

## The Center of Excellence in Atmospheric Science (2002–2019) — from molecular and biological processes to the global climate

Anna Lintunen<sup>1)2)3)\*</sup>, Juho Aalto<sup>2)3)</sup>, Ari Asmi<sup>1)†</sup>, Mika Aurela<sup>4)</sup>, Jaana Bäck<sup>2)3)</sup>, Mikael Ehn<sup>1)</sup>, Ekaterina Ezhova<sup>1)</sup>, Hannele Hakola<sup>4)</sup>, Kari Hartonen<sup>5)6)</sup>, Jussi Heinonsalo<sup>2)3)</sup>, Heidi Hellén<sup>4)</sup>, Teemu Hölttä<sup>2)3)</sup>, Tuija Jokinen<sup>1)‡</sup>, Leena Järvi<sup>1)</sup>, Heikki Järvinen<sup>1)4)</sup>, Juha Kangasluoma<sup>1)</sup>, Veli-Matti Kerminen<sup>1)</sup>, Pasi Kolari<sup>1)</sup>, Kajar Köster<sup>7)</sup>, Egle Köster<sup>8)</sup>, Liisa Kulmala<sup>4)</sup>, Theo Kurten<sup>5)</sup>, Ari Laaksonen<sup>4)</sup>, Hanna K. Lappalainen<sup>1)4)</sup>, Tuomas Laurila<sup>4)</sup>, Katrianne Lehtipalo<sup>1)4)</sup>, Heikki Lihavainen<sup>9)4)</sup>, Annalea Lohila<sup>1)4)</sup>, Mari Losoi<sup>10)11)12)</sup>, Annikki Mäkelä<sup>2)3)</sup>, Risto Makkonen<sup>4)1)</sup>, Ivan Mammarella<sup>1)</sup>, Santtu Mikkonen<sup>13)</sup>, Dmitri Moisseev<sup>1)4)</sup>, Anne Ojala<sup>1)2)</sup>, Tuukka Petäjä<sup>1)</sup>, Mari Pihlatie<sup>11)12)</sup>, Albert Porcar-Castell<sup>2)3)</sup>, Arnaud P. Praplan<sup>4)</sup>, Jouni Pulliainen<sup>4)</sup>, Jukka Pumpanen<sup>7)</sup>, Pekka Rantala<sup>1)</sup>, Marja-Liisa Riekkola<sup>5)6)</sup>, Kaisa Rissanen<sup>2)3)</sup>, Sami Romakkaniemi<sup>14)</sup>, José Ruiz-Jimenez<sup>5)6)</sup>, Nina Sarnela<sup>1)</sup>, Simon Schallhart<sup>4)</sup>, Pauliina Schiestl-Aalto<sup>1)</sup>, Janne Rinne<sup>15)16)</sup>, Eeva-Stiina Tuittila<sup>8)</sup>, Hanna Vehkamäki<sup>1)</sup>, Timo Vesala<sup>1)2)</sup>, Yrjö Viisanen<sup>4)</sup>, Annele Virtanen<sup>13)</sup>, Ilona Ylivinkka<sup>1)</sup>, Pertti Hari<sup>2)</sup> and Markku Kulmala<sup>1)</sup>

<sup>1)</sup> Institute for Atmospheric and Earth System Research (INAR)/Physics, Faculty of Science, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland  
(\*corresponding author's e-mail: anna.lintunen@helsinki.fi)

<sup>2)</sup> Institute for Atmospheric and Earth System Research/Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland

<sup>3)</sup> Department of Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland

<sup>4)</sup> Finnish Meteorological Institute, Erik Palménin aukio 1, FI-00560 Helsinki, Finland

<sup>5)</sup> Department of Chemistry, University of Helsinki, P.O. Box 55, FI-00014 Helsinki, Finland

<sup>6)</sup> Institute for Atmospheric and Earth System Research (INAR)/Chemistry, Faculty of Science, University of Helsinki, P.O. Box 55, FI-00014 Helsinki, Finland

<sup>7)</sup> Department of Environmental and Biological Sciences, University of Eastern Finland, P.O. Box 111, FIN-80101 Joensuu, Finland

<sup>8)</sup> School of Forest Sciences, University of Eastern Finland, P.O. Box 111, FI-80100 Joensuu, Finland

<sup>9)</sup> Svalbard Intergrated Arctic Earth System, P.O. Box 156, N - 9171 Longyearbyen, Norway

<sup>10)</sup> Department of Environmental and Biological Sciences, University of Eastern Finland, P.O. Box 1627, FI-70211 Kuopio, Finland

<sup>11)</sup> Institute for Atmospheric and Earth System Research/Agricultural Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 56, FI-00014 Helsinki, Finland

<sup>12)</sup> Department of Agricultural Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 56, FI-00014 Helsinki, Finland

<sup>13)</sup> Department of Applied Physics, University of Eastern Finland, FI-70211 Kuopio, Finland

<sup>14)</sup> Finnish Meteorological Institute, P.O. Box 1627, FI-70211 Kuopio, Finland

<sup>15)</sup> *Natural Resources Institute Finland (Luke), Latokartanonkaari 9, FI-00790 Helsinki, Finland*

<sup>16)</sup> *Department of Physical Geography and Ecosystem Science, Lund University, Lund Sweden*

<sup>†</sup> *Currently at Research Data Alliance AISBL, Boulevard Louis Schmidt 24, Etterbeek 1040, Belgium*

<sup>‡</sup> *Currently at Climate & Atmosphere Research Centre (CARE-C), The Cyprus Institute, P.O. Box 27456, Nicosia, CY-1645, Cyprus*

*Received 14 Mar. 2022, final version received 27 Jan. 2023, accepted 1 Feb. 2023*

Lintunen A., Aalto J., Asmi A., Aurela M., Bäck J., Ehn M., Ezhova E., Hakola H., Hartonen K., Heinonsalo J., Hellén H., Hölttä T., Jokinen T., Järvi L., Järvinen H., Kangasluoma J., Kerminen V.-M., Kolari P., Köster K., Köster E., Kulmala L., Kurten T., Laaksonen A., Lappalainen H.K., Laurila T., Lehtipalo K., Lihavainen H., Lohila A., Losoi M., Mäkelä A., Makkonen R., Mammarella I., Mikkonen S., Moisseev D., Ojala A., Petäjä T., Pihlatie M., Porcar-Castell A., Praplan A. P., Pulliainen J., Pumpanen J., Rantala P., Riekkola M.-L., Rissanen K., Romakkaniemi S., Ruiz-Jimenez J., Sarnela N., Schallhart S., Schiestl-Aalto P., Rinne J., Tuittila E.-S., Vehkamäki H., Vesala T., Viisanen Y., Virtanen A., Ylivinkka I., Hari P. & Kulmala M. 2023: The Center of Excellence in Atmospheric Science (2002–2019) — from molecular and biological processes to the global climate. *Boreal Env. Res.* 28: 15–80.

The study of atmospheric processes related to climate requires a multidisciplinary approach, encompassing physics, chemistry, meteorology, forest science, and environmental science. The Academy of Finland Centre of Excellence in atmospheric sciences (CoE ATM) responded to that need for 18 years and produced extensive research and eloquent results, which are summarized in this review. The work in the CoE ATM enhanced our understanding in biogeochemical cycles, ecosystem processes, dynamics of aerosols, ions and neutral clusters in the lower atmosphere, and cloud formation and their interactions and feedbacks. The CoE ATM combined continuous and comprehensive long-term in-situ observations in various environments, ecosystems and platforms, ground- and satellite-based remote sensing, targeted laboratory and field experiments, and advanced multi-scale modeling. This has enabled improved conceptual understanding and quantifications across relevant spatial and temporal scales. Overall, the CoE ATM served as a platform for the multidisciplinary research community to explore the interactions between the biosphere and atmosphere under a common and adaptive framework.

## Introduction

Life on Earth, the biosphere, interacts closely with the atmosphere, and is sensitive to changes in its composition and functioning. These interactions occur on spatial scales from nanometers to global, and time scales from nanoseconds to millennia (Wanner *et al.* 2008, Kulmala *et al.* 2009a). In addition to the atmosphere, the biosphere interacts with the hydrosphere, cryosphere and lithosphere, and changes in any of these components affect the others through material and energy flows, and linked processes and feedbacks. Accordingly, global climate system is strongly influenced by biosphere through the effect of vegetation cover on surface radiation budget, sensible and latent heat fluxes, and atmospheric composition, and there-

fore understanding biotic processes is necessary for correctly analyzing the global climate system (Krinner *et al.* 2005, Arneth *et al.* 2010). Although biosphere–atmosphere feedbacks are globally widespread and regionally strong, current Earth system models underestimate these feedbacks (Green *et al.* 2017). One reason for this is that the Earth observations are traditionally rather fragmented. The Earth system can be studied piece by piece, but to be able to study complicated interactions and feedbacks between different Earth components and to foresee changes in the Earth system, a holistic, interdisciplinary approach is needed (Kulmala 2018).

Currently, humanity is facing severe global changes in the Earth system. Each of the last four decades has been successively warmer than

any decade before it since 1850, and the global surface temperature (in 2011–2020) is already 1.09°C above the pre-industrial (1850–1900) level (IPCC 2021). Despite decades of research, there are still many areas of uncertainty in understanding the global climate system and its changes. The critical issues that need continued scientific efforts are called Grand Challenges, and include e.g. the role of clouds and aerosols in the climate system, sea-level rise, water availability, cryospheric processes, and linking extreme events to climate change (Beniston 2013). Fundamental in solving these Grand Challenges is in addition to holistic scientific efforts, an adequate Earth observation network (Kulmala 2018), easy access to climate research data and data compatibility.

Due to the Grand Challenges related to global warming, the remaining allowable net carbon emission to stay below the 1.5°C Paris temperature target is highly uncertain. The Intergovernmental Panel on Climate Change (IPCC) recognizes atmospheric aerosols as the single largest source of uncertainty in human-driven climate change (IPCC 2013, 2021). The effects of these aerosols include the direct effect of aerosols on radiative forcing, their impact on cloud formation and properties, and their feedbacks in the natural carbon cycle. The Academy of Finland's Center of Excellence in Atmospheric Sciences (CoE ATM) has worked for 18 years to increase the understanding on and to quantify various biogeochemical cycles, ecosystem processes, dynamics of aerosols, ions and neutral clusters in the lower atmosphere, cloud formation and their interactions and feedbacks. The COntinental Biosphere-Aerosol-Cloud-Climate (COBACC) feedback loop demonstrates the complexity of interactions existing between biosphere processes and aerosol formation and growth (Kulmala *et al.* 2013a, 2014, Fig. 1). The COBACC theoretical framework has been developed in the CoE ATM and used to test and develop new theoretical understanding. In COBACC, the higher temperatures and atmospheric CO<sub>2</sub> levels boost ecosystem carbon sink and biomass production, which leads to increased biogenic secondary organic aerosol and cloud condensation nuclei concentrations, causing cooling. Enhanced aer-

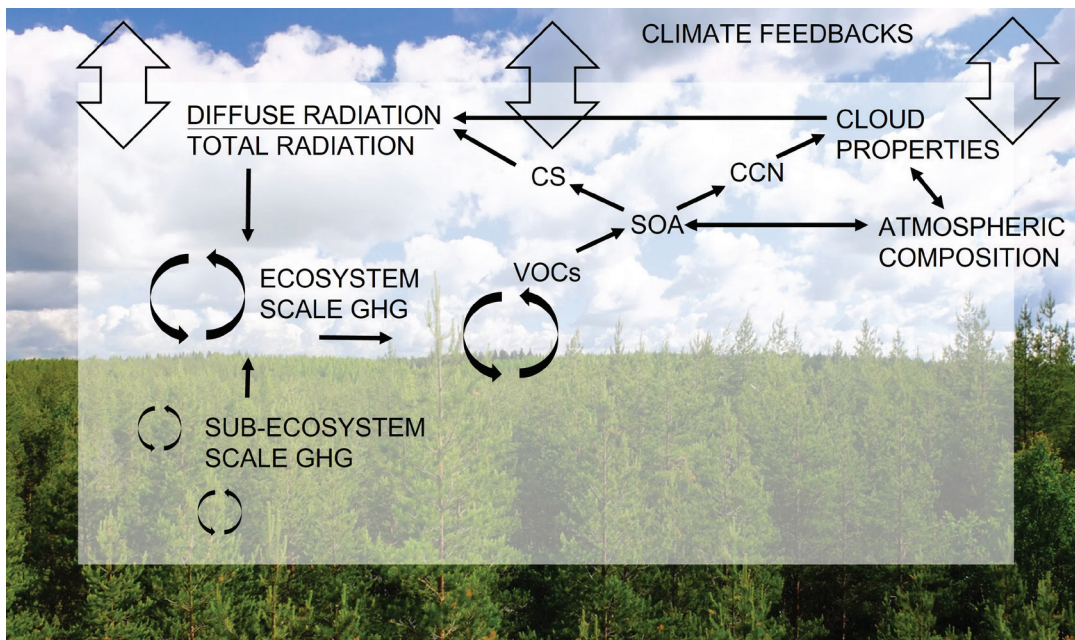
osol and cloud nuclei concentrations further increase the fraction of diffuse solar radiation that feeds back to plant biomass production, because plants can utilize diffuse radiation more efficiently than direct radiation in biomass production. COBACC connects the two main cooling agents, carbon sink and aerosol source, to each other, and combines physical, chemical and biotic phenomena and feedbacks (Arneth *et al.* 2010, Carslaw *et al.* 2010, Mahowald 2011). Human actions, such as emission policies and land use changes, also have a substantial impact on the complex couplings between atmospheric aerosols, trace gases, greenhouse gases (GHG), clouds and climate (Arneth *et al.* 2009, Raes *et al.* 2010, Shindell *et al.* 2012, Boy *et al.* 2019, Artaxo *et al.* 2022). Aerosols link air quality with weather and climate, introducing additional feedbacks, particularly through boundary layer dynamics (Kulmala 2015, Petäjä *et al.* 2016a).

Here we present an overview of the CoE ATM's approach and key scientific advancements from 2002–2019. A unique feature and a key component in the success of the group has been the comprehensive, long-term and co-located measurements of various Earth components and close collaboration with scientists from different disciplines. This interdisciplinary approach is needed to understand the interactions and feedbacks among Earth components and ultimately to solve the Grand Challenges of the Earth.

## Approach

### Scientific approach

We measure material and energy flows in and between different ecosystems and the atmosphere to understand the biosphere–atmosphere interactions. Mass and energy flows are like an interdisciplinary language which allows an information flow between disciplines. This is especially important between biological/ecological and physical and chemical sciences. Thus, in a fundamental level, the aim of the consecutive CoEs has been to understand the processes and interactions in the biosphere–atmosphere continuum by combining the multidisciplinary



**Fig. 1.** The CoE ATM has focused on studying the Earth surface–atmosphere interactions, feedbacks and the individual ecosystem and atmospheric processes involved. The emission of volatile organic compounds (VOCs) from an ecosystem (that can be any type of ecosystem, including e.g. urban area or agricultural field) is linked to ecosystem activity and greenhouse gas (GHG) emission. VOCs participate in the formation of secondary organic aerosols (SOA) in the atmosphere. SOA directly affects atmospheric composition, forms cloud condensation nuclei (CCN) affecting cloud formation and properties, and build up condensation sink (CS) that further increases the amount of diffuse radiation the ecosystem is receiving. Diffuse radiation can be used by the ecosystem more efficiently than direct radiation in photosynthesis, thus increasing ecosystem carbon sink. These ecosystem–atmosphere interactions feed back to global climate, which is shown with the big arrows at the top of the picture: Increasing atmospheric CO<sub>2</sub> concentration increases ecosystem carbon assimilation and increasing air temperature affects many of the ecosystem and atmospheric processes involved, whereas increasing cloudiness and CS cools air temperature by reflecting sunlight back to space and increasing ecosystem carbon sink decreases the atmospheric CO<sub>2</sub> concentrations.

expertise of the consortium, i.e. learning from the dialogue between the disciplines and the disciplinary-specific methodologies to provide new insights into the processes (e.g. Kulmala *et al.* 2005, Hari and Kulmala 2008, Kulmala *et al.* 2009b).

