12, doi:10.3402/tellusa.v68.31590, 2016.

3245 Vestenius, M., Hellén, H., Levula, J., Kuronen, P., Helminen, K. J., Nieminen, T., Kulmala, M., and Hakola,

3246 H.: Acidic reaction products of monoterpenes and sesquiterpenes in atmospheric fine particles in a boreal

3247 forest, Atmos. Chem. Phys., 14, 7883–7893, doi:10.5194/acp-14-7883-2014, 2014.

3248 Wickström, S., Jonassen, M., Vihma, T., and Uotila, P.: Trends in cyclones in the high latitude North

3249 Atlantic during 1979-2016, Q. J. R. Meteorol. Soc., 146, 762– 779, doi:10.1002/qj.3707, 2020.

3250 Wiedensohler, A., Ma, N., Birmili, W., Heintzenberg, J., Ditas, F., Andreae, M. O., and Panov, A.:

3251 Infrequent new particle formation over the remote boreal forest of Siberia, Atmos. Environ., 200, 167-169,

3252 doi:10.1016/j.atmosenv.2018.12.013, 2019.

3253 Vihma, T., Uotila, P., Sandven, S., Pozdnyakov, D., Makshtas, A., Pelyasov, A., Pirazzini, R., Danielsen, F.,

3254 Chalov, S., Lappalainen, H. K., Ivanov, V., Frolov, I., Albin, A., Cheng, B., Dobrolyubov, S., Arkhipkin, V.,

3255 Myslenkov, S., Petäjä, T., and Kulmala, M.: Towards an advanced observation system for the marine Arctic

3256 in the framework of the Pan-Eurasian Experiment (PEEX), Atmos. Chem. Phys., 19, 1941-1970,

3257 doi:10.5194/acp-19-1941-2019, 2019.

3258   Vihma, T., Graversen, R., Chen, L., Dörthe H., Skific, N., Francis, J.A., Tyrrell, N., Hall, R., Hanna, E.,
3259   Uotila, P., Dethloff, K., Karpechko, A. Y., Björnsson, H. and Overland, J. E.: Effects of the tropospheric
3260   large-scale circulation on European winter temperatures during the period of amplified Arctic warming, Int J
3261   Climatol., 40, 509– 529, doi:10.1002/joc.6225, 2020

3262   Wild, B., Andersson, A., Bröder, L., Vonk, J., Hugelius, G., McClelland, J.W., Song, W., Raymond, P.A.,
3263   and Gustafsson, Ö.: Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing
3264   permafrost Proceedings of the National Academy of Sciences, 116 (21) 10280-10285., 2019.

3265   Williams, P. J., and Smith, M. W.: The Frozen Earth: Fundamentals of Geocryology, Cambridge University
3266   Press, Cambridge, UK, 1989.

3267   Virkkula, A., Chi, X., Ding, A., Shen, Y., Nie, W., Qi, X., Zheng, L., Huang, X., Xie, Y., Wang, J., Petäjä,
3268   T., and Kulmala, M.: On the interpretation of the loading correction of the aethalometer, Atmos. Meas.
3269   Tech., 8, 4415-4427, doi:10.5194/amt-8-4415-2015, 2015.

3270   WMO, 2019 Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services.
3271   Volume 1: Concept and Methodology, Grimmond, S., Bouchet, S., Molina, L., Baklanov, A., Joe, P. et al.,
3272   WMO-No. 1234, https://library.wmo.int/doc_num.php?explnum_id=9903, 2019.

3273   Voigt, C., Marushchak, M.E., Lamprecht, R.E., et al.: Nitrous oxide emissions from thawing permafrost,
3274   PNAS May 2017, 201702902; DOI: 10.1073/pnas.1702902114.

3275   Voigt, C., Lamprecht, R. E., Marushchak, M. E., Lind, S. E., Novakovskiy, A., Aurela, M., Martikainen, P. J.
3276   and Biasi, C.: Warming of subarctic tundra increases emissions of all three important greenhouse gases -
3277   carbon dioxide, methane, and nitrous oxide, Glob. Change Biol., 23(8), 3121-3138, doi:10.1111/gcb.13563,
3278   2016.

3279   Wolf-Grosse, T., Esau, I., and Reuder, J.: The large-scale circulation during air quality hazards in Bergen,
3280   Norway, Tellus A: Dyn. Meteorol. Oceanogr., 69, 16, doi:10.1080/16000870.2017.1406265, 2017a.

3281   Wolf-Grosse, T., Esau, I., and Reuder, J.: Sensitivity of local air quality to the interplay between small- and
3282   large-scale circulations: a large-eddy simulation study, Atmos. Chem. Phys., 17(11), 7261-7276,
3283   doi:10.5194/acp-17-7261-2017, 2017b.

3284   Voropay N.N., Ryazanova A.A., Dyukarev E.A. Variability of vegetation index NDVI during periods of
3285   drought in the Tomsk Region, IOP Conf. Series: Earth Environ. Sci., 381, 012096, doi:10.1088/1755-
3286   1315/381/1/012096, 2019.