The need to understand mass and energy flows led to the development of network of Stations for Measuring Earth Surface–Atmosphere Relations (SMEAR; Hari *et al.* 2016). The first SMEAR station (SMEAR I) was established in Värriö, Northern Finland (Hari *et al.* 1994). At this station, the particular focus was on timely topics at the time, i.e., acidification, acid rain and their effects on forests. Over the following years, more SMEAR stations were constructed with SMEAR II in Hyytiälä being the most

comprehensive of them all (Hari and Kulmala 2005). The SMEAR stations have provided the experimental backbone also for studies on urban air quality (SMEAR III, Järvi *et al.* 2009a) and aerosol–cloud interactions (SMEAR IV, Leskinen *et al.* 2009). Pallas–Sodankylä Global Atmospheric Watch station is another station (in addition to SMEAR I) in Northern Finland and provides, e.g., the longest continuous data set of high-precision atmospheric CO<sub>2</sub> concentration in Finland, dating back to 1996 (Hatakka *et al.* 2003, Kilkki *et al.* 2015). The SMEAR concept has expanded also to study atmosphere–forest interactions in a hemi-boreal forest in Estonia (Noe *et al.* 2015), air quality–savannah interactions in South Africa (Venter *et al.* 2018), air quality–boundary layer–precipitation processes

in Eastern China (Ding *et al.* 2013a, 2016a, Petäjä *et al.* 2016a), and air quality–aerosol–haze processes (Kulmala *et al.* 2021a, Liu *et al.* 2020) in a Chinese gigacity environment (Kulmala *et al.* 2021a). Such comprehensive ground-based observations are needed (Kulmala 2015, Kulmala 2018) together with satellite remote sensing data (e.g. Sun 2017), multiscale modeling and integration of the results (e.g. Kerminen *et al.* 2010, Petäjä *et al.* 2021a, 2021b) to tackle the challenges the societies are facing now and in the future.

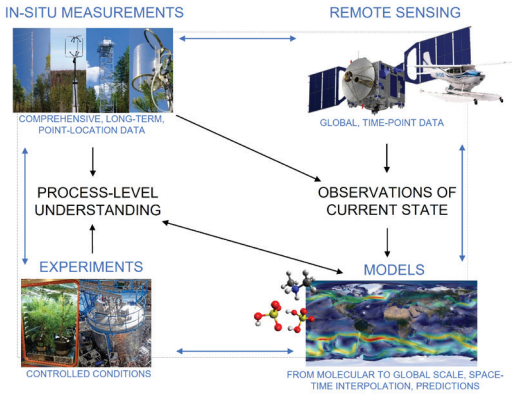
Although the fundamental approach has not changed over the years, the thematic focus of the CoE ATM has developed and widened as we have deployed the framework to a variety of research questions in different environments. For example, experimental determination of fluxes between the biosphere and the atmosphere originally enabled us to study photosynthesis and CO<sub>2</sub> exchange (e.g. Hari *et al.* 1999a,b). Over the years, we have extended this approach to include, for example, biogenic volatile organic compounds (BVOCs, Aalto *et al.* 2014, Rantala *et al.* 2015, Héllen *et al.* 2018), methane (Rinne *et al.* 2018, Vainio *et al.* 2021), nitrous oxide (Korkiakoski *et al.* 2020) and carbonyl sulfide (Kohonen *et al.* 2020). Under the SMEAR umbrella, we have studied the material flows in addition to different forests in pristine wetlands (Rinne *et al.* 2018), urban areas (Karttunen *et al.* 2020) and over lakes (Erkkilä *et al.* 2018). Recently, SMEAR-type measurements have started also on agricultural ecosystems (Heimsch *et al.*, 2021) and on a cutover wetland. The analysis has tackled not only vertical exchange but also lateral transport of water and dissolved organics (e.g. Rasilo *et al.* 2015).

With the comprehensive observational data, we have connected the emission of BVOCs from the biosphere, their atmospheric oxidation, the formation of fresh atmospheric aerosol particles and the production of secondary organic aerosol (Kulmala *et al.* 2013b, Ehn *et al.* 2014). In order to observe these processes, we have developed novel aerosol technologies, such as the Particle Size Magnifier (PSM, Vanhanen *et al.* 2011), which is able to detect aerosol particles down to 1 nm in size. At the same time, we have developed atmospheric mass spectrometric

techniques to determine the chemical composition of the trace gases and clusters (e.g. Petäjä *et al.* 2009, Sipilä *et al.* 2010, Kulmala *et al.* 2013b, Ehn *et al.* 2014). Furthermore, we have contributed significantly to the development of a Neutral cluster and Air Ion Spectrometer (NAIS) (Manninen *et al.* 2009, 2010, Mirme and Mirme 2013, Kulmala *et al.* 2013b). These techniques are currently deployed worldwide to resolve the chemistry and physics behind secondary aerosol formation in different environments in the atmosphere and in controlled laboratory experiments (e.g. Kerminen *et al.* 2018, Yao *et al.* 2018, Chu *et al.* 2019, Wang *et al.* 2020, Bianchi *et al.* 2021).

The comprehensive observations at SMEAR stations enable us to expand the scale and relevance of individual observations. The interdisciplinary observations from the ecosystem sciences (e.g. photosynthesis, emission of BVOCs), chemistry (e.g. atmospheric oxidation), aerosol science (e.g. formation and growth of aerosol particles), atmospheric and cloud physics (e.g. aerosol activation to cloud droplets) and meteorology (e.g. boundary layer dynamics, formation of precipitation) allow us to explore the influence of biogenic emissions to atmospheric optical properties, precipitation, cloud properties and ultimately to radiative forcing (e.g. Paasonen *et al.* 2013, Kulmala *et al.* 2014, Kulmala *et al.* 2020, Petäjä *et al.* 2021a). Thus, one cornerstone in the CoE ATM approach has been the co-location of different environmental measurements, and we have actively integrated these measurements in Finland and promoted their integration also in Europe and globally.

The CoE ATM research infrastructure (INAR RI) belongs to the Finnish RI roadmap 2021–2024. INAR RI integrates the measurements of four European research infrastructures: Integrated Carbon Observation System (ICOS), Aerosol, Clouds, and Trace Gases Research Infrastructure (ACTRIS), Integrated European Long-Term Ecosystem, Critical Zone & Socio-Ecological Research Infrastructure (eLTER) and Infrastructure for Analysis and Experimentation on Ecosystems (AnaEE). The CoE ATM was providing data and acted for years as the national focal point of Finnish activities in these research infrastructures.



**Fig 2.** The ATM CoE scientific approach was to combine comprehensive in situ observations in different types of environments, ecosystems and platforms, ground- and satellite-based remote sensing, targeted laboratory and field experiments and multi-scale modeling.

Overall, the CoE ATM has served as a platform for the multidisciplinary research community to explore different aspects in the biosphere–atmosphere interactions under a common and adaptive framework that combines experimental work, theoretical thinking and multiscale modeling following the research philosophy principles of realism. In its traditional form, realism expresses the belief that reality exists independently of us. In the past century, realism has undergone two important developments that also reflect the progress in science (Tuomivaara *et al.* 1994, Bunge 2006, 2018, 2019, Agazzi 2014): 1) the recognition of the importance of theory and its critical use of theory in science; and 2) the systemic way of thinking. Over a long enough period, observations, experimental work, theoretical thinking and multiscale modeling have interacted and evolved in the CoE ATM towards joint and coherent answers to formulated science questions. In the future, this community will have the tools developed during the CoE ATM era to tackle a suite of global grand challenges.

## Methods

The key strength of our holistic scientific approach is to combine: 1) continuous and comprehensive long-term in situ observations

in different types of environments, ecosystems and platforms; 2) ground- and satellite-based remote sensing; 3) targeted laboratory and field experiments; and 4) advanced multi-scale modeling, in order to provide improved conceptual understanding and quantifications over the relevant spatial and temporal scales (Fig. 2). The holistic approach and innovative method and instrument development allows us to address interdisciplinary research questions related to current and future climate change drivers and their impacts on ecosystem functioning, and to provide harmonized comprehensive data to unravel mechanisms and feedbacks involved in ecosystems' responses and feedback to climate.

The CoE ATM has operated five highly instrumented boreal and sub-arctic research stations in Finland: the four SMEAR stations and the GAW station in Pallas-Sodankylä. The SMEAR concept promotes the integration and co-location of different Earth component measurements from different disciplines. This has enabled us to study the complicated interactions between the different Earth components and led to important new findings, especially regarding aerosol formation and growth. The north-boreal SMEAR I station was set up in 1991 in a Scots pine forest in Eastern Lapland (67.77°N, 29.58°E, Hari *et al.* 1994), and it provides atmospheric, meteorological and ecosystem data. The south-boreal SMEAR II station was set up in 1995 in a Scots pine forest in southern Finland (61.85°N, 24.28°E), and it is the world-leading station on ecosystem-atmosphere data due to its comprehensive research program and its unique time series of aerosol formation and biogeochemical fluxes (Hari and Kulmala 2005, Kulmala *et al.* 2021b). The SMEAR II station has satellite stations on a nearby lake and a wetland site. The urban SMEAR III station was established in 2004 in Helsinki city (60.2°N, 24.97°E, Järvi *et al.* 2006), and it provides in addition to atmospheric and micrometeorological data, also urban vegetation data. A boreal SMEAR IV station (62.9°N, 27.65°E, Leskinen *et al.* 2009) joined the SMEAR network in 2009, and it provides atmospheric data focusing especially on aerosol-cloud interactions. The sub-arctic Pallas-Sodankylä GAW station (67.97°N, 24.12°E) is an atmosphere-ecosys-

tem supersite that comprises satellite sites at a Scots pine forest, wetland, lake and fell-top tundra (Aurela *et al.* 2015a). Atmospheric composition measurements started at the station in 1991. The CoE ATM has been intensively involved in developing a global Earth observatory (Kulmala 2018) to promote multidisciplinary integration, and provide a global reference for synergies, co-location and complementarities already implemented in the CoE ATM.

In addition to continuous field observations, extensive field campaigns and remote measurements have been important to extend the spatial range of the measurements. As an example of field campaigns, our researchers from the Finnish Meteorological Institute and the University of Helsinki have been collaborating in Antarctic research already for two decades (e.g. Koponen *et al.* 2003, Sipilä *et al.* 2016, Jokinen *et al.* 2018). In terms of ground-based, airborne or spaceborne measurements, we have used data from laser scanning (Liu *et al.* 2019), drones (Aleksyichik *et al.* 2021a), radars (Li and Moisseev 2020), aircrafts (Petäjä *et al.* 2016b), zeppelin (European project PEGASOS, Lampilahti *et al.* 2021) and satellites (Sun *et al.* 2017). The Earth Observation techniques (space-borne remote sensing) provide spatially continuous, frequent observational data sets that can be applied to the validation of the climate model predictions for the large scale, to the trend analyses of essential climate variables, to the analyses of spatially distributed processes and to develop further the physical models through the improvement of the model parametrization or static background fields (Fig. 2).

CoE ATM research laboratories include Aerosol Laboratories in the Universities of Helsinki and Eastern Finland and in the Finnish Meteorological Institute, and Ecophysiological laboratory and Laboratory for Analytical Chemistry in the University of Helsinki. Research has also been done at The Cosmics Leaving Outdoor Droplets (CLOUD) chamber at CERN particle accelerator facility (Wang *et al.* 2020). In addition to measurements, strong modelling expertise was a central part of the CoE ATM. Modelling was used intensively at different spatial and temporal scales, rang-

ing from modelling molecules and molecular clusters in computational aerosol physics (e.g. Besel *et al.* 2020) to modelling global climate with Earth System Models (Sporre *et al.* 2020) as part of Europe-wide consortium EC-Earth that participates in the Coupled Model Inter-comparison Project (CMIP6) featuring climate models for the 2021 IPCC sixth assessment report with different model configurations.

## Open data

Open Science is one of the key principles of modern scientific work, and the CoE ATM has played a strong role in the development in this field as well. The CoE has a long experience with open data issues, as the SMEAR station datasets have been from the very beginning openly available to the scientific communities (<https://smear.avaa.csc.fi/>, Junninen *et al.* 2009). Practical developments of the original and the later updated SmartSMEAR platforms have created a possibility to openly visualize and access most of the infrastructure-based observations in the stations. In addition, the CoE campaign-type observations are generally available to public in different international repositories, and most of the articles in the CoE have been published in open access journals.

The connection to the European Strategy Forum on Research Infrastructures (ESFRI) developments has been a key part of the open science activities, and the CoE has been leading two large cluster projects (ENVRI PLUS and ENVRI FAIR) on environmental ESFRI open data collaboration, as well been a major participant in similar developments in individual ESFRI RIs, particularly in ACTRIS, ICOS and eLTER. CoE participants are also key personnel in many overall developments in the open science communities. Participation in the Research Data Alliance activities, particularly in the data citation, versioning and identification working groups have been active (e.g. Rauber *et al.* 2015, Klump *et al.* 2020). As a part of ENVRI collaboration, the CoE has also been deeply involved in the development of the European Open Science Cloud (e.g. Petzold and Asmi 2020, Gotz *et al.* 2020).

## Collaboration and PEEEX initiative

The CoE ATM research community was formed of researchers from the University of Helsinki, the Finnish Meteorological Institute and the University of Eastern Finland, and had direct working connections with ~2000 researchers in ~50 countries over the years. An important part of this collaboration was coordination of environmental research infrastructure networks in Europe and globally. The CoE ATM was also a key partner in the CLOUD consortium at CERN. CoE ATM participated in all CLOUD campaigns, elucidating several new particle formation mechanisms (e.g. Riccobono *et al.* 2014, Dunne *et al.* 2016, Kirkby *et al.* 2016, Tröstl *et al.* 2016, Wang *et al.* 2020, He *et al.* 2021) and was also involved in the cloud and ice formation experiments (e.g. Nichman *et al.* 2017).

To expand the CoE ATM collaboration from Europe and USA to northern Eurasia, a Pan-Eurasian Experiment (PEEX) program ([www.atm.helsinki.fi/peex](http://www.atm.helsinki.fi/peex)) was initiated in 2012 (Kulmala *et al.* 2015, Lappalainen *et al.* 2014, 2016). Especially regions in Russia, China and the new Silk Road economic regions, have a significant impact on the global climate but a limited environmental data coverage. The PEEEX program aims to enhance coordinated, comprehensive and integrated environmental measurements especially in these areas (Aleksyichik *et al.* 2016, Hari *et al.* 2016, Kulmala 2018, Lappalainen *et al.* 2018, Vihma *et al.* 2019, Petäjä *et al.* 2021b), and a number of bi-lateral research projects with Russian and Chinese universities and research institutes has been carried out in the PEEEX framework (Lappalainen *et al.* 2022a). The collaboration with the Russian organizations has been suspended since March 2022. We have a long on-going collaboration with Estonia particularly organizing joint workshops like Air Ions, Clusters and Atmospheric Aerosols Workshop (Kulmala *et al.* 2016a), and a first SMEAR station outside Finland was established in Järveselja, Estonia in 2014. In 2011, a Station for Observing Regional Processes of the Earth System (SORPES) started operation about 20 km north-east of downtown Nanjing, China (Ding *et al.*

2013b). This SMEAR-type station is a cross-disciplinary research and experiment platform developed by Nanjing University in collaboration with University of Helsinki (Ding *et al.* 2016b). In 2019, another SMEAR-type station ("Beijing Haze", hosted by the Beijing University of Chemical Technology BUCT) started in operation in Beijing (Liu *et al.* 2020). In addition to research activities, PEEEX contributes to education, works towards solving the UN sustainable development goals and addresses the role of science diplomacy when collaborating towards these global aims under different geopolitical conditions (Kulmala *et al.* 2021b; Lappalainen *et al.* 2022b). Unique observations already over 10 years on greenhouse gas concentrations (Ivakhov *et al.*, 2019) and fluxes (Aurela *et al.* 2015b, Juutinen *et al.* 2017, Tuovinen *et al.* 2019), oceanic and continental aerosol production and black carbon sources (Asmi *et al.* 2016) at Tiksi, Northern Sakha (Yakutia) has extended the observational network to most remote permafrost Siberia on the coast of the Arctic Ocean (Uttal *et al.* 2016).

The scientific core of the PEEEX program has been tightly connected to the CoE ATM (Kulmala *et al.* 2015, Lappalainen *et al.* 2016) and expanded the geographical range of the COBACC feedback analysis to the Northern Eurasia, especially to Siberia (Lappalainen *et al.* 2015, 2019). As an example, PEEEX collaboration has provided new information e.g. on the interaction between aerosols, solar radiation and the gross primary production (Ezhova *et al.* 2018). As a concrete example, new particle formation (NPF) was studied at Fonovaya in 2016–2018, and the results were compared with other boreal SMEAR-like stations in Europe (Finland and Estonia, Demakova *et al.* 2021). It was confirmed that NPF happens less often in Siberia than in the European boreal sites. The factors driving NPF were similar between the sites (shortwave radiation, condensation sink and SO<sub>2</sub>), but NPF at Fonovaya was often associated with the wind direction from the industrial areas of Russia and Kazakhstan (Demakova *et al.* 2021), whereas NPF in the European sites was largely associated with the air masses coming from the clean sector in the North. Other recent research highlights in



PEEX collaboration has focused on permafrost areas of north-west Siberia: it was found that permafrost is thawing at the studied locations due to warm and/or snowy winters (Ezhova *et al.* 2021) and even in locations with the least pronounced snow insulation effect, the temperature on the top of permafrost increased at the rate  $0.56^{\circ}\text{C yr}^{-1}$  (Kukkonen *et al.* 2020). Permafrost thaw was critical for an outbreak of anthrax on Yamal peninsula in 2016 after 70 years of epidemiologically stable situation (Timofeev *et al.* 2019, Ezhova *et al.* 2021). Finally, increasing probability of tundra fires was demonstrated in northwest Siberia, where fires has promoted a vegetation shift from tundra to forest (Sizov *et al.* 2021). In addition to the COBACC research framework, the other scientific driver of the PEEX program has been studying air quality in urban environments. While the CoE ATM has studied atmospheric composition in a relatively clean city environment (e.g. Järvi *et al.* 2009a), PEEX collaboration has allowed to study air quality in the most polluted environments in the globe, especially in Chinese megacities and in Beijing (Kulmala 2015, Petäjä *et al.* 2016a).

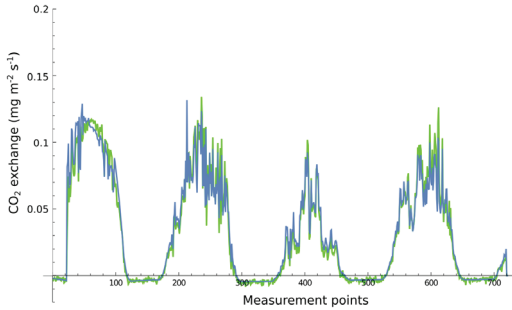
The link from the CoE ATM scientific breakthroughs towards innovations has been established via close co-operation with enterprises, especially with the three university spin-off companies established during the CoE ATM era: Airmodus Ltd. that provides aerosol particle counters and mass-spectrometer products, Karsa Ltd. that produces detectors of trace amounts of explosives for air cargo and other safety purposes, and SMEAR Ltd. that provides infrastructures and services needed for expanding the SMEAR network with the aim of a global network GlobalSMEAR. The CoE ATM had collaboration also with tens of other enterprises in terms of instrument, method and product testing and development, expertise in environmental services and process understanding, emission measurements, and carbon accounting development. One example of the current SMEAR-based applications is the MegaSense project, where machine learning techniques are used for the calibration of low-cost sensors with a few highly accurate SMEAR-type measurement stations (Motlagh *et al.* 2020).

## Scientific progress

### Greenhouse gases

Abundance of greenhouse gases (GHG) in the atmosphere makes life on Earth possible, but anthropogenic GHG emissions are the primary cause of current climate change. Carbon dioxide ( $\text{CO}_2$ ) is the most abundant GHG after water vapour (water vapour amplifies the warming produced by the other GHG), and atmospheric  $\text{CO}_2$  concentration has increased from the pre-industrial times with  $\sim 139$  ppm being over 420 ppm in May 2022 (<https://smear.avaa.csc.fi/>). Another important greenhouse gas is methane ( $\text{CH}_4$ ), which absorbs much more infrared radiation per molecule than  $\text{CO}_2$  and thus has a very high global warming potential. However,  $\text{CH}_4$  remains in the atmosphere for a much shorter time than  $\text{CO}_2$  due to atmospheric oxidation. Increased greenhouse gas concentrations in the atmosphere are changing the climate and thus have a major effect on all living organisms on Earth, including forest ecosystems. Boreal and arctic areas are warming two to four times as fast as the global average (e.g. Mikkonen *et al.* 2015, Ruostenoja and Räisänen 2021, Rantanen *et al.* 2022). In the short term, the forests in high latitudes can grow even more due to longer growing seasons (Pulliainen *et al.* 2017), whereas soil respiration may increase due to higher temperatures. This seems to lead to increase of the seasonal amplitude of the atmospheric  $\text{CO}_2$  concentration due to the different seasonality of photosynthesis and respiration (Hu *et al.*, 2021). On a longer and larger scale, it is evident that climate change is a risk for forests due to increased risk for drought (Brodribb *et al.* 2020, Lindroth *et al.* 2020), pest infestations (Kolb *et al.* 2016) and more frequent and intense forest fires (Brando *et al.* 2014). While forest ecosystems are affected by climate change, the climate is also affected by forests.

The most important climate change mitigation potential of forests is linked to their carbon sink. Forests and other terrestrial ecosystems remove about one-third of the  $\text{CO}_2$  annually emitted to the atmosphere by human activity (Friedlingstein *et al.* 2020). Boreal regions contain more organic carbon than any



**Fig 3.** Example of measured (green line) and modelled (blue line) Scots pine branch  $\text{CO}_2$  exchange from SMEAR I station. Measured and modelled values are shown for four consecutive days in year 2012, each day having 180 measurement points.

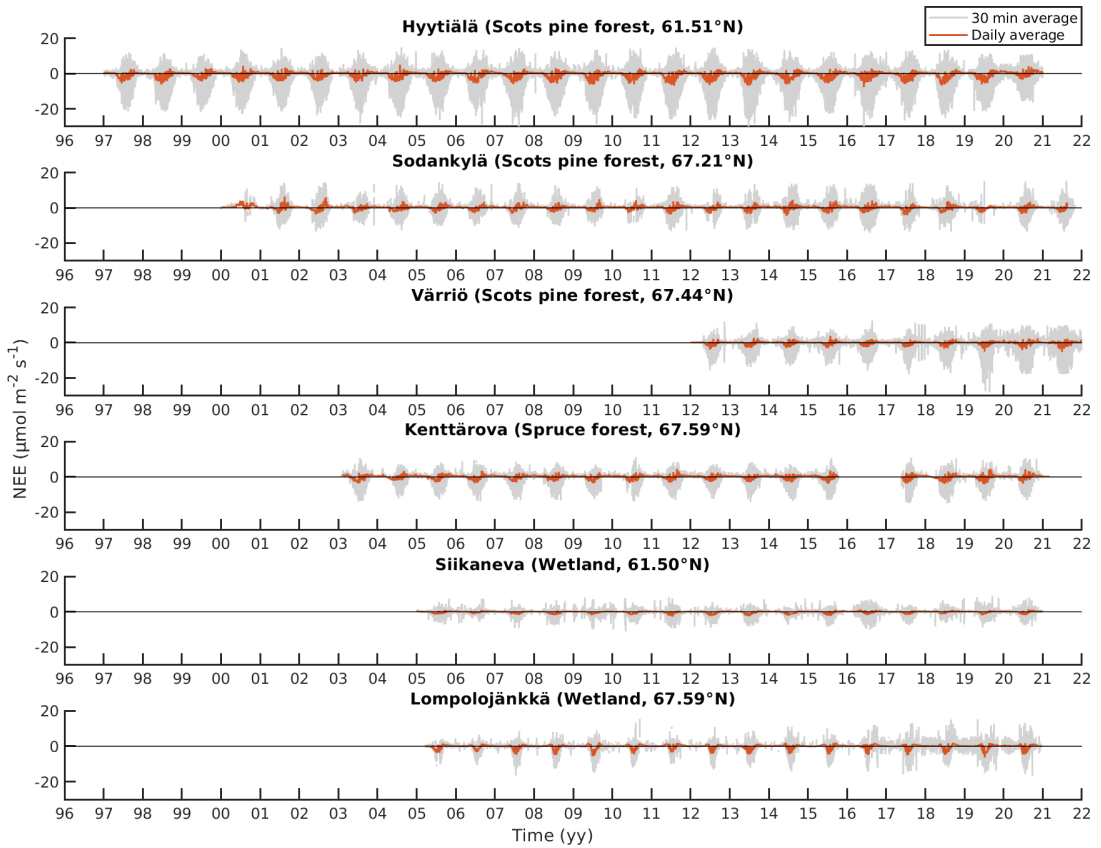
other terrestrial ecosystem due to their large soil carbon stocks (Scharlemann *et al.* 2014). The carbon balance of an ecosystem is the difference between its carbon gains via photosynthesis and losses mainly via respiration from plants and heterotrophs, such as microbes that decompose soil organic matter. The annual carbon uptake in photosynthesis of boreal forests is relatively low, which is a characteristic of these forests — but due to the cool and humid climate, the annual carbon loss in respiration is even lower, which makes the contribution of boreal forests to global terrestrial carbon sink equal to that of tropical forests (Tagesson *et al.* 2020). However, climate change may cause unexpected feedbacks to soil carbon stock due to higher tree growth and increased carbon allocation belowground. There are indications that increased plant growth and nutrient acquisition correlates negatively with soil carbon stocks (Terrer *et al.* 2021), the trade-off being related to soil nutrients mining, which decreases soil organic carbon storage. As climate change induced disturbances (e.g. fires, pathogen or herbivore outbreaks) may become more frequent, more research is needed to better understand how the positive and negative feedbacks such as elevated temperatures and  $\text{CO}_2$  levels affect soil carbon stocks in the boreal zone.

## Photosynthesis

Photosynthetic  $\text{CO}_2$  uptake was one of the first fluxes between the biosphere and the atmos-

phere that the physicists and forest scientists studied together in the CoE ATM (e.g. Hari *et al.* 1999a,b). Photosynthesis provides material and energy for plant metabolism and growth and is the origin of vast majority of organic material in the living ecosystems. The light reactions of photosynthesis capture energy in solar radiation binding it into short-lived chemical compounds. The carbon reactions assimilate atmospheric  $\text{CO}_2$  to convert this energy into stable carbon compounds, sugars. The availability of solar radiation, kinetic energy (related to the temperature of the leaf), carbon dioxide, as well as the physiological state of the plant determine how much sugars can be synthesized by a plant. Accordingly, the dependency of photosynthesis on light, temperature and  $\text{CO}_2$  availability can be used to model its dynamic response to the environment (see Hari *et al.* 2014). Models can be further developed by taking into account stomatal functioning as gases enter and exit leaves through small pores, stomata, whose opening and closing are actively regulated by plants. When stomata are open to take  $\text{CO}_2$  into leaves, water is simultaneously lost to the atmosphere. In the developed model (Hari *et al.* 1986, 2014, 2018), it was assumed that the transpiration cost for a plant is proportional to the amount of transpiration and that the goal of the stomatal regulation is to maximize the difference between photosynthetic production and transpiration cost during several days. Later on, the model was further developed (Hari *et al.* 2017a,b, 2018) by taking into account seasonal endogenous (i.e. plant internal origin) regulation of photosynthesis that has emerged in evolution and determines the seasonal efficiency of photosynthesis (Fig. 3). To summarize, we constructed our theory and model in three steps: 1) synthesis of sugars; 2) optimal regulation of stomatal action; and 3) seasonal cycles of photosynthesis. Our theory and model is able to predict 90–95% of the variance of the measured photosynthesis.

Simultaneously with the development of the above-described leaf-level photosynthesis model over the years, the theories and measurements have extended to various GHG fluxes and processes, temporal and spatial scales and types of ecosystems.



**Fig 4.** Time series of net ecosystem exchange of  $\text{CO}_2$  (NEE) at six different measurement sites in Finland: a south-boreal pine-dominated SMEAR II forest site in Hyytiälä, two subarctic pine-dominated forest sites in Sodankylä and SMEAR I in Väriö, a subarctic spruce-dominated forest site in Kenttäröva, a south-boreal open wetland site in Siikaneva and a sub-arctic open wetland site in Lompolonjänkki. Grey lines show data in original 30 min resolution and red lines show daily averages. NEE is obtained from micrometeorological eddy covariance measurements and is stability-filtered, storage-corrected and gap filled (see Kolari *et al.* 2009).

### Ecosystem-scale greenhouse gas fluxes

We have quantified the carbon and energy balances of the boreal pine forest stand at a south-boreal SMEAR II site, and the seasonal and interannual drivers of the flux components (Kolari *et al.* 2009, Launiainen 2010) using the eddy-covariance (EC) technique (Aubinet *et al.* 2012). When it comes to the seasonal variability of energy partitioning, we found a clear role of the surface conductance ( $g_s$ ). In spring, because of low values of  $g_s$ , the available energy is mainly used as sensible heat flux (the ratio between sensible and latent heat flux = 4–6), while the evapotranspiration takes over in July–August when the ratio has minimum values of 0.7–0.9 (Launiainen 2010). In the SMEAR II forest, the

annual net ecosystem exchange (NEE, Fig. 4) of carbon has varied from the years 2001–2017 — from  $-152$  to  $-309$   $\text{g C m}^{-2} \text{yr}^{-1}$ , the mean annual carbon sink being  $-252$   $\text{g C m}^{-2} \text{yr}^{-1}$  (Launiainen *et al.* 2022). In forests with closed canopies, trees contribute almost 90% of the ecosystem gross primary production (GPP) and the highest cumulative, annual net carbon uptake coincides with the earliest onset of growing season (Kolari *et al.* 2009), whereas warm autumns result in an increased respiration (Vesala *et al.* 2010). In the sub-arctic SMEAR I and Pallas-Sodankylä sites, the annual  $\text{CO}_2$  fluxes are clearly lower leading to less negative NEE, i.e. smaller carbon sink, or even a carbon source over a year (Fig. 4). At Kenttäröva spruce forest in Pallas, the annual NEE was close to zero with an interan-

nual variation ranging from a moderate CO<sub>2</sub> uptake ( $-49 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) to a high CO<sub>2</sub> release ( $+73 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) (Aurela *et al.* 2015a). Taking into account the carbon accumulating in the growing trees, the annual NEE estimates suggest that in most years the soil is losing carbon. This conclusion was supported by soil chamber flux measurements conducted with the chamber technique (T. Penttilä, unpubl. data). At Sodankylä, the annual NEE in 2001–2020 varied from +2 to  $+120 \text{ g C m}^{-2} \text{ d}^{-1}$  with a mean of  $69 \text{ g C m}^{-2} \text{ yr}^{-1}$  (M. Aurela unpubl. data), indicating that the soil is losing considerably carbon each year. One, perhaps not full, explanation for this could be the groundwater coming from a nearby wetland percolating the sandy soil and bringing excess carbon to the soil. Part of this carbon is mineralized into CO<sub>2</sub> and exhaled out from the soil at the forest site (Marttila *et al.* 2021).