3287   Voropay, N. N., Kichigina, N. V.: Long-term changes in the hydroclimatic characteristics in the Baikal
3288   region, IOP Conf. Ser.: Earth Environ. Sci., 107, 012042, 2018.

3289   Xausa, F., Paasonen, P., Makkonen, R., Arshinov, M., Ding, A., Denier Van Der Gon, H., Kerminen, V.-M.,
3290   and Kulmala, M.: Advancing global aerosol simulations with size-segregated anthropogenic particle number
3291   emissions, Atmos. Chem. Phys., 18, 10039–10054, doi:10.5194/acp-18-10039-2018, 2018.

3292 Xiao., S., Wang, M. Y., Yao, L., Zhou, B., Yang, X., Chen, J. M., Wang, D. F., Fu, Q. Y., Worsnop, D. R.
3293 and Wang, L.: Strong atmospheric new particle formation in winter in urban Shanghai, China, Atmos. Chem.
3294 Phys., 15, 1769-1781, 2015.

3295 Xie, Y. N., Ding, A. J., Nie, W., Mao, H. T., Qi, X. M., Huang, X., Xu, Z., Kerminen, V. K., Petäjä, T., Chi,
3296 X., Virkkula, A., Boy, M., Xue, L., Guo, J., Sun, J., Yang, X., Kulmala, M., and Fu, C. B.: Enhanced sulfate
3297 formation by nitrogen dioxide: Implications from in situ observations at the SORPES station, J Geophys.
3298 Res.: Atmos., 120(24), 12679-12694, doi:10.1002/2015jd023607, 2015.

3299 Yan, C., Yin, R., Lu, Y., Dada, L., Yang, D., Fu, Y., Kontkanen, J., Deng, C., Garmash, O., Ruan, J.,
3300 Baalbaki, R., Schervish, M., Cai, R., Bloss, M., Chan, T., Chen, T., Chen, Q., Chen, X., Chen, Y., Chu, B.,
3301 Dällenbach, K., Foreback, B., He, X., Heikkinen, L., Jokinen, T., Junninen, H., Kangasluoma, J., Kokkonen,
3302 T., Kurppa, M., Lehtipalo, K., Li, H., Li, H., Li, X., Liu, Y. Ma, Q., Paasonen, P., Rantala, P., Pileci, R. E.,
3303 Rusanen, A., Sarnela, N., Simonen, P., Wang, S., Wang , W., Wang, Y. Xue, M., Yang, G., Yao, L., Zhou,
3304 Y., Kujansuu, J., Petäjä, T., Nie, W., Ma, N., Ge, M., He, H., Donahue, N. M.,Worsnop, D. R., Kerminen,
3305 V.-M., Wang, L., Liu, Y., Zheng, J., Kulmala, M., Jiang, J. and Bianchi, F. (2021) The synergistic role of
3306 sulfuric acid, bases, and oxidized organics governing new-particle formation in Beijing. *Geophys. Res. Lett.*
3307 (in press).

3308 Yang, F., Li, C., Leppäranta, M., Shi, X., Zhao, S. and Zhang, C.: Notable increases in nutrient
3309 concentrations in a shallow lake during seasonal ice growth, Water Sci. Technol., 74(12), 2773–2883, 2016.

3310 Yang, Y., Leppäranta, M. J., Ki, Z., Cheng, B., Zhai, M., and Demchev, D.: Model simulations of the annual
3311 cycle of the landfast ice thickness in the East Siberian Sea, Advances in Polar Sciences, 26(2), 168-178,
3312 doi:10.13679/j.advps.2015.2.00168, 2015.

3313 Yao, L., Garmash, O., Bianchi, F., Zheng, J., Yan, C., Kontkanen, J., Junninen, H., Mazon, S.B., Ehn, M.,
3314 Paasonen, P., Sipilä, M., Wang, M.Y., Wang, X.K., Xiao, S., Chen, H.F., Lu, Y.Q., Zhang, B.W., Wang,
3315 D.F., Fu, Q.Y., Geng, F.H., Li, L., Wang, H.L., Qiao, L.P., Yang, X., Chen, J.M., Kerminen, V.-M., Petäjä,
3316 T., Worsnop, D.R., Kulmala, M. and Wang, L.: Atmospheric new particle formation from sulfuric acid and
3317 amines in a Chinese megacity, Science, 361, 278-281, 2018.

3318 Yasunaka, S., Siswanto, E., Olsen, A., Hoppema, M., Watanabe, E., Fransson, A., Chierici, M., Murata, A.,
3319 Lauvset, S. K., Wanninkhof, R., Takahashi, T., Kosugi, N., Omar, A. M., van Heuven, S., and Mathis, J. T.:
3320 Arctic Ocean CO2 uptake: an improved multiyear estimate of the air–sea CO2 flux incorporating chlorophyll
3321 a concentrations, Biogeosciences, 15, 1643–1661, doi:10.5194/bg-15-1643-2018, 2018.