Besides CO<sub>2</sub>, other trace gases have been extensively investigated. The boreal forest is a significant sink of carbonyl sulphide (COS) during the growing season at day-time and the observed fluxes correlate well with GPP estimated from the observed CO<sub>2</sub> fluxes (Kohonen *et al.* 2022,; see also Whelan *et al.* 2018). We observed the five growing season (April–August) average net uptake of COS in the SMEAR II forest totaling  $58.0 \text{ g S ha}^{-1}$  with 37% inter-annual variability (Vesala *et al.* 2022). COS is a promising proxy for photosynthesis as plants take up COS through their stomata in a similar way as CO<sub>2</sub>, but it is not emitted back to the atmosphere unlike CO<sub>2</sub>. Regarding ozone (O<sub>3</sub>), seasonal and interannual variability of O<sub>3</sub> deposition fluxes over a forest stand were also analysed using a decade of observations. Rannik *et al.* (2012) found the highest O<sub>3</sub> deposition velocity ( $4 \text{ mm s}^{-1}$ ) in SMEAR II during the peak growing season, and the lowest during winter ( $1 \text{ mm s}^{-1}$ ). The day-time non-stomatal deposition of O<sub>3</sub> varied from 26% to 44% from the start of the growing season until the end. Although the non-stomatal conductance was partly explained by vapour pressure deficit (VPD), temperature and monoterpene concentration, it was concluded that other processes and/or surface chemical reactions with unknown compounds may play a role (Rannik *et al.* 2012).

The dynamics of wetland GHG exchange have been studied in Siikaneva since 2004 (Aurela *et al.* 2007, Rinne *et al.* 2007a, Riutta *et al.* 2007, Fig. 4). Siikaneva is a protected wetland complex of ca.  $12 \text{ km}^2$  that mainly consists of oligotrophic fen vegetation (aapa mire) with ombrotrophic raised bog areas. EC measurements were initiated at the fen site ( $61^{\circ}500 \text{ N}$   $24^{\circ}120 \text{ E}$ ) in 2004 for CO<sub>2</sub> and in 2005 for CH<sub>4</sub> and have been carried on ever since. In the bog site ( $61^{\circ}5027 \text{ N}$ ,  $24^{\circ}101 \text{ E}$ ) that has less water exchange than the fen site, the EC measurements of CO<sub>2</sub> and CH<sub>4</sub> were carried out between 2011 and 2016 (Rinne and Tuittila 2012). At both sites, EC measurements were accompanied with chamber measurements and ecological studies. The annual CO<sub>2</sub> sink was on average higher in the fen than in the bog, but net ecosystem exchange (NEE) also varied more in the fen than in the bog. In the fen site, annual NEE ranged between sink of  $96 \text{ g C m}^{-2}$  and source of  $27 \text{ g C m}^{-2}$ , with an 8-year mean of  $-53 \text{ g C m}^{-2}$  (Rinne *et al.* 2018). For the bog site, annual NEE (converted from growing season values to annual estimates based on Wilson *et al.* (2016)) ranged between sink of  $50 \text{ g C m}^{-2}$  and source of  $1 \text{ g C m}^{-2}$ , with a 6-year mean of  $-36 \text{ g C m}^{-2}$  (Aleksyichik *et al.* 2021b). Methane is important not only to the GHG exchange but for the carbon balance of the wetland systems, being nearly 20% of the annual net CO<sub>2</sub> uptake at these ecosystems (Rinne *et al.* 2018, Korrensalo *et al.* 2018, Aleksyichik *et al.* 2021b) produced throughout the whole peat profile (Putkinen *et al.* 2009) and throughout the annual cycle (Juottonen *et al.* 2008). Methane emission was slightly higher in the fen (10-year average  $9.7 \text{ g C m}^{-2}$ ) than in the bog (estimated 6-year average  $8.2 \text{ g C m}^{-2}$ ). Similarly to NEE, methane emission had higher interannual range of 6.0 to  $14 \text{ g C m}^{-2}$  in the fen than the 7.4 to  $9.7 \text{ g C m}^{-2}$  in the bog. In the bog, ebullition formed up to 8% of the total methane emission during the peak season (Männistö *et al.* 2019). The temporal variation of ecosystem level methane emission is observed to depend mostly on peat temperature and gross primary production (GPP, Rinne *et al.* 2007a, Rinne *et al.* 2018). Methane emission seems to be quite insensitive to observed short term water table variations, while seasonal droughts have an effect on both

methane and carbon dioxide exchange (Rinne *et al.* 2020). Field observations have been combined with the development of HIMMELI process model for calculating methane emissions from wetlands (Raivonen *et al.* 2017). Model results indicate that the CH<sub>4</sub> emissions largely depend on the prescribed rate of anoxic respiration and the sensitivity of the total CH<sub>4</sub> emission to other input variables is mainly mediated via the concentrations of dissolved gases, in particular, the O<sub>2</sub> concentrations that affect the CH<sub>4</sub> production and oxidation rates.

At Pallas Lompolojärnkä wetland, the annual CO<sub>2</sub> balance averaged  $-42 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2006–2010 (Aurela *et al.* 2015a), indicating a slightly smaller CO<sub>2</sub> sink as compared to Siikaneva. The annual CH<sub>4</sub> emission on the other hand, has been significantly higher, up to  $20 \text{ g CH}_4\text{-C m}^{-2} \text{ yr}^{-1}$ , at Lompolojärnkä as compared to many other Nordic wetlands (Lohila *et al.* 2016, Rinne *et al.* 2020). The spatial variation of CH<sub>4</sub> emission has been shown to be closely linked to the proximity of the stream (Zhang *et al.* 2020).

In contrast to forests and wetlands, lakes in the boreal landscape are carbon sources with distinct flux maxima in the spring and autumn at the time of mixing periods (Huotari *et al.* 2011, Mammarella *et al.* 2015). However, continuous measurements over several years have revealed that contrary to the common paradigm, boreal brown water lakes, surrounded by coniferous forests and wetlands, regularly act as a carbon sink for a short period in mid-summer (Huotari *et al.* 2011, Golub *et al.* 2021). According to the long-term GHG flux measurements, the amount of carbon vented out from a lake, whether surrounded by managed or pristine coniferous forest, corresponds up to 10% of the NEE of the surrounding terrestrial ecosystem (Huotari *et al.* 2011). At Lake Pallasjärvi, which is an oligotrophic subarctic lake, the emission of CO<sub>2</sub> into the atmosphere was about  $120 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$  (Lohila *et al.* 2015), which was considerably less than in the Huotari *et al.* (2011) study at a polyhumic lake in southern Finland.

EC measurements have been extended also to urban areas to continuously monitor the surface fluxes of momentum, energy, water, CO<sub>2</sub> and aerosol particle number (Vesala *et al.* 2008,

Järvi *et al.* 2009a, Nordbo *et al.* 2013). Using EC observations from two sites in Helsinki, representing semi-urban and densely built urban neighborhoods, we have shown direct correlation between carbon emissions and urban surface cover (Nordbo *et al.* 2012), derived empirical relationships for urban biogenic emissions and mixed fleet emission factors for CO<sub>2</sub> and particles (Järvi *et al.* 2009b, 2012), and examined uncertainties of urban EC measurements (Järvi *et al.* 2018). Detailed information has been complemented with urban land surface modelling to examine in detail the emission strengths and variability of CO<sub>2</sub> and energy emissions in Helsinki (Järvi *et al.* 2019) and large-eddy simulation modelling to quantify source areas and uncertainties of urban EC observations (Auvinen *et al.* 2017).

Overall, long-term experience has led to substantial advances in GHG and other trace gases measurement techniques, including the development of state of the art tools (Mammarella *et al.* 2016) and methodologies (Mammarella *et al.* 2009, Taipale *et al.* 2010, Nordbo *et al.* 2014, Rantala *et al.* 2014, Rannik *et al.* 2016, Kohonen *et al.*, 2019) to estimate ecosystem scale gas fluxes and their uncertainty, also within the context of international infrastructures such as ICOS (e.g. Franz *et al.* 2018, Nemitz *et al.* 2018; Rebmann *et al.* 2018; Sabbatini *et al.* 2018). Beside methodological issues, the underlying physical processes affecting fluxes have been investigated. We have shown that the canopy morphology and atmospheric stability affects the turbulent flow characteristics inside the canopy (Launiainen *et al.* 2007), and how, in particular during stable night-time conditions, the subcanopy flow decouples from the one above canopy (Aleksyechik *et al.* 2013), suppressing the vertical turbulent mixing and enhancing the non-turbulent transport of matter (Mammarella *et al.* 2007, Rannik *et al.* 2009a).

### Tree greenhouse gas emissions and growth

In addition to ecosystem scale GHG flux measurements, we have developed chamber techniques to measure GHG fluxes from different ecosystem components, mainly tree branches

(Hari *et al.* 1999a, Aalto *et al.* 2014, 2015), stems (Vanhatalo *et al.* 2015, Rissanen *et al.* 2020, Lintunen *et al.* 2021) and forest floor (Pumpanen *et al.* 2004, Pihlatie *et al.* 2013, Koskinen *et al.* 2014, Korhikoski *et al.* 2017). As described earlier, measuring and modelling photosynthetic process of trees, its environmental drivers and endogenous regulation have received great attention in the CoE ATM (e.g. Mäkelä *et al.* 2004, Hari *et al.* 2017b). Similarly, its variability across sites and years has been studied e.g. by Kolari *et al.* (2007) and Gea-Izquierdo *et al.* (2010). Long-term studies on trees also allowed development of a new whole-tree level theory on the optimization of stomatal control in leaves based on maximizing the instantaneous phloem transport rate (Nikinmaa *et al.* 2013). Understanding stomatal regulation is crucial in predicting the impact of changing climate on tree gas exchange. Later, we have further developed the process understanding of photosynthesis with an approach that includes the effect of non-stomatal limitations in models of tree gas-exchange (Hölttä *et al.* 2017, Lintunen *et al.* 2020, Salmon *et al.* 2020). Other examples of research related to tree gas exchange processes include studying tree gas exchange during drought (Duursma *et al.* 2008, Salmon *et al.* 2020) or cold stress (Lintunen *et al.* 2014, Lindfros *et al.* 2015), modelling and measuring of CO<sub>2</sub> fluxes from tree stems (Hölttä and Kolari 2009, Lintunen *et al.* 2021), and measuring phloem transport in trees (Paljakka *et al.* 2017) that is linked to tree gas exchange via e.g. the sink control of photosynthesis. In addition to CO<sub>2</sub> and H<sub>2</sub>O, we have studied the exchange of CH<sub>4</sub> and N<sub>2</sub>O from tree stems and canopies (Machacova *et al.* 2016, 2019) to understand their role in the GHG balance of forests.

Besides improving process understanding, the results of tree ecophysiological studies can be used for constructing ecosystem level GHG flux and budget estimates. Small-scale observations are upscaled to stand level by models that incorporate the responses of photosynthesis and respiration to environmental drivers and the description of the spatial variability of the drivers within forest stand (Mäkelä *et al.* 2006), most notably the variability of light (Vesala *et al.* 2000). The upscaling results also provide

independent reference data for evaluating the accuracy and precision of GHG fluxes and budgets obtained by micrometeorological methods. Synthesis of carbon, nitrogen and water balances determined with different methods was presented by Ilvesniemi *et al.* (2009, 2010), Korhonen *et al.* (2013) and Kolari *et al.* (2009). This approach of combining bottom-up upscaling with direct measurement has been also applied for other gases than GHGs, for instance upscaling of O<sub>3</sub> deposition and comparison with EC (Altimir *et al.* 2006). The sub-ecosystem scale studies can also be used for studying the climate sensitivity of different ecosystem components. Kulmala *et al.* (2019) studied year-to-year variation in ecosystem photosynthesis at the subarctic SMEAR I station and found that the year-to-year variation is minor in tree canopy and smaller compared to that of ground vegetation. Similarly, Matkala *et al.* (2021) found using shoot chamber and EC data at SMEAR I that subarctic conifers showed high resilience in the CO<sub>2</sub> and water fluxes to extreme events.

Increasing availability of long-term EC data has made it possible to construct canopy-scale models of photosynthesis that are directly parameterised using EC data. Mäkelä *et al.* (2008) constructed a light use efficiency (LUE) based daily time-step model of canopy GPP that was statistically fitted to data from several flux sites in temperate and boreal regions. This approach was further developed by Peltoniemi *et al.* (2015) to include simple soil water dynamics and evapotranspiration. The resulting model, PRELES, runs with daily weather data with minimum site information including fraction of absorbed photosynthetically active radiation and soil water holding capacity. A Bayesian calibration study including data from several boreal flux sites suggested that the model can be used with generic parameter values across boreal coniferous forests (Minunno *et al.* 2016). A further development was to estimate climate and vegetation type specific parameters for PRELES, extending its use from boreal to global (Tian *et al.* 2020).

In addition to shoot and ecosystem level flux measurements and modelling, we are also investigating and developing the potential of optical methods to track the dynamics of photosynthesis across spatial and temporal scales, from sec-

onds to seasons, from leaves to satellite pixels (Porcar-Castell *et al.* 2021). Being spatially explicit, optical data such as spectral reflectance or chlorophyll fluorescence offer excellent possibilities to integrate biophysical processes across scales, for example, via the assimilation of satellite solar-induced fluorescence into land-surface models to improve surface GPP estimates (Bacour *et al.* 2019, Raczka *et al.* 2019). Importantly, the use of spectral reflectance and chlorophyll fluorescence data requires a sound and quantitative understanding of the mechanistic connection between the signals and the factors that control their variation across scales, which has been one of our core activities (Porcar-Castell *et al.* 2014, 2021). Temporally, we have elucidated the factors that couple/decouple the seasonal connection between the photochemical reflectance index (Porcar-Castell *et al.* 2012) or the emission of chlorophyll fluorescence (Porcar-Castell 2011, Zhang *et al.* 2019) and photosynthesis. Spatially, we use radiative transfer models to quantify how the information content of the signals scales from the leaf to the plant canopy under the action of canopy structure (Liu *et al.* 2019), light gradients (Atherton *et al.* 2017), and their dynamics (Xu *et al.* 2021). Lately, we are also developing new methods for the standardization (Rajewicz *et al.* 2019), measurement (Atherton *et al.* 2019, Van Wittenberghe *et al.* 2021) and interpretation (Atherton *et al.* 2016) of multiscale reflectance and fluorescence data.

The long-term flux measurements together with data on environmental factors have allowed detailed tree growth analysis (Kulmala *et al.* 2016b, 2017a) and combined with modelling, the analyses have revealed that annual changes in photosynthesis are reflected to the secondary and primary growth of pines in different manners (Schiestl-Aalto *et al.* 2015). Growth measurements and modelling have allowed for analyzing how photosynthesized carbon is allocated into the growth of different tree organs, energy production or storages and how these allocation patterns differ seasonally and within longer time scales (Schiestl-Aalto *et al.* 2013, 2015, 2019). We have found that in our conditions, temperature variation alone explains by far the most part of the daily growth variation, whereas

other factors such as photosynthesis or drought affect growth processes at longer timescales. The combination of measurements and process-based models has also enabled quantifying the unmeasurable sink of carbon by root symbionts which based on our analysis is about 6% of the annual GPP (Schiestl-Aalto *et al.* 2019).

During the CoE ATM, we developed a better understanding of the dynamics of cambial growth and its short-term responses to environmental conditions and photosynthetic production. Hölttä *et al.* (2010) demonstrated that the dynamics of cambial growth can be modelled using a mechanistic whole tree level framework including photosynthesis and xylem and phloem transport and a detailed description of cell division, enlargement and cell wall thickening. Chan *et al.* (2016) managed to derive the dynamics of short-term cambial growth from simultaneous measurements of xylem and whole tree diameter change, and show how temperature and water availability affects cambial growth. Further, Chan *et al.* (2018) demonstrated how the short-term dynamics of cambial growth and growth respiration were tightly connected to photosynthetic production.

Ding *et al.* (2020) were able to detect the timing and drivers of growth of fine roots with a novel fine root growth measurement technique. Ryhti *et al.* (2021) quantified the partitioning of forest floor CO<sub>2</sub> source flux to components of tree root, ground vegetation, fungal and heterotrophic respiration. Those results increase understanding of belowground processes and also allow for a more comprehensive understanding of whole tree carbon allocation.

### Greenhouse gas fluxes from soil and forest floor

To gain a deeper understanding of the net GHG exchange of an ecosystem, we need to study not only tree processes, but also soil and forest floor. Forest floor plays a major role in the carbon balance of forest ecosystems, especially in boreal forests. Due to relatively open tree canopy and high light conditions on the soil surface, the forest floor vegetation may contribute significantly to the CO<sub>2</sub> uptake, especially in young

forests. The GPP of ground vegetation was first quantified by Kolari *et al.* (2006) and later, the momentary rate and drivers for the photosynthesis of the most common ground vegetation species were further studied by Kulmala *et al.* (2008, 2011a). In Värriö at SMEAR I, the share of ground vegetation in the total ecosystem GPP flux is approx. 43–49% (Kulmala *et al.* 2019) whereas in Hyytiälä at SMEAR II, the GPP of ground vegetation is annually approx. 146 g m<sup>-2</sup> (Kulmala *et al.* 2011b), which is ~13% of the GPP of the whole ecosystem.

Carbon is transferred from soil to the atmosphere in soil respiration, which originates from two major sources; decomposition of soil organic matter (heterotrophic respiration) and respiration of roots and associated mycorrhizal fungi (autotrophic respiration). The majority of soil respiration originates from the soil surface humus layer and the surface of the mineral soil which contributed about 70% of the total soil CO<sub>2</sub> emissions at the SMEAR II station in Hyytiälä (Pumpanen *et al.* 2008). To understand interacting soil processes, the forest floor CO<sub>2</sub> flux was partitioned using the trenching method (root exclusion) combined with vegetation removal treatments. The respiration of tree roots contributed 48%, heterotrophic soil respiration 30%, respiration of ground vegetation 18% and the respiration of hyphae of mycorrhizal fungi 4% of the total soil respiration (Ryhti *et al.* 2021). Heterotrophic respiration increased in the trenched treatments without ground vegetation over time, due to the "Gadgil effect". Our results indicate intense interaction between plant roots and soil microbes that affect forest floor CO<sub>2</sub> efflux (Ryhti *et al.* 2021) and soil carbon stocks. For this reason, the soil microbial communities, microbial interactions between trees and ground vegetation and the impact of decomposition of microbial necromass to soil organic matter stability were investigated at SMEAR II site or in the greenhouse and laboratory experiments (Adamczyk *et al.* 2016, 2019a,b, Kieloaho *et al.* 2016, Santalahti *et al.* 2016, Sietiö *et al.* 2018, 2019). Depending on the development stage of the forest, the proportion of autotrophic and heterotrophic respiration may be remarkably different and has a large seasonal variation as a major part of the autotrophic respiration is

originating from the recently assimilated carbon which is transported to the root system and emitted to soil in the respiration of fine roots and the associated fungi (Palonen *et al.* 2018, Pumpanen *et al.* 2015, Ryhti *et al.* 2022).

Disturbances affect significantly the carbon fluxes in forest ecosystems. For example, wildfire or windthrow may kill a large proportion of trees and decrease the photosynthetic capacity and may increase the decomposable material in soil surface. Clear-cutting can cause huge emissions of CO<sub>2</sub> and N<sub>2</sub>O and minor emissions of CH<sub>4</sub> in drained wetland forest, while the partial harvest does not significantly affect the soil GHG fluxes (Korkiakoski *et al.* 2019, 2020). Similar to clear-cutting and burning of slash (Virkkula *et al.* 2014), wildfires also result in drastic changes in the soil microbiome (Sun *et al.* 2016, Zhou *et al.* 2020) and change the greenhouse gas fluxes between soil and the atmosphere (Köster *et al.* 2014, 2015a, 2016). Especially, the CO<sub>2</sub> effluxes decrease as a result of fire as a large proportion is originating from roots system which is adversely affected by fire (Köster *et al.* 2014) but the fire also increases the soil CH<sub>4</sub> sink (Köster *et al.* 2015a).

At SMEAR II station in Hyytiälä, long-term measurements of forest floor exchange show that the site has been a strong CH<sub>4</sub> sink during the almost 20 years of measurements (Skiba *et al.* 2009, Vainio *et al.* 2021), and a small but significant source of N<sub>2</sub>O (Pihlatie *et al.* 2007). Extensive forest floor flux measurements revealed that small moist patches of the forest floor emit significant amounts of CH<sub>4</sub> during wet periods, however, these wet spots do not markedly decrease the sink strength of the soil in the forest. Similar to mature trees in the forest (Machacova *et al.* 2016), forest floor shrubs *Vaccinium myrtillus*, *Vaccinium uliginosum* and small Scots pine seedlings emit small amounts of CH<sub>4</sub> while the belowground parts consume CH<sub>4</sub> (Halmeenmäki *et al.* 2017) but the net fluxes of the soil surface still showed net CH<sub>4</sub> uptake into the forest floor.

At Kenttäröva spruce forest growing on podzolic moraine in Pallas, the whole forest floor turned into a CH<sub>4</sub> source after a very wet growing season for more than half a year time (Lohila *et al.* 2016). As a result, the landscape scale

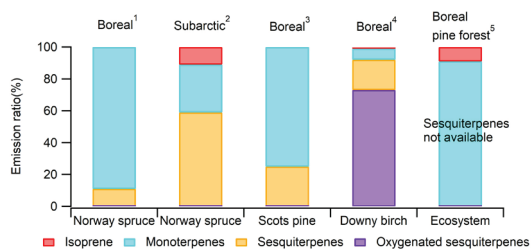


methane emission — 10% of the landscape being open wetlands — more than doubled during a wet year as compared to a more normal year, and that was due to the upland forest soil, not the wetlands. Recently it was confirmed that in a meteorologically normal year, at the peak growing season, the whole catchment acts as a source of CH<sub>4</sub> (Räsänen *et al.* 2021). For CH<sub>4</sub> production to take place in upland soils, inundated conditions and input of fresh carbon is needed, which was proven in lab experiments done with Kenttäröva soils (Korkiakoski *et al.* 2021).

Herbivory also affects the greenhouse gas fluxes between the soil and the atmosphere. Our studies in reindeer grazed areas close to the SMEAR I station in Värriö in Eastern Lapland have shown that grazing significantly reduced lichen coverage and biomass and increased the biomass and coverage of mosses (Köster *et al.* 2015b, 2017, 2018). These grazing-induced changes in vegetation composition affect both positively and negatively GHG fluxes from the forest field layer in a northern boreal forest (Köster *et al.* 2018). Higher CO<sub>2</sub> emissions and CH<sub>4</sub> uptake were detected from grazed areas, and the gas fluxes were affected by soil temperature, moss and lichen coverage (Köster *et al.* 2015b, 2018). Non-grazed areas were a small N<sub>2</sub>O sink.

## Volatile organic compounds (VOC)

Volatile organic compounds emitted by natural ecosystems have major effects on atmospheric chemistry and new particle formation. Therefore, their sources and emissions have been widely studied in the CoE ATM. We have developed new methods for dynamic chamber (Kolari *et al.* 2012, Aaltonen *et al.* 2013, Vanhatalo *et al.* 2015, Barreira *et al.* 2017) and ecosystem scale flux measurements (Rantala *et al.* 2014, 2015) as well as for reactivity measurements (Mogensen *et al.* 2015, Praplan *et al.* 2017) and measurements of new compound groups (Hellén *et al.* 2012, Kieloaho *et al.* 2013, 2016, Helin *et al.* 2017, 2020). The observations cover long-term ecosystem scale fluxes (e.g. Rantala *et al.* 2015, Schallhart *et al.* 2018) and leaf level measurements from main tree species (e.g. Hakola *et al.* 2006, 2017, Hellén *et al.* 2021) as well as other



**Fig 5.** Relative contributions of different compound groups in the foliar mass emissions of different tree species and in a Scots pine forest stand during the peak emission period (July). References: <sup>1</sup>measured at SMEAR II site in 2019 (246 samples) using the methods described in Hellén *et al.* (2021), <sup>2</sup>measured at Pallas in Northern Finland in 2020 (383 samples) using the methods described in Hellén *et al.* (2021), <sup>3</sup>Hakola *et al.* (2006), <sup>4</sup>Hellén *et al.* (2021), <sup>5</sup>Schallhart *et al.* (2018).

forest compartments, such as tree trunks, soil and understory vegetation (e.g. Kieloaho *et al.* 2013, 2017, Rissanen *et al.* 2016, 2020, Mäki *et al.* 2017, 2019a, b, Vanhatalo *et al.* 2015). We have also conducted field and laboratory experiments to reveal processes behind emissions and their linkages with biotic and abiotic drivers (e.g. Ehn *et al.* 2014, Bianchi *et al.* 2019). Once emitted to the atmosphere, VOCs can react with oxidants to form less volatile oxidation products. These reactions take place at very different rates depending on the precise VOC and oxidant, and the products can have highly variable tendencies to form aerosols (e.g. Ehn *et al.* 2014, Bianchi *et al.* 2019). In addition to monoterpenes (MTs), we have succeeded in measuring also very reactive compounds, such as sesquiterpenes (SQT), in the emissions and ambient air and in describing the temporal variability in concentrations (Hellén *et al.* 2018, 2020).

## VOC emissions from trees and forest floor

MTs are clearly the most abundant terpenoid compound group (in mass) emitted from boreal forest vegetation (Rinne *et al.* 2009, Rantala *et al.* 2015, Schallhart *et al.* 2018). The summary in Fig. 5 shows relative contributions of different terpenoid groups emitted from different tree species and whole ecosystem scale. The ecosystem

scale measurements do not contain SQTs and oxygenated sesquiterpenes were only measured in downy birch and boreal Norway spruce emissions. The emission rates are following the diurnal and seasonal temperatures, and in a few cases also variations in irradiation levels, as is the case with isoprene. Therefore, highest emission rates are usually measured in mid-summer and during the daytime.

Content and emission of different MTs has been observed also to vary a lot within each coniferous tree species, reflecting the inherited "chemotype" of the trees (Bäck *et al.* 2012, Hakola *et al.* 2017). Two main compounds,  $\alpha$ -pinene and  $\Delta^3$ -carene formed together 40–97% of the monoterpene proportions in both the branch emissions of Scots pines and in the air concentrations in the surrounding forest. The emissions were dominated either by  $\alpha$ -pinene (ca. 10% of the trees), or  $\Delta^3$ -carene (ca. 20%). This has large implications to the models describing the boundary layer atmospheric chemistry, since these MT isomers have very different chemical reactivities with the main oxidants and considerable differences in secondary organic aerosol (SOA) formation (Kurtén *et al.* 2017, Thomsen *et al.* 2021).

Continuous, long term observations on Scots pine needle and shoot VOC emissions has revealed that the conventional view on temperature and light as emission controlling factors is likely too simplifying. For example, new foliar biomass growth has been found to be a significant source of many VOCs (Aalto *et al.* 2014). Also the photosynthetic recovery in spring, especially during the period when light use efficiency is still low after the cold winter season, can cause a transient increase in both MT synthesis and emissions (Aalto *et al.* 2015).

In addition to forest canopy, Scots pine stems have been identified as a small source of MT (Vanhatalo *et al.* 2015). The stem MT emissions are generally highest at mid-summer and in daytime, but large emission peaks may occur in spring (Vanhatalo *et al.* 2015). Drivers for stem MT emissions include temperature, soil humidity and potentially pressure of resin (high in MT content) within the stem (Rissanen *et al.* 2016, 2020, Vanhatalo *et al.* 2015).

The forest floor accounted 2–93% of the forest stand MT emissions (Mäki *et al.* 2019a). The highest MT emissions were measured from the decomposing litter in autumn, whereas the understorey vegetation was a MT sink due to adsorption to the leaf surfaces (Mäki *et al.* 2017). MT and SQT concentrations were high in the organic soil and the top mineral soil due to high abundance of decomposing litter, tree roots and root-associated microbes (Mäki *et al.* 2019b). Stand type regulates MT and SQT emissions from the forest floor in hemiboreal and boreal climates (Mäki *et al.* 2019c). The decaying wood is an MT and SQT source as fungal species synthesize these compounds to interact with other fungal species based on the laboratory experiment (Mali *et al.* 2019). Noteworthy emissions of MT and SQT were also observed in situ measurements from the decaying wood disks and logs.

Barreira *et al.* (2017) observed that  $\alpha$ -pinene and  $\Delta^3$ -carene constituted 80-90% of the measured monoterpenes in the soil chambers. Solid phase microextraction technique was successfully utilized for the sampling of BVOCs together with portable gas-chromatograph-mass spectrometer (GC-MS) analysis on the site. A good correlation was found with the Proton-transfer-reaction mass spectrometer (PTR-MS) results. Nearby sawmill was found to be one emission source affecting the results when the wind was from southeast (Barreira *et al.* 2017, Liao *et al.* 2011). We have also found that soil at Hyttiälä is a source of dimethylacetamide and a sink of diethanolamine (DEA), while the direction of estimated flux was dependent on soil temperature, soil water content and soil pH, but also on soil solution concentration of alkyl amines (Kieloaho *et al.* 2013, 2017).

Wetlands have been found to be strong emitters of isoprene (Haapanala *et al.* 2006, Hellén *et al.* 2006, 2020) while MT emissions of only 10% of isoprene emissions (Hellén *et al.* 2020) have been observed at a subarctic wetland. However, SQT emissions at the subarctic wetland site were several times higher than MT emissions, especially in early summer. Main emitted SQTs were tentatively identified as  $\alpha$ -farnesene, cadinene and  $\beta$ -cadinene. Due to their high reactivity, they have strong impact on local atmospheric chemistry.

## Ecosystem scale emission measurements of VOCs

Since 2000, the potential of the EC method to measure VOCs exchange also at the ecosystem scale has been evident (e.g. Rinne *et al.* 2001, Karl *et al.* 2002). Initially, only two days of methanol flux data was published. However, the development of improved methods and more powerful instrumentation led to longer datasets, which covered a greater range of VOCs. Rinne *et al.* (2007b) presented four days of ecosystem exchange of four VOCs, as well as their calculated chemical degradation. These first measurements of ecosystem exchange in Hyytiälä were obtained using Disjunct Eddy Covariance (DEC; Rinne and Ammann 2012, Rinne *et al.* 2021) and they confirmed the enclosure measurement results, that the major emitted VOCs are the monoterpenes, methanol and acetone. From 2006 onwards, the DEC measurements were made semi-continuously in Hyytiälä. In 2010, the VOC flux measurement method was changed to the gradient technique, as Rantala *et al.* (2014) showed that with the used setup of the measurements and the low concentration environment, the gradient technique was more reliable than DEC. Schallhart *et al.* (2018) reported the first 10Hz EC fluxes using a Proton-Transfer-Reaction — Time Of Flight (PTR-TOF) in Hyytiälä. Due to the capability to the PTR-TOF to measure whole VOC spectra with high frequency, this setup was already able to measure the exchange of 25 different VOCs.