3322 Ye, Z., Liu, J., Gu, A., Feng, F., Liu, Y., Bi, C., Xu, J., Li, L., Chen, H., Chen, Y., Dai, L., Zhou, Q., and Ge,
3323 X.: Chemical characterization of fine particulate matter in Changzhou, China, and source apportionment with
3324 offline aerosol mass spectrometry, Atmos. Chem. Phys., 17, 2573–2592, doi:10.5194/acp-17-2573-2017,
3325 2017.

3326 Ylivinkka, I., Kaupinmäki, S., Virman, M., Peltola, M., Taipale, D., Petäjä, T., Kerminen, V.-M., Kulmala,

3327 M., and Ezhova, E.: Clouds over Hyytiälä, Finland: an algorithm to classify clouds based on solar radiation

3328 and cloud base height measurements, Atmos. Meas. Tech., 13, 5595–5619, 2020.

3329 He, Y., Chen, F., Jia, H., and Valery, G.: Bondur: Different Drought Legacies between Rain-fed and

3330 Irrigated Croplands in a Typical Russian Agricultural Region, Remote Sens., 12(11), 1700,

3331 doi:10.3390/rs12111700, 2020

3332 Zaidan, M. A., Haapasilta, V., Relan, R., Junninen, H., Aalto, P. P., Kulmala, M., Laurson, L., and Foster, A.

3333 S.: Predicting atmospheric particle formation days by Bayesian classification of the time series features,

3334 Tellus B: Chem. Phys. Meteorol., 70, 10, doi:10.1080/16000889.2018.1530031, 2018a.

3335 Zaidan, M. A., Haapasilta, V., Relan, R., Paasonen, P., Kerminen, V.-M., Junninen, H., Kulmala, M., and

3336 Foster, A. S.: Exploring non-linear associations between atmospheric new-particle formation and ambient

3337 variables: a mutual information approach, Atmos. Chem. Phys., 18, 12699-12714, doi:10.5194/acp-18-

3338 12699-2018, 2018b.

3339 Zanatta, M., Laj, P., Gysel, M., Baltensperger, U., Vratolis, S., Eleftheriadis, K., Kondo, Y., Dubuisson, P.,

3340 Winiarek, V., Kazadzis, S., Tunved, P., and Jacobi, H.-W.: Effects of mixing state on optical and radiative

3341 properties of black carbon in the European Arctic, Atmos. Chem. Phys., 18, 14037–14057, doi:10.5194/acp-

3342 18-14037-2018, 2018.

3343 Zapadinsky, E., Passananti, M., Myllys, N., Kurten, T., and Vehkamäki , H.: Modeling on Fragmentation of

3344 Clusters inside a Mass Spectrometer, Journal of Physical Chemistry, A 123 (2), 611-624,

3345 https://doi.org/10.1021/acs.jpca.8b10744, 2019.

3346 Zha, Q., Yan, C., Junninen, H., Riva, M., Sarnela, N., Aalto, J., Quéléver, L., Schallhart, S., Dada, L.,

3347 Heikkinen, L., Peräkylä, O., Zou, J., Rose, C., Wang, Y., Mammarella, I., Katul, G., Vesala, T., Worsnop, D.

3348 R., Kulmala, M., Petäjä, T., Bianchi, F., and Ehn, M.: Vertical characterization of highly oxygenated

3349 molecules (HOMs) below and above a boreal forest canopy, Atmos. Chem. Phys., 18, 17437–17450,

3350 doi:10.5194/acp-18-17437-2018, 2018.

3351 Zhang, J., Liu, C., and Chen, H.: The modulation of Tibetan Plateau heating on the multi-scale northernmost

3352 margin activity of East Asia summer monsoon in northern China, Global Planet. Change, 161, 149–161,

3353 2018.

3354 Zhang, S., Zhang, J. H., Bai, Y., Koju, U. A., Igbawua, T., Chang, Q., Zhang, D., and Yao, F. M.: Evaluation

3355 and improvement of the daily boreal ecosystem productivity simulator in simulating gross primary

3356 productivity at 41 flux sites across Europe, Ecol. Model., 368, 205-232,

3357 doi:10.1016/j.ecolmodel.2017.11.023, 2018.

3358 Zhang-Turpeinen, H., Kivimäenpää, M., Aaltonen, H., Berninger, F., Köster, E., Köster, K., Menyailo, O.,

3359 Prokushkin, A., and Pumpanen, J.: Wildfire effects on BVOC emissions from boreal forest floor on

3360   permafrost soil in Siberia, Science of the Total Environment, 134851, doi:10.1016/j.scitotenv.2019.134851,

3361   2020.

3362   Zhao, H., Li, X., Zhang, Q., Jiang, X., Lin, J., Peters, G. P., Li, M., Geng, G., Zheng, B., Huo, H., Zhang, L.,

3363   Wang, H., Davis, S. J., and He, K.: Effects of atmospheric transport and trade on air pollution mortality in

3364   China, Atmos. Chem. Phys., 17, 10367–10381, doi:10.5194/acp-17-10367-2017, 2017.

3365   Zhdanova, E. Y., Chubarova, N. Y., and Lyapustin, A. I.: Assessment of urban aerosol pollution over the

3366   Moscow megacity by the MAIAC aerosol product, Atmos. Meas. Tech., 13, 877–891, doi:10.5194/amt-13-

3367   877-2020, 2020.

3368   Zhou, Y., Dada, L., Liu, Y., Fu, Y., Kangasluoma, J., Chan, T., Yan, C., Chu, B., Daellenbach, K. R.,

3369   Bianchi, F., Kokkonen, T. V., Liu, Y., Kujansuu, J., Kerminen, V.-M., Petäjä, T., Wang, L., Jiang, J., and

3370   Kulmala, M.: Variation of size-segregated particle number concentrations in wintertime Beijing, Atmos.

3371   Chem. Phys., 20, 1201–1216, doi:10.5194/acp-20-1201-2020, 2020.

3372   Zilitinkevich, S., Druzhinin, O., Glazunov, A., Kadantsev, E., Mortikov, E., Repina, I., and Troitskaya, Y.:

3373   Dissipation rate of turbulent kinetic energy in stably stratified sheared flows, Atmos. Chem. Phys., 19, 2489–

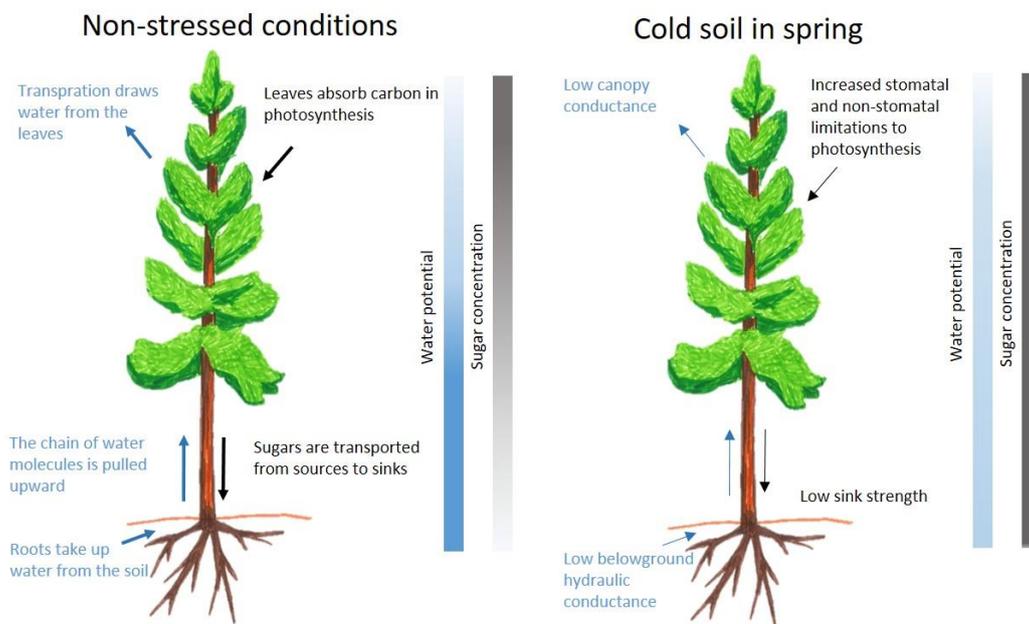
3374   2496, doi:10.5194/acp-19-2489-2019, 2019.

3375   Öström, E., Putian, Z., Schurgers, G., Mishurov, M., Kivekäs, N., Lihavainen, H., Ehn, M., Rissanen, M. P.,

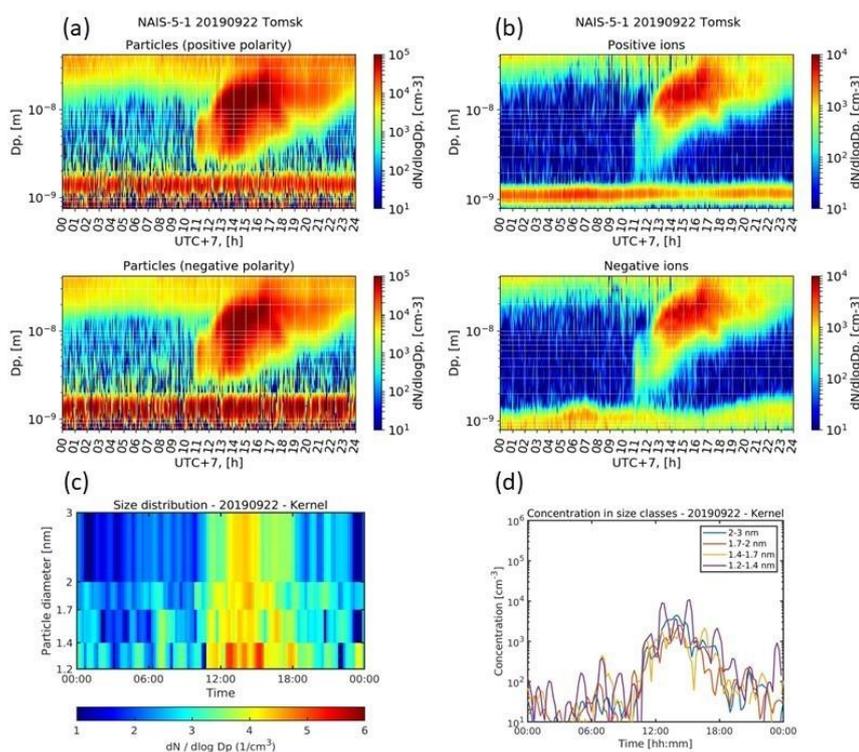
3376   Kurtén, T., Boy, M., Swietlicki, E., and Roldin, P.: Modeling the role of highly oxidized multifunctional