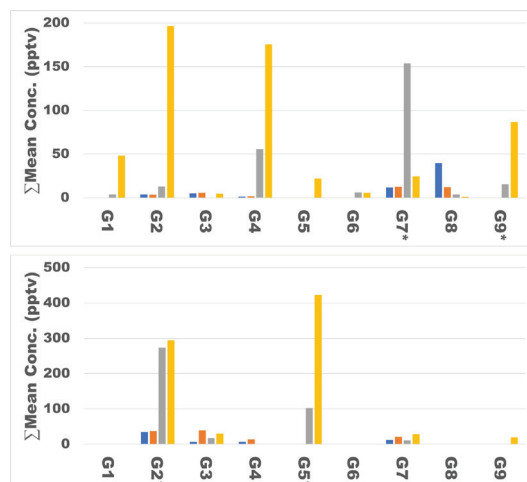
The micrometeorological flux measurements have shown a wide variety of VOCs emitted from pine forest ecosystems (Schallhart *et al.* 2018). A combination of laboratory experiments and analysis of micrometeorological MT flux data have indicated that around half of the monoterpenes emitted from pine forest originate as *de novo* emission directly from synthesis, the rest being evaporative emission from resin (Ghirardo *et al.* 2010, Taipale *et al.* 2011, Rantala *et al.* 2015). Micrometeorological flux measurements have also revealed a seasonal trend in the normalized emission potential on monoterpenes (Taipale *et al.* 2011, Rantala *et al.* 2015). The earlier micrometeorological flux measurements using surface layer gradient technique and gas

chromatography — mass spectrometry analysis has revealed the MT emissions from Scots pine forests to be dominated by  $\alpha$ -pinene (60-70%) and  $\Delta^3$ -carene (12-26%) (Rinne *et al.* 1999, 2000). The chemical reactions strongly modify the above-canopy fluxes of highly reactive compounds, such as some sesquiterpenes, but are less important for compounds with chemical lifetimes about half-an hour or more, such as isoprene and monoterpenes (Rinne *et al.* 2007b, 2012).

## Development of air sampling and analyses techniques of VOCs

In addition to emission measurements of VOCs, we measure VOC concentrations in the atmosphere. We have developed techniques to sample atmospheric VOCs, and in this section, we describe in more detail some of this sampling development. Due to their important role in the new particle formation, aliphatic amines are an especially interesting group of VOCs. To measure the low gas phase concentrations of e.g. ammonia, primary, secondary and tertiary amines, solid phase microextraction (SPME) with on-fiber derivatization was developed for air samples (Parshintsev *et al.* 2015). Further developments include SPME Arrow sampling for the collection of amines (Helin *et al.* 2015) and functionalized mesoporous silica coated SPME Arrow sampling for aliphatic amines (Lan *et al.* 2019a). The developed technique enabled collection of samples even at quite low temperatures and to determine diethylamine and triethylamine with very low concentrations. We have also developed a fully automated online dynamic in-tube extraction (ITEX) for continuous sampling and analysis of VOCs in air. With this sampling approach combined with gas chromatography mass spectrometer, we were able to observe day/night variations for very low concentrations of anthropogenic VOCs such as toluene, p-xylene, and 1,2,3-trimethylbenzene (Lan *et al.* 2019b).

The applicability of a drone as a carrier for miniaturized air sampling systems (SPME Arrow and ITEX) has been proved in the recent years in the CoE ATM (Ruiz-Jimenez *et al.* 2019, Lan *et al.* 2021). The versatility, flexibility and easy



**Fig 6.** Variation of the gas phase (upper figure) and aerosol particle composition (lower figure) with the sampling height for samples collected at the SMEAR II station (blue: 5 m and orange: 50 m sampling heights) and Qvidja farm (grey 50 m and yellow 150 m sampling heights). G1, Organic oxygen compounds; G2, lipid-like molecules; G3, carbonyl compounds; G4, alcohols; G5, organonitrogen compounds; G6, benzene and its substituted derivatives; G7, ketones; G8, aldehydes; and G9, prenyl lipids. \*Mean concentration found in the samples divided by 10 (Lan *et al.* 2021).

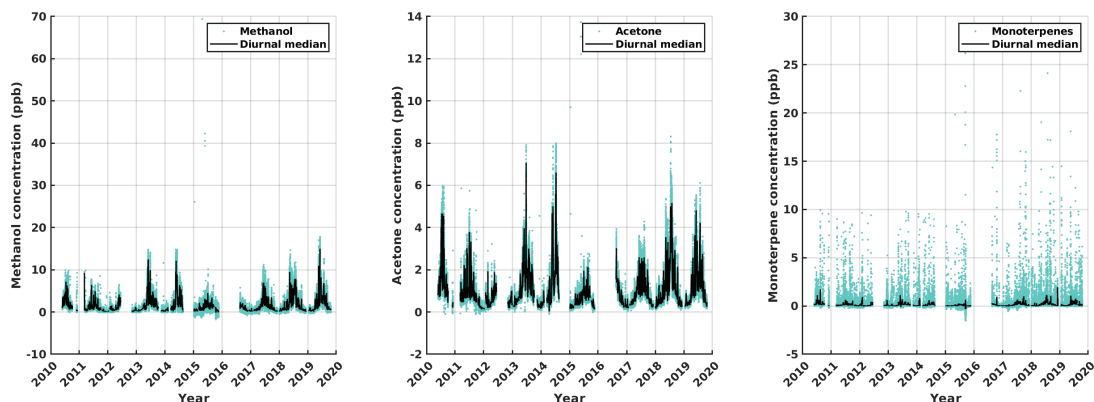
operation of the sampling systems with a drone allow sampling at different heights and positions even in places that are difficult to access, being a good tool also for low cost vertical profiling studies and offering an interesting alternative to other traditional sampling platforms such as building/tower, balloons, and aircrafts. In case of ITEX, high selectivity can be obtained with careful selection of the trapping material and by small accessories prior the sorbent trapping of VOCs (particle removal, removal of ozone, water and other non-targeted compounds). Utilizing drone sampling platform, air samples were collected during summer 2019 at the SMEAR II station and agricultural Qvidja farm (Finland) using SPME Arrow coated with two different coatings, and ITEX packed with 10% polyacrylonitrile. The total number of VOCs identified was 347. Quantitative/semi-quantitative results were achieved by the use of individual Partial Least Squares Regression models developed using the gas phase standard compounds provided by a permeation system (Ruiz-Jimenez *et al.*, 2020). The simultaneous sampling by active

(ITEX) and passive (SPME) systems allowed the clarification of the VOCs distribution between gas phase and particles. Average gas phase VOC concentrations were from 0.1 (toluene, the SMEAR II station) to 680 ng L<sup>-1</sup> (acetone, Qvidja farm). In aerosols, average VOC concentrations ranged from 0.1 (1,4-cyclohexadiene, the SMEAR II station) to 2287 ng L<sup>-1</sup> (megastigma-4,6,8-triene, Qvidja farm). Clear differences were observed for gas phase and aerosol particles based on the sampling site and height (see Fig. 6, Lan *et al.* 2021).

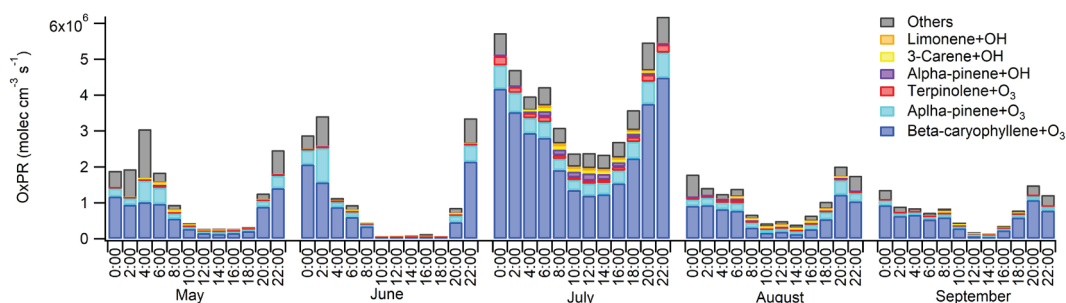
### Ambient VOC concentrations and their atmospheric chemistry

The long-term observations allow us to draw conclusions of the interannual variability and the seasonal cycle of ambient concentrations of VOCs. The concentration measurements reflect both the emission rates from all sources at the concentration footprint area, which is larger than flux footprint, but also the impact of chemical reactions and turbulent meteorological factors on the chemistry and mixing of the atmospheric boundary layer. The concentrations in the boreal forest at SMEAR II site are dominated by monoterpenes, methanol, acetone and acetaldehyde, and frequently peak in July, but considerable year-to-year variation exists (Fig. 7).

Species specific ambient air concentrations have been measured in the boreal forest at SMEAR II during two years using in situ GC-MS (Hellén *et al.* 2018). These molecular level results enabled detailed characterization of importance of detected VOCs on local atmospheric chemistry (Fig. 8). Both mono- and sesquiterpene oxidation was dominated by ozone. Major terpenes producing oxidation products at the site were  $\beta$ -caryophyllene and  $\alpha$ -pinene, which both are known to have high SOA yields. Oxidation of other VOCs than terpenes showed very minor contributions. Species specific in situ GC-MS measurements were conducted also at a sub-arctic wetland surrounded by the coniferous forests in Northern Finland in 2018 (Hellén *et al.* 2020). Daily mean ambient air concentrations of MTs and



**Fig 7.** All data (points) and diurnal median concentrations (solid line; measured with the PTR-MS) of methanol, acetone and monoterpenes at 33 m height (> 10 m above the canopy top) over the 10-year measurement period, 2010-2019.



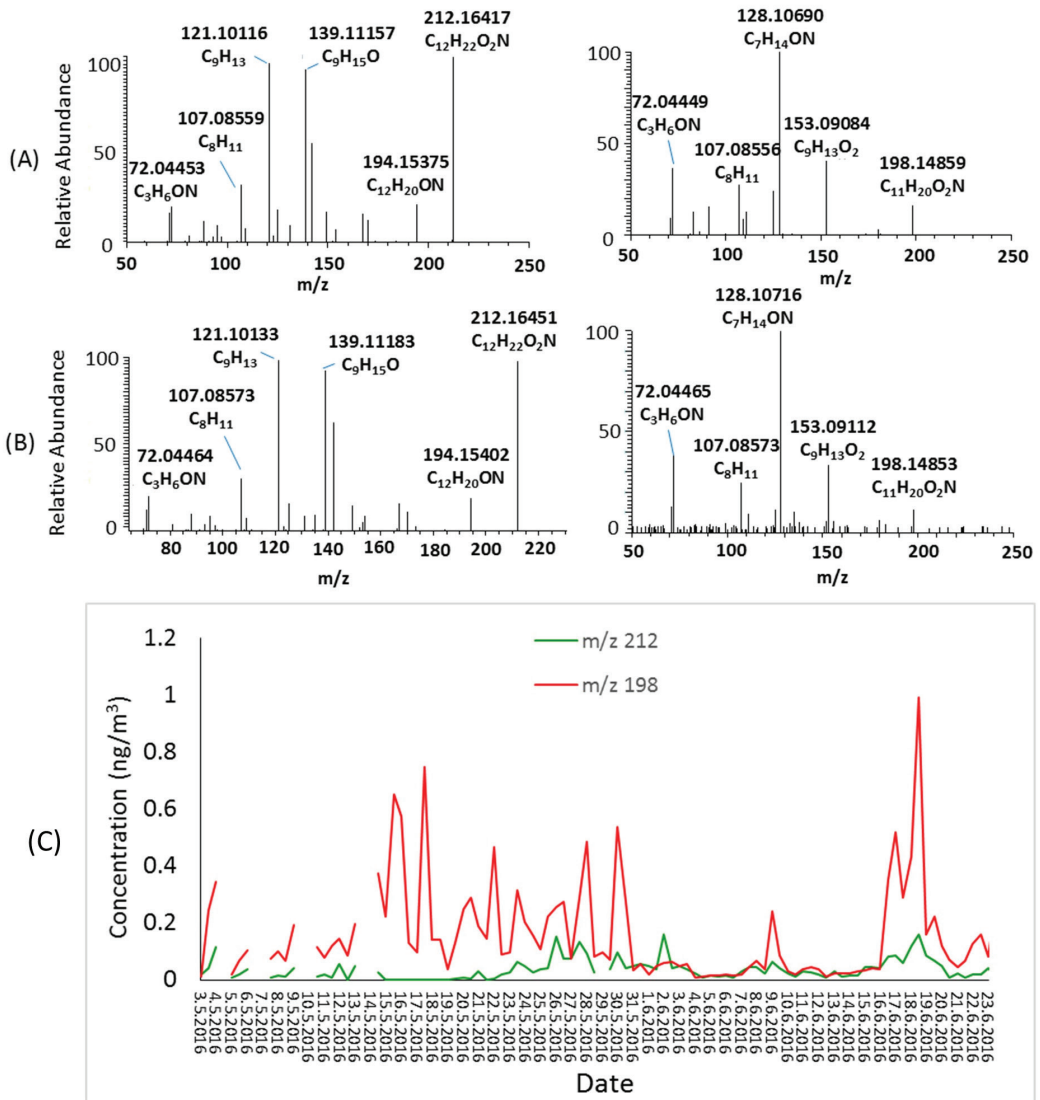
**Fig 8.** Diurnal variations in production rates for secondary organic compounds (OxPRs) from the oxidation of terpenes with different oxidants (hydroxyl radical, OH; ozone, O<sub>3</sub>; and nitrate radical, NO<sub>3</sub>) in the boreal forest at SMEAR II in 2016. OxPRs were calculated from the concentrations of VOCs and O<sub>3</sub> measured at the site and from the modelled concentrations of OH and NO<sub>3</sub> as described in Hellén *et al.* (2018).

SQTs at this site had strong correlation with ozone concentrations indicating that BVOC emissions from these ecosystems have a strong impact also on the local ozone levels.

Although the oxidation of other VOCs than terpenes have smaller contributions to SOA formation, clear enhancement of NPF and SOA formation has been seen in the presence of dimethylamine (DMA). Laboratory and field studies on reaction between pinonaldehyde and DMA, and on the ozonolysis of  $\alpha$ -pinene in the presence of DMA have detected several mid to low vapor pressure nitrogen-containing compounds, and some of the oxidation products (e.g. C<sub>11</sub>H<sub>20</sub>O<sub>2</sub>N and C<sub>12</sub>H<sub>22</sub>O<sub>2</sub>N) obtained in the flow reactor experiments were also detected in the aerosol particles collected in the SMEAR II station utilizing high resolution mass spectrometer techniques (Fig. 9,

Duporté *et al.* 2016, 2017). In addition, oxidation products of sesquiterpenes have been synthesized in the laboratory and one of them,  $\beta$ -nocaryophyllone aldehyde, could also be detected from the aerosol particles (Parshintsev *et al.* 2008).

Total hydroxyl radical (OH) reactivity can be used to investigate how well reactive compounds (in ambient air or from emissions) are chemically characterized. Comparing total OH reactivity measured experimentally with the OH reactivity expected from the known chemical compounds present in the air (or in emissions) provide information about the fraction of reactive compounds that are not detected. Total OH reactivity studies have found high fraction of missing (i.e., unexplained) OH reactivity in the boreal forest air (Nölscher *et al.* 2012, Yang *et al.* 2016, Praplan *et al.*



**Fig 9.** Liquid chromatography (LC)-positive electrospray ionization (ESI+)-Orbitrap tandem mass spectrometry (MS-MS) fragmentation pattern of product ions at  $m/z$  198.148 and 212.164 from (A)  $\alpha$ -pinene + O<sub>3</sub> + DMA flow reactor experiment and (B) PM<sub>1</sub> (i.e. diameter less than 1 micron) sample collected in SMEAR II station in Hyytiälä, Finland (23 May 2016 day), (bottom figure) long time (3 May–23 June 2016) monitoring of the two product ions in the PM<sub>1</sub> samples collected in Hyytiälä (Duporté *et al.* 2017).

2019). This so-called missing reactivity has been suggested to stem from unknown primary emissions or oxidation products of VOCs (often, only the precursors are routinely measured). In our recent studies we showed that, based on model estimates, currently known oxidation products are only able to explain a

minor fraction (< 4.5%) of the missing reactivity in the boreal forest air (Praplan *et al.* 2019). Moreover, using young trees, we found large fractions of missing reactivity directly in the direct emissions of main boreal tree species, in particular under stress conditions (Praplan *et al.* 2020).