3377   organic molecules for the growth of new particles over the boreal forest region, Atmos. Chem. Phys., 17,

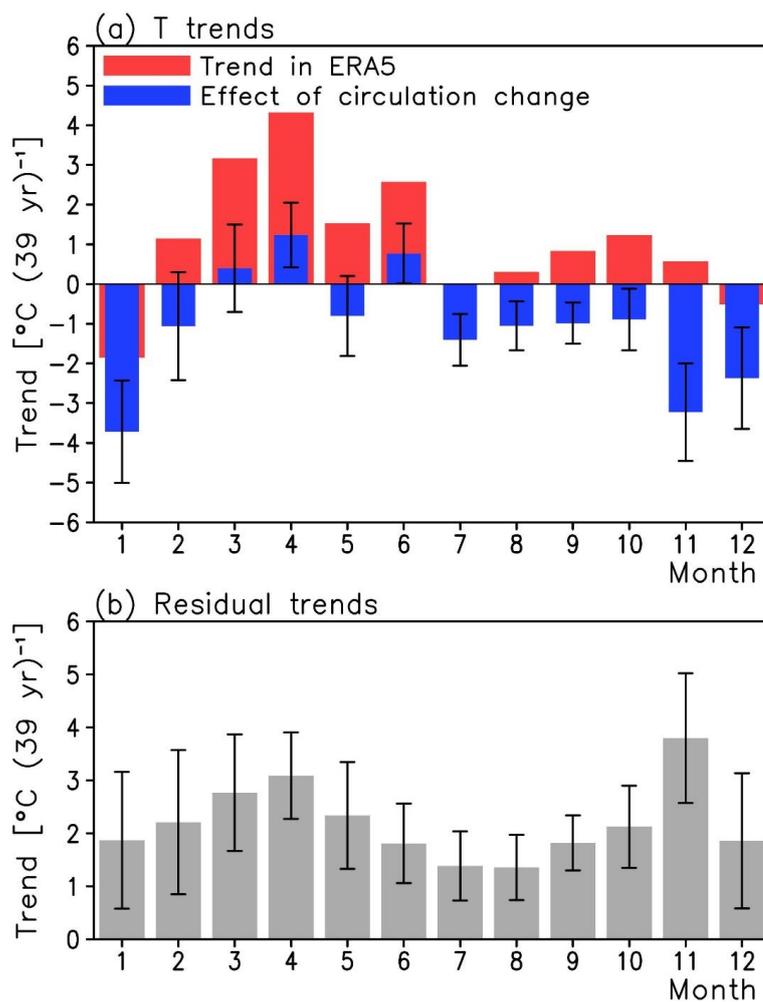
3378   8887–8901, doi:10.5194/acp-17-8887-2017, 2017.

3379

3380

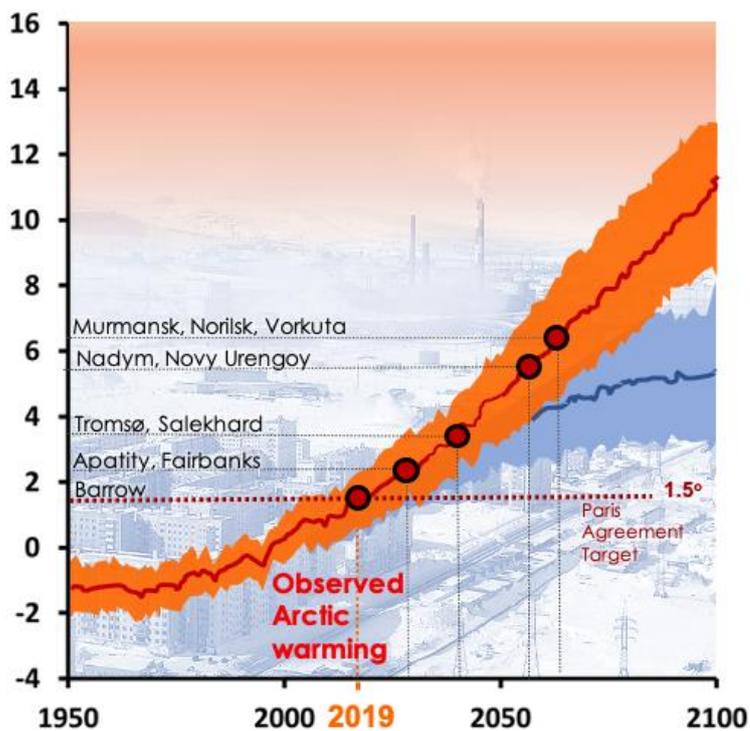
3381   Figure 1.

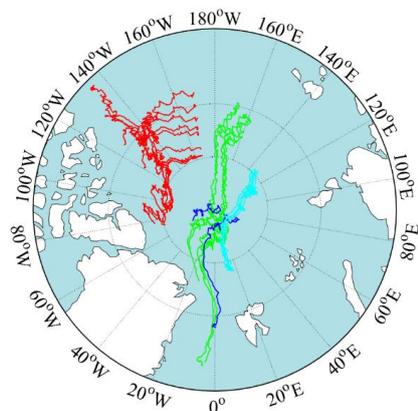
3382

3383

3384   Figure 2.

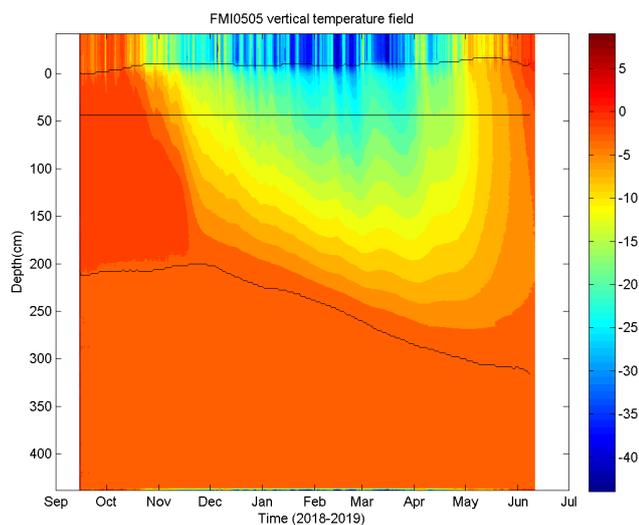
3385

3386

3387   Figure 3.

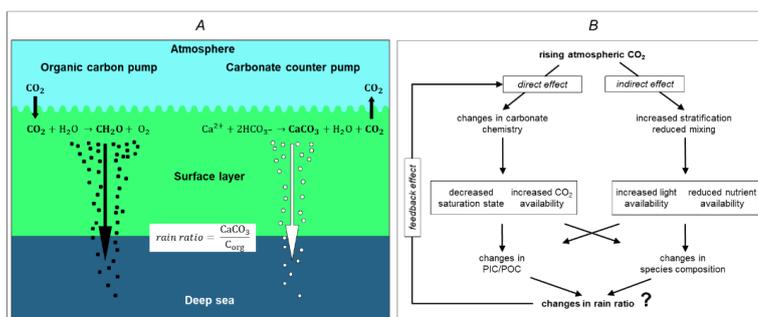
3388

3389

3390   Figure 4.

3391

3392   Figure 5.

3393

3394

3395   Figure 6.

3396

3397

3398   Figure 7.

3399

3400

3401   Figure 8.

3402

3403

3404   Figure 9.

3405

3406   Figure 10.

3407

3408

3409

3410

3411   **Figure 1.** A recent field and modelling study shows that cold soil decreases belowground hydraulic

3412   conductance (i.e. less root water uptake), and further canopy conductance in mature, boreal trees in spring

3413   (Lintunen et al. 2020). Cold temperature also decreases sink strength (i.e. less sugars are needed for metabolism

3414   and growth). Low sink strength increases sugar concentration in leaves, which decreases photosynthesis due

3415   to increased stomatal and non-stomatal limitations for photosynthesis (Hölttä et al., 2017; Salmon et al., 2020).

3416   **Figure 2.** Example of results from the state-of-the-art aerosol instruments NAIS and PSM displaying NPF

3417   event at Fonovaya station, Siberia, on 22.09.2019. Particles of different polarity, NAIS (a), ions of different

3418   polarity, NAIS (b), particle number distribution at the smallest sizes, PSM (c), number concentration of the

3419   smallest particles in different size bins, PSM (d).

3420

3421   **Figure 3.** Linear trends of monthly mean temperature in Western Siberia (55°-65°N, 65°-90°E) in years 1979-

3422   2018. In (a), the red bars show the trend in the ERA5 reanalysis and the blue bars the circulation-related trend.

3423   In (b), the residual trends are shown. The error bars indicate the 5-95% uncertainty range in the circulation-

3424   related trend and the residual trend based on interannual variability. Redrawn from Räisänen (2020).

3425

Figure 4. The northern urban heat islands are forerunners of the global warming. Winter season future temperatures for the Arctic (60–90°N) averaged over 36 CMIP5 global climate models and expressed as departures from the means for the 1981–2005 period. The red line is the ensemble mean for RCP8.5, the blue line is for RCP4.5. Shaded areas denote ± one standard deviation from the ensemble mean (Overland et al., 2014; and Fig. 2.15 of AMAP, 2017). The observed surface UHIs are shown as red dots collocated with the expected future Arctic temperature anomalies, e.g., the observed wintertime urban temperature anomaly in Nadym corresponds to the regional warming as expected to be reached by 2060. Observe that the present Arctic climate is already 1.5°C warmer than the historical normals 1960-1990.