## Aerosol formation and growth

In the previous section, we focused on VOC emissions and their atmospheric concentrations that have a major role in the formation of new atmospheric particles. In this section, we proceed from the VOCs to the formation and growth of atmospheric aerosol particles, because this phenomenon has a dominant role in the global particle number concentration budget (Dunne *et al.* 2016) and it is a major contributor to atmospheric cloud condensation nuclei (CCN) concentrations (Spracklen *et al.* 2008, Merikanto *et al.* 2009, Gordon *et al.* 2017). As a result, atmospheric new particle formation (NPF) has a potential to influence clouds and climate (Makkonen *et al.* 2009, Kazil *et al.* 2010), and to participate in several climatically-relevant feedback mechanisms. In our CoE, we have investigated aerosol formation and growth under laboratory conditions and using various computational methods, developed new instruments for this purpose, and applied all this knowledge to field measurements and their interpretation. The combined effect of all these activities has been a greatly enhanced understanding of atmospheric NPF and its potential influences, along with a number of new research tools to be used in future from process-level atmospheric studies to global climate simulations.

### Aerosol precursors

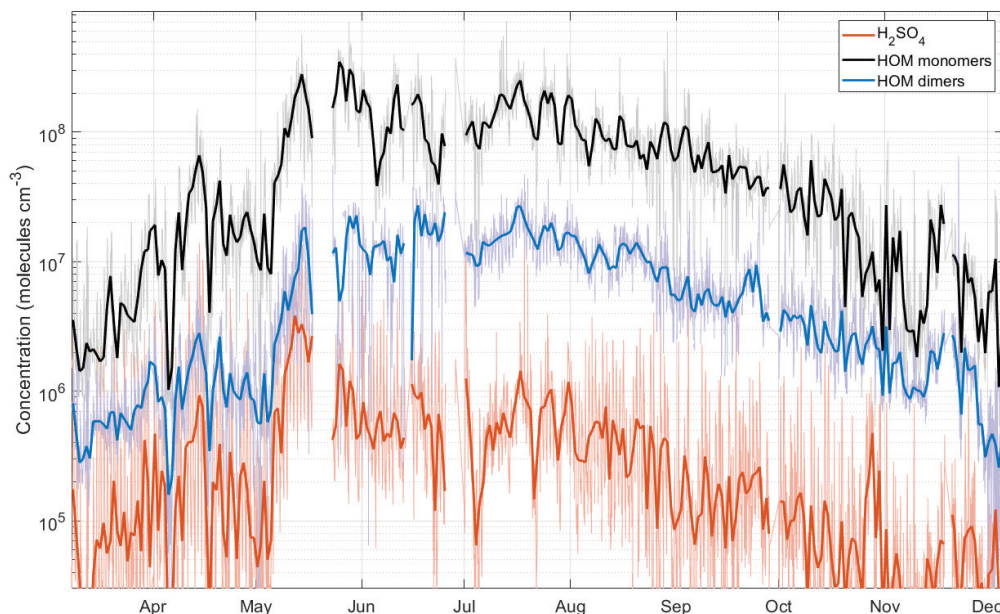
The formation and growth of new aerosol particles is driven by nucleation and condensation of low-volatile vapors (Kulmala *et al.* 2013b). The most important of these aerosol precursors are typically low-volatile organics for the condensational growth (Ehn *et al.* 2014), and sulfuric acid for the initial formation of small clusters (Sipilä *et al.* 2010), often in conjunction with some stabilizing bases such as ammonia or amines (Almeida *et al.* 2013). Under certain atmospheric conditions, also iodine-containing acids can play a key role (Sipilä *et al.* 2016; He *et al.* 2021). The upcoming sections detail the findings of CoE ATM in studying aerosol formation from these, and also other, precursors. However, much of the understanding has developed from

the detailed direct observations of these aerosol precursors in the gas phase, which in turn has been largely driven by the developments within the field of mass spectrometry.

The mass spectrometer development within CoE ATM got started with the first atmospheric pressure interface — time of flight (APi-TOF) mass spectrometer that we characterized for ambient ion chemistry measurements in 2010 (Junninen *et al.* 2010). This new technique provided a near universal interface for atmospheric pressure sampling. The APi-TOF allows both anion and cation measurements and these key features have now been utilized in laboratory and field studies. The APi-TOF is a superior tool for the detection of molecular ion clusters and has provided detailed information on acid-base (mainly sulfuric acid-ammonia or sulfuric acid-amines) nucleation mechanisms (e.g. Kirkby *et al.* 2011).

The next step in instrumental development features the integration of a chemical ionization inlet on the APi-TOF (CI-APi-TOF). Jokinen *et al.* (2012) demonstrate how this set up is capable of detecting atmospheric sulfuric acid in very low quantities ( $\sim 4 \times 10^4$  molecules  $\text{cm}^{-3}$ ). This technique has since been utilized in dozens of field and laboratory studies, yielding scientific breakthroughs such as the first ambient observations of iodine acid driven particle formation in coastal areas (Sipilä *et al.* 2016) and Highly Oxygenated organic Molecules (HOM) that are key players in growing atmospheric nanoparticles (Ehn *et al.* 2014). The mechanism forming HOM, namely autoxidation (Crouse *et al.* 2013), had been completely underestimated in the atmospheric oxidation of VOCs. Later studies have found that autoxidation is crucial for forming condensable and low-volatile vapors from a variety of VOC types, including monoterpenes (Jokinen *et al.* 2014), sesquiterpenes (Jokinen *et al.* 2016), aromatics (Wang *et al.* 2017), and even alkanes (Wang *et al.* 2021).

The first ambient APi-TOF deployment took place at SMEAR II from April–May 2009 (Ehn *et al.* 2010), while the first CI-APi-TOF measurements were conducted at the same site from March–April 2011 (Jokinen *et al.* 2012). Continuous measurements of aerosol precursors using a CI-APi-TOF began at SMEAR II in 2014 (Sulo



**Fig 10.** The daily median concentrations of precursor gases measured with CI-API-TOF at SMEAR II station at 35 m altitude in 2018. The 30 min average of sulfuric acid ( $\text{H}_2\text{SO}_4$ ), HOM monomers ( $m/z$  290–430 Th) and dimers ( $m/z$  430–620 Th) is shown in shaded colors displaying the diurnal variation. The HOMs are divided to monomers and dimers based on assumption that most of them are oxidation products of monoterpenes. The used data is analysed by unit mass resolution and the calibration constant is received from sulfuric acid calibration.

*et al.* 2021), and at SMEAR I in 2019 (Jokinen *et al.* 2022). These data provide crucial support for a variety of aerosol formation studies, as it provides key information on the concentrations of different aerosol precursors like sulfuric acid and HOM (Fig. 10).

Using the knowledge we gained from the early APi-TOF development and observations of sulfuric acid clustering with ambient bases, we developed a high sensitivity detector for ammonia and amines using sulfuric acid and its clusters as the CI-API-TOF reagent ion (Sipilä *et al.* 2015). We deployed this instrument at the SMEAR II station gaining information of dimethyl amine with concentrations even down to 70 ppqv (parts per quadrillion, 0.07 pptv). Understanding the role of ambient bases and developing detection technologies is an ongoing project. Since contaminants and memory effects often complicate the detection of bases, we took a step to develop chemical ionization inlets to a sheath flow-free design. The result was a multi-scheme chemical ionization inlet (MION, Rissanen *et al.* 2019) that we coupled with the

APi-TOF. This inlet also allows fast switching between ion mode and CI-mode that was not possible before, and required separate instruments. We have also been involved in development of online analysis of gas and particle composition (Lopez-Hilfiger *et al.* 2014) using a filter inlet for gases and aerosols (FIGAERO) inlet that allows the detection of both gas phase aerosol precursors and particle molecular composition simultaneously.

#### Laboratory studies on new particle formation and growth

The teams participating in our CoE have more than 30-year experience in conducting nucleation experiments and related studies under laboratory conditions. The first results from experimental homogeneous nucleation studies using a laminar flow diffusion chamber from Finnish Meteorological Institute were published in 2000 (Lihavainen *et al.* 2000), as a part of a worldwide joint experiment on homogeneous nucleation.



The objective of this experiment was to measure homogenous nucleation rates of n-pentanol with helium as a carrier gas with all available tested instruments at the time. Measurements with the developed laminar flow diffusion chamber were expanded to a series of alcohols from n-propanol to n-octanol (Hyvärinen *et al.* 2004, Görke *et al.* 2014). Several studies on carrier gas pressure and kind were also carried out (e.g. Brus *et al.* 2008). Homogenous nucleation of water in laminar flow diffusion chamber was measured to extend the earlier experimental data sets, and the measurements were found to agree surprisingly well (Manka *et al.* 2010). The experience from unary homogenous nucleation experiments was utilized in building a flow chamber (Brus *et al.* 2010), which was used for investigating water-sulfuric acid nucleation (Sipilä *et al.* 2010). The roles of different bases on water-sulfuric acid nucleation was also investigated, however no effect was found at the relatively high concentrations used in these experiments (Neitola *et al.* 2014).

Surface tensions and densities of  $\text{H}_2\text{SO}_4 + \text{NH}_3 + \text{water}$  solutions were measured for the first time as a part of atmospheric nucleation and growth studies (Hyvärinen *et al.* 2005). Through surface tension measurements, we investigated the role of other substances typically found in atmospheric aerosols during new particle formation and growth events. These included sulphuric acid- dimethylamine- water solutions (Hyvärinen *et al.* 2004) as well as aqueous solutions of oxalic, malonic, succinic, maleic, malic and cis-pinonic acids (Hyvärinen *et al.* 2006).

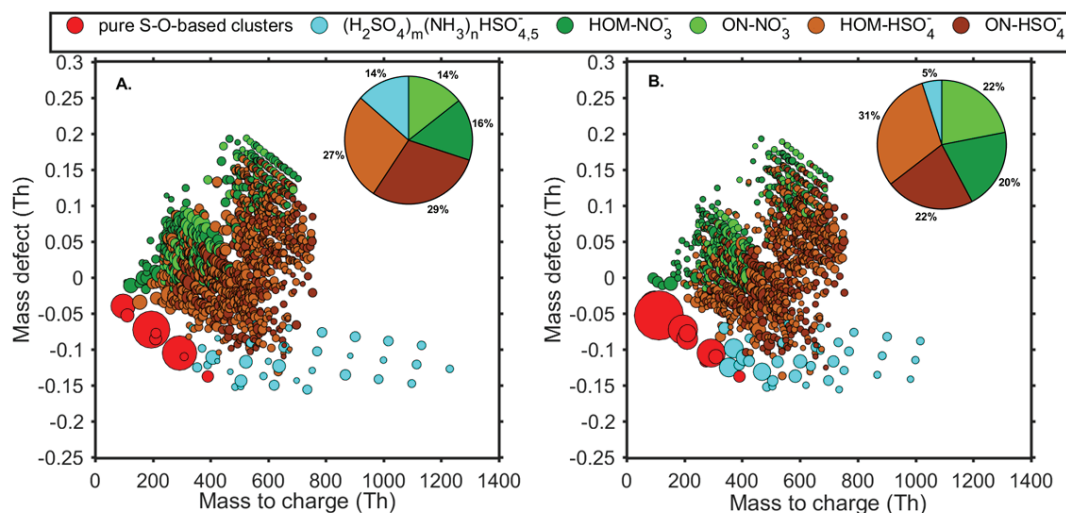
In 2009, the Cosmics Leaving Outdoors Droplets (CLOUD) project started its first experiments at the CLOUD chamber facility at CERN (European Center for Nuclear Research) in Switzerland. The project aims to investigate whether and how ionization from galactic cosmic rays can influence particle and cloud formation, with potential implications for climate. Due to the high cleanliness and controllability of the CLOUD chamber and its suitability for conducting nucleation experiments at atmospherically relevant levels of precursor vapors, the experiments in the CLOUD chamber have greatly advanced our basic understanding of the chemical and physical mechanisms of new particle formation.

In the first major publication from CLOUD, Kirkby *et al.* (2011) showed that binary sulfuric acid-water nucleation, which was previously thought to be one of the main nucleation mechanisms, is inefficient at sulfuric acid levels relevant for atmospheric boundary layer. However, small amounts of ammonia or amines (Kirkby *et al.* 2011, Almeida *et al.* 2013) was found to greatly enhance particle formation rates, making ternary nucleation one of the important pathways. Other major breakthroughs from the CLOUD experiment have been e.g. showing that highly oxygenated organic molecules (HOMs) from alpha-pinene ozonolysis can form (Kirkby *et al.* 2016) and grow (Tröstl *et al.* 2016) particles without the involvement of sulfuric acid, and that nitric acid could participate in rapidly growing particles in cold polluted climates (Wang *et al.* 2020). Dunne *et al.* (2016) presents the most comprehensive evaluation so far on the importance of the CLOUD results on the global atmosphere.

The CoE has had an important contribution to the CLOUD experiment since the beginning, especially by providing the direct measurements of the size distribution and composition of the forming clusters and ions using recently developed instrumentation (see the section about instrument development related to aerosol formation and growth) and lately also by leading the experiments focusing on simulating boreal-forest-type (Lehtipalo *et al.* 2018, Yan *et al.* 2020) and marine-type (He *et al.* 2021) particle formation. Figure 11 shows an example from the experiments aiming to replicate NPF in boreal forest. The Finnish CLOUD team have especially concentrated on probing the chemical composition of the forming clusters and particles (e.g. Keskinen *et al.* 2013, Schobesberger *et al.* 2013), explaining the particle growth mechanisms (Lehtipalo *et al.* 2016, Stolzenburg *et al.* 2020), and studying the effect of ions (Franchin *et al.* 2015, Wagner *et al.* 2017).

### Computational aerosol physics

Prior to 2002, particle formation in the atmosphere was modelled almost exclusively based on a classical thermodynamic liquid drop description of even the smallest clusters. Some early quantum



**Fig 11.** The composition of negative ions and ion clusters recorded with the API-TOF during CLOUD experiments simulating boreal-forest NPF (left) and during a springtime NPF event in Hyytiälä (right), showing a remarkable similarity. Different groups of compounds are identified with different colors. Figure from Lehtipalo *et al.* 2018.

chemical calculation had already been performed for individual cases, such as the smallest clusters of sulfuric acid and water or ammonia (Kurdi and Kochanski 1989, Bandy and Ianni 1998, Beichert and Schrems 1998, Ianni and Bandy 1999, 2000, Re *et al.* 1999). Though it was not widely realized at the time, the structural and energetic data of these early studies already demonstrated that the liquid drop model fails catastrophically for the smallest sulfuric acid–base clusters due to an incorrect description of proton transfer (Elm *et al.* 2020). While these and other early insights from first principles calculations (e.g. Kurtén *et al.* 2008) were useful, the development of actual quantum chemistry-based particle formation models required the systematic calculation of formation thermodynamics for a sufficiently large set of clusters (e.g. Herb *et al.* 2011, Ortega *et al.* 2012, Henschel *et al.* 2014, DePalma *et al.* 2014), using progressively more accurate methods (as described below), and the combination of thermodynamic data with cluster population dynamics models solving the birth–death equations.