Figure 5. Trajectories of SIMBA buoys deployed in the Arctic in the period 2018-2019. Red: CHINARE (10 buoys), green: NABOS (5 buoys), dark blue: CAATEX (2 buoys), and light blue: MOSAiC (15 buoys). SIMBA is a thermistor string-based ice mass balance (IMB) buoy. It measures high-resolution (2 cm) vertical environment temperature (ET) profiles (4 times a day) through the air-snow-sea ice-ocean column. The heating temperature (HT) measured by the thermistor string once per day is based on the use of a small identical heater on each sensor. The ET and HT data are used to derive snow depth and ice thickness. SIMBA uses GPS module to track the buoy location. The Iridium satellite is used for data transmission. A total 15 SIMBA buoys have been deployed in the Arctic Ocean during the Chinese National Arctic Research Expedition (CHINARE) 2018 and the Nansen and Amundsen Basins Observational System (NABOS) 2018 field expeditions in late autumn. In 2019 17 SIMBA buoys were deployed during the CAATEX (2) and MOSAIC expeditions (15, leg 1).

Figure. 6. SIMBA observations on the temporal evolution of the snow depth, ice thickness, and the temperature profile from the ocean through snow and sea ice to air. The results were obtained applying the algorithm by Liao et al. (2018). The black lines are snow surface (top), Initial freeboard (middle) and ice base (bottom). 0 level refers to snow/ice interface. The colors indicate the temperature in °C.

Figure 7. **A**: Biological pumps resulting in (i) atmospheric CO_2 sink and(ii) calcium carbonate transport from surface to deep ocean; **B**: anticipated forward and feedback alterations in ocean ecology driven by atmospheric CO2 increase. PIC=particulate inorganic carbon; POC=particulate organic carbon (modified after Rost & Riebesell, 2004).

Figure 8. Field data for ice decay in Lake Kilpisjärvi in 2013 showing decrease of ice thickness by surface melting and bottom melting and increase of porosity until breakage of ice cover.

Figure 9. Hydrogeochemical signature of large river system –Selenga River case study. The figure represent metal(loid)s partitioning (Median values) in the Selenga river basin in the upper (Mongolian) and downstream (Russian) part between 20 July -10 August 2011 under dominant high water (A) and 07 June -10 July 2012 under dominant low water conditions. Dark orange fill corresponds to the share of suspended forms of elements > 75% (green), light orange – 75-50%, light blue – 50-25%, dark blue – < 25%. The figure indicate that in the large river system some metals are mostly found in the dissolved form (84–96% of Mo, U, B, and

Sb on an average), whereas many others predominantly existed in suspension (66–87% of Al, Fe, Mn, Pb, Co, and Bi). A consistently increasing share of metals in suspended particulate modes (about 2–6 times) is observed under high discharge conditions For details and other hydrological seasons refer to (Kasimov et al., 2020b).

Figure 10. Changes in 2-meter temperature (ºC, upper panels) and precipitation (%, lower panels) during the 21st century. Present-day climatology is averaged over years 1981-2010 and end-of-century climatology over 2070-2099. Winter (left) and summer (right) are shown separately. Dotted areas indicate high variability in model ensemble (for temperature: standard deviation of 21st century change exceeds 1ºC; for precipitation: standard deviation of 21st century change exceeds 100% or present-day precipitation). The model results are from IPCC AR5, based on 42 individual models in CMIP5 experiments under the RCP4.5 scenario.

Table 1. Systems, key topical areas, research question introduced in the PEEX Science Plan (SP) (Kulmala et al. 2015; 2016a, Lappalainen et al. 2018) connected to the addressed research themes over last 5 yeas by the PEEX questionary (APPENDIX 1). The addressed research themes and the results are overviewed in Chapter 3.

PEEX – SP System	PEEX - SP key topical area	PEEX - SP research question (Q-No)	Addressed research themes during the last 5 years
Land	Changing land ecosystem processes	**How could the land regions and processes that are especially sensitive to climate change be identified, and what are the best methods to analyze their responses? (Q-1)**	• high-latitude photosynthetic productivity and vegetation changes (greening, browning) • new methodologies determining Earth surface characteristics
Land	Risk areas of permafrost thawning	**How fast will permafrost thaw proceed, and how will it affect ecosystem processes and ecosystem-atmosphere feedbacks, including hydrology and greenhouse gas fluxes ? (Q-2)**	• soil temperature evolution • changing GHG fluxes, carbon sink-source dynamics due to permafrost thawning
Land	Ecosystem structural changes	**What are the structural ecosystem changes and tipping points in the future evolution of the Pan-Eurasian ecosystem? (Q-3)**	• changes in soil microbial activity e.g. effect of forest fires • changes of the Northern soils and functioning of the Arctic tundra in global carbon cycling context

Atmosphere	Atmospheric composition and chemistry	**What are the critical atmospheric physical and chemical processes with large-scale climate implications in a northern context? (Q4)**	• carbon (C) balance in the boreal forests; methane (CH_4) balance at the Arctic; carbon monoxide (CO), ozone (O_3) at the Northern Eurasian region • Sources and properties of atmospheric aerosols in boreal and Arctic environments • black carbon and dust in the atmosphere and on snow at the Northern high latitudes • methodological and model developments related to atmospheric chemistry and physics
Atmosphere	Urban air quality and megacities, ABL	**What are the key feedbacks between air quality and climate at northern high latitudes and in China? (Q5)**	• recent observations on air quality in China • Anthropogenic emissions and environmental pollution in Russia
Atmosphere	Weather and atmospheric circulation	**How will atmospheric dynamics (synoptic scale weather, boundary layer) change in the Arctic-boreal regions? (Q6)**	• cold & warm episodes • cyclone density dynamics • circulation effect on temperature and moisture • cloudiness in Arctic • atmospheric boundary layer (ABL) dynamics
Water	The Artic Ocean in the climate system	**How will the extent and thickness of the Arctic sea ice and terrestrial snow cover change? (Q-7)**	• Sea ice dynamics and thermodynamics with atmospheric and ocean dynamics • Snow depth/mass and sea ice thickness • Sea ice research supporting navigation • Ocean floor, sediments: composition and fluxes • River runoff effecting the hydrological processes at coastal marine environments in Russia
Water	Arctic marine ecosystem	**What is the joint effect of Arctic warming, ocean freshening, pollution load and acidification on the Arctic marine ecosystem, primary production and carbon cycle? (Q-8)**	• Living marine organisms weaken or even subdue CO_2 accumulation
Water	Lakes and large-scale river systems	**What is the future role of Arctic-boreal lakes, wetlands and large river systems, including thermokarst lakes and running waters of all size, in biogeochemical cycles, and how will these changes affect societies) ? (Q-9)**	• organic carbon, carbon balance, ice cover at lakes in the Northern high latitudes • specific charachteristis of the Lake Baikal and Selenga River delta in Russia • specific charachteristis of Asian water lakes

Society	Anthropogenic impact	**How will human actions such as land-use changes, energy production, the use of natural resources, changes in energy efficiency and the use of renewable energy sources influence further environmental changes in the region? (Q-10)**	• Mitigation e.g method for the natural risk assessment in Russia and new clean energy technologies
Society	Environmental impact	**How do the changes in the physical, chemical and biological state of the different ecosystems, and the inland, water and coastal areas affect the economies and societies in the region, and vice versa? (Q-11)**	• Reindeer grazing effects on the ground vegetation structure and biomass
Society	Natural hazards	**In which ways are populated areas vulnerable to climate change? How can their vulnerability be reduced and their adaptive capacities improved? What responses can be identified to mitigate and adapt to climate change? (Q-12)**	• Emerging zoonotic diseases • UV variation effects on health • Air pollution in different scales and environments (street-level urban air pollution, transported air pollution in urban environments, air pollution at the Arctic) and related health effects;
Feedbacks	Key topics: Atmospheric composition, biogeochemical cycles: water, C, N, P, S	**How will the changing cryospheric conditions and the consequent changes in ecosystems feed back to the Arctic climate system and weather, including the risk of natural hazards? (Q-13)**	• *Research needs:* quantification of the COntinental Biosphere-Aerosol-Cloud-Climate (COBACC) feedback loop at different Northern boreal environments • Gold & high region quantification of BVOC – aerosols feedback loop at the Tibetan /Himalayan Plateau:
Feedbacks	Key topics: Atmospheric composition, biogeochemical cycles: water, C, N, P, S	**What are the net effects of various feedback mechanisms on (i) land cover changes, (ii) photosynthetic activity, (iii) GHG exchange and BVOC emissions (iv) aerosol and cloud formation and radiative forcing ? How do these vary with climate change on regional and global scales? (Q-14)**	• *Research needs:* The Arctic greening and browning calls for a multi-disciplinary scientific approach together, improved modelling tools and new data in order to solve scientific questions related to the net effects of various feedback mechanisms connecting the biosphere-atmosphere - human activities

Feedbacks	Key topics: Atmospheric composition, biogeochemical cycles: water, C, N, P, S	**How are intensive urbanization processes changing the local and regional climate and environment? (Q-15)**	• *Research needs:* accelerating urbanization calls for studies on the effects of on air pollution, local climate and the effects these changes have on global climate. Integrated studies should lead to services for society, cities helping to mitigate hazards storms, flooding, heat waves, and air pollution episodes (see also 3.2.1)

3479

3480

3481 **Code/Data availability:** This is an review paper and the data availabity is introduced in the

3482 original articles.

3483 **Author contribution:** Co-authors have provided text and/or relevant references. Some of them

3484 have been editors of the specific chapters of the manuscript.

3485 **Competing interests:** no spesific competing interests