The flagship cluster dynamic model of the CoE ATM is the Atmospheric Cluster Dynamics Code (ACDC, McGrath *et al.* 2012). Until now, the collision rates used by ACDC have been taken

from kinetic gas theory and existing ion–molecule parametrizations, while the evaporation rates are derived via detailed balance from formation free energies calculated using quantum chemistry (Ortega *et al.* 2012). Work is underway to compute more accurate collision rates taking long-range interactions such as dipole–dipole attraction into account using molecular dynamics (Halonen *et al.* 2019). Our computational scheme was validated by comparison to experimental results from the CLOUD chamber (Almeida *et al.* 2013, Olenius *et al.* 2013). A key finding of these joint experimental–modelling studies has been that the rate of sulfuric acid-driven new particle formation can be immensely increased by extremely low (part-per-trillion or even lower) concentrations of for example basic vapors such as amines — as we predicted already in 2008 (Kurtén *et al.* 2008). It is noteworthy that the threshold concentrations at which these vapors affect new-particle formation may be far below their detection limits using many common measurement techniques. Also, while chemical ionization-based mass spectrometry is an immensely powerful tool for studying atmospheric new particle formation, both the ionization process, and the subsequent high-energy collisions in the ion optics, may bias the

results. The charged cluster distributions detected by chemical ionization mass spectrometers may thus not match the original, usually predominantly neutral, distribution. Fortunately, quantum chemical calculations combined with ion cluster fragmentation models can be used to address both issues, and ultimately reconstruct an unbiased cluster distribution (Passananti *et al.* 2019, Zapadinsky *et al.* 2019).

Our breakthroughs in understanding of atmospheric new-particle formation at a molecular level have been facilitated by the combination of the conceptual and methodological frameworks of computational and physical chemistry with those of atmospheric aerosol physics. On the computational side, key developments allowing the construction of quantum chemistry-based particle formation models include the continuous increase of computing power, the emergence of density functional methods capable of describing intermolecular interactions sufficiently accurately to compute reliable structures and vibrational frequencies of molecular clusters with at least several tens of atoms, and the development of cost-effective variants of coupled-cluster theory (e.g. DLPNO-CCSD(T)) allowing — albeit often only after extensive benchmarking and tweaking of settings — the calculation of near-quantitative binding energies for these clusters. See Elm *et al.* (2020) for a review of the relevant computational methods. As the system size for which accurate quantum chemical calculations are possible has grown, the bottleneck for ACDC-type modelling has become the conformational sampling of molecular cluster structures (Kubečka *et al.* 2019). This problem has been accentuated as focus has expanded from structurally relatively simple sulfuric acid–base systems to clusters containing also large and flexible organic oxidation products (Elm 2019, Shi *et al.* 2019, Zanca *et al.* 2020). We have accordingly developed a systematic and automated approach for the configurational sampling of molecular clusters.

### Instrument development related to aerosol formation and growth

Condensation particle counter (CPC) development in the University of Helsinki began around

year 2000 when the pulse height counting technique (Saros *et al.* 1996), developed at the University of Minnesota, was modified to the commercial CPCs maybe by TSI (USA), and this pulse height CPC was used in field measurements to detect newly formed particles in the atmosphere. The pulse height CPC was used in Mace Head, Ireland, and in Hyytiälä SMEAR II station, Finland, to monitor the nanoparticle size distributions in the size range of 3–10 nm (Aalto *et al.* 2001, O'Dowd *et al.* 2002). To detect nanoparticles even smaller than 3 nm, the flow profile in the commercial TSI CPC growth stage was made turbulent on purpose (Mordas *et al.* 2008a). This allowed detecting nanoparticles close to 1 nm without major interference from homogeneous droplet formation, and was utilized as a battery of four CPCs at SMEAR II to detect atmospheric clusters (Kulmala *et al.* 2007a). Development of the pulse height CPC technology was continued by decreasing the size of the smallest detectable particle size down to 1 nm by increasing the supersaturation ratio over the limit of homogeneous butanol droplet formation. The pulse height analysis was used to separate homogeneously nucleated droplets from ambient particles. This version of the pulse height CPC was used in SMEAR II station to detect atmospheric cluster size distributions even down to the molecular size around 1 nm (Sipilä *et al.* 2008, 2009, Lehtipalo *et al.* 2009).

The next major step in the development of CPCs was the adaption of the flow mixing technology (Okuyama *et al.* 1984, Sgro and Fernández de la Mora 2004) to the monitoring of atmospheric clusters. Vanhanen *et al.* (2011) constructed a particle size magnifier (PSM) that is capable of activating and growing even 1 nm particles for the detection in an external CPC. When used in so-called supersaturation scanning mode, it enables the continuous measurement of particle size distributions in the size range of 1–3 nm in the atmosphere (Lehtipalo *et al.* 2022). The PSM has played a major role in elucidating the particle formation mechanisms together with the mass spectrometers in several different atmospheric locations, and chamber and laboratory studies.

Parallel to the CPC development, the CoE was active in advancing the mobility particle

sizing technology. Especially, the collaboration with University of Tartu has led to developments in the ion mobility spectrometers for atmospheric size distribution measurements (Kulmala *et al.* 2016a). The first ion spectrometers used in the CoE to measure the atmospheric ion size distribution were the Balanced Scanning Mobility Analyzer (BSMA) (Tammet 2006) and Air Ion Spectrometer (AIS) (Mirme *et al.* 2007), both manufactured by AIREL Ltd., Estonia. The next big step forward was the development of the Neutral cluster and Air Ion Spectrometer (NAIS), which utilizes unipolar charging prior to detection with electrical mobility analyzers (Mirme and Mirme 2013). This enables the measurement of the total aerosol size distribution in the size range from ~2–42 nm in particle diameter. Due to its robustness and easy operation, the NAIS has been widely used around the world both for long-term measurements and during specific measurement campaigns (e.g. Manninen *et al.* 2009, 2010).

Since the rapid development of several applications to measure the particle concentration and size distribution of newly formed particles, efforts were aimed at narrowing down the uncertainties in these measurements, which is still a scientific challenge especially in the sub-5 nm size range (Kangasluoma *et al.* 2020). This has required development also in the methods to test and validate the instrumentation. Several new methods to produce and size select particles were adopted, including mobility standards produced by electrospraying, wire-generators and high-resolution differential mobility analyzers (e.g. Sipilä *et al.* 2009, Kangasluoma *et al.* 2013, 2016). Several international instrument intercomparison and calibration workshops have been organized in the aerosol laboratory in Helsinki (Mordas *et al.* 2008b, Asmi *et al.* 2009, Gagne *et al.* 2011, Kangasluoma *et al.* 2017). This work will continue in future under the ACTRIS Cluster Calibration Center at University of Helsinki, which is part of the ACTRIS Center for Aerosol In-Situ Measurements.

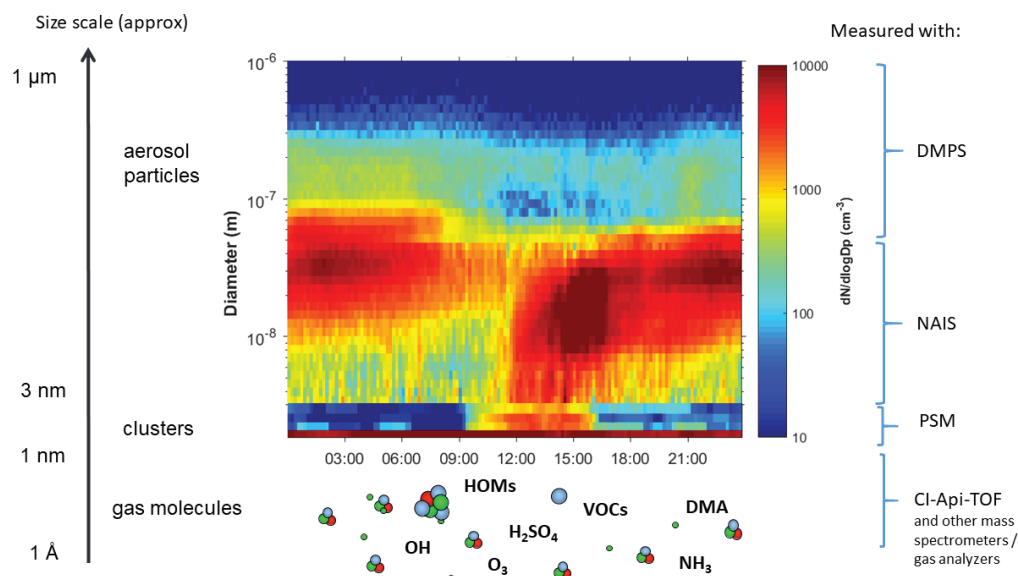
### In situ atmospheric observations and their analysis

Observations indicating atmospheric new particle formation (NPF) date back more than a cen-

tury (see Malila 2018, and references therein). However, it was not until the late 1990s when this phenomenon was recognized to extend beyond local scales (Mäkelä *et al.* 1997), often taking simultaneously place over tens to hundreds of kilometers in horizontal direction. At the beginning of our CoE ATM, we had already developed the basic tools to characterize regional NPF, including the particle formation and growth rates, condensation and coagulation sinks, and categorizing how frequently and intensively this phenomenon occurs in a certain environment (Kulmala *et al.* 2001a, 2001b). It soon became apparent that atmospheric NPF is predominantly a daytime phenomenon, typically starting soon after the sunrise and continuing for a few hours, whereas the growth of newly-formed particles to larger sizes remains visible up to couple of days in atmospheric observations (Kulmala *et al.* 2004a).

Observing and characterizing atmospheric NPF has been one of the central research topics in our CoE, so that over the years we have measured NPF in tens of different locations covering all the continents (Kerminen *et al.* 2018, Nieminen *et al.* 2018, Chu *et al.* 2019). Perhaps the most important finding of these studies has been the relatively frequent and wide-spread occurrence of regional NPF in almost all continental environments ranging from polar areas to highly-polluted megacities and mountain-top locations. Currently, we have long-term, continuous observations of atmospheric NPF from three boreal forest locations (Asmi *et al.* 2011, Kyrö *et al.* 2014, Nieminen *et al.* 2014), Crete in the Mediterranean (Kalivitis *et al.* 2019), a polluted Po Valley area in Italy (Hamed *et al.* 2007), and from an urban Budapest, Hungary (Mikkonen *et al.* 2020, Salma *et al.* 2021). In addition to making it possible to conduct detailed analyses on the factors influencing atmospheric NPF over very different time scales, these observations have revealed influences of both anthropogenic (mainly sulfur) and natural (mainly biogenic aerosol precursor compounds) emission changes on atmospheric NPF.

Measurements of atmospheric NPF have advanced considerably over the years as a result of instrumental developments (see the previous section). During the first years of CoE, investi-



**Fig 12.** The development in measurement technology during CoE has enabled continuous measurements of the most important aerosol precursors vapors, clusters and the particle size distribution starting from  $\sim 1$  nm, which are crucial for studying atmospheric new particle formation.

gating atmospheric NPF was based entirely on particle number size distribution measurements starting from particle diameters of 3–10 nm (Dal Maso *et al.* 2005). Later, measurements were extended to the sub-3 nm size range, first to ions (Laakso *et al.* 2004), then to neutral clusters and aerosol particles (e.g. Kulmala *et al.* 2007b, 2013b, Manninen *et al.* 2009), and eventually to molecules and small clusters participating in the very early steps of atmospheric NPF (Ehn *et al.* 2014). These advances are illustrated in Fig. 12. Our CoE was the first to measure the initial steps of atmospheric NPF molecule by molecule (Sipilä *et al.* 2016). More recently, we obtained similar information from Antarctica (Jokinen *et al.* 2018), high-latitude arctic (Beck *et al.* 2021), mountain-top region in Himalayas (Bianchi *et al.* 2021), and heavily polluted megacities in China (Yao *et al.* 2018, Cai *et al.* 2021, Yan *et al.* 2021). One important conclusion based on these studies is the apparent diversity of dominating cluster formation mechanisms in different atmospheric environments.

Concurrent with the development of atmospheric observations, more details were brought into identifying, characterizing and classifying

atmospheric NPF (Leino *et al.* 2016, Dada *et al.* 2018, Joutsensaari *et al.* 2018). New theoretical tools and model frameworks were developed to understand the dynamics of molecular clusters (see the section on computational aerosol physics), and the subsequent aerosol formation and growth in the sub 3 to 5-nm size range, including semi-empirical formulas which connect new particle formation rates with concentrations of nucleating vapours (Sihto *et al.* 2006, Paasonen *et al.* 2010) and nano-Köhler theory which describes the activation of molecular clusters for further growth (Kulmala *et al.* 2004b, Kontkanen *et al.* 2018). A crucial factor in determining whether NPF may occur or not in any atmospheric environment is the competition between the cluster growth and their removal by coagulation onto larger pre-existing particles (McMurry and Friedlander 1979, McMurry 1983). During our CoE ATM, we have developed several expressions to estimate how this phenomenon influences newly formed aerosol particle populations (Kerminen and Kulmala 2002, Lehtinen *et al.* 2007, Korhonen *et al.* 2014). In spite of this progress, we still do not have a full scientific understanding on why atmospheric NPF is able

to take place under heavily polluted conditions encountered in some of the megacities (Kulmala *et al.* 2017b).

The growth of newly formed particles to cloud condensation nuclei (CCN), corresponding to a particle diameter of at least a few tens of nm, takes typically from a few hours to a couple of days in the lower atmosphere (Kerminen *et al.* 2018). Our CoE reported the first, direct observational evidence linking atmospheric NPF to CCN production (Kurtén *et al.* 2003, Lihavainen *et al.* 2003), and later more quantitative data on atmospheric CCN production resulting from NPF were obtained from several sites around the world (Sihto *et al.* 2011, Kerminen *et al.* 2012, and references therein). In polluted environments, atmospheric NPF followed by particle growth can contribute to a particle population that forms a haze (Guo *et al.* 2014, Kulmala *et al.* 2021a). We found indications that by reducing NPF by emission control, we might delay haze formation and thereby substantially reduce the annual number of haze days in polluted environments (Kulmala *et al.* 2021a).

While there are evidently multiple compounds and processes influencing the particle growth to larger sizes (Mikkonen *et al.* 2011, Riipinen *et al.* 2012, Vakkari *et al.* 2015), the important role of organic vapours of largely biogenic origin in this growth was recognized already at the early stages of our CoE (Kulmala *et al.* 2001a, Tunved *et al.* 2006). Our most recent observations, combined with laboratory experiments and model simulations, have brought much new insight into the growth of newly formed particles to larger sizes (Ehn *et al.* 2014, Jokinen *et al.* 2015, Tröstl *et al.* 2016, Lehtipalo *et al.* 2018, Paasonen *et al.* 2018). In particular, HOM have been shown to be important contributors to NPF (Ehn *et al.* 2014, Tröstl *et al.* 2016), yet the ability of these to grow new particles of different sizes is highly sensitive to the atmospheric conditions under which they were formed (Yan *et al.* 2020). The oxidation processes converting any VOC into condensable HOM is strongly influenced by factors such as temperature (Quéléver *et al.* 2019), atmospheric mixing (Zha *et al.* 2018), nitrogen oxides (Yan *et al.* 2020), and photochemistry (Yan *et al.*

2016). Further studies are needed to quantitatively link both aerosol formation and growth to various atmospheric precursor compounds and conditions.

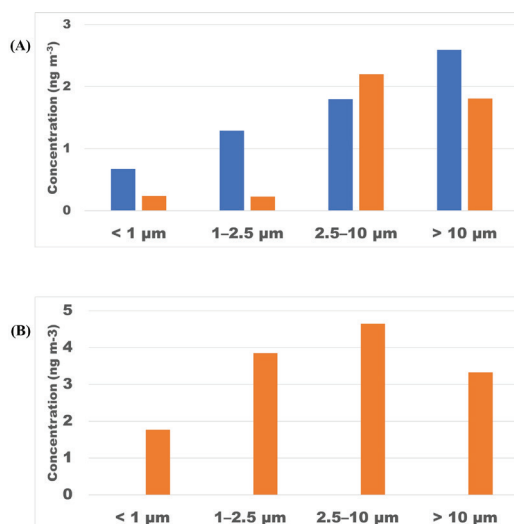
## Aerosol composition and bioaerosols

Measuring the bulk composition of aerosol particles in the accumulation mode provides a way to estimate the main sources for the aerosols at a given location. The SMEAR II site has therefore had continuous online measurements of aerosol chemical composition since 2012 (Heikkinen *et al.* 2020). Thanks to the long data set, we could distinguish how the aerosol has a bimodal pattern across a year. One mass concentration peak occurs in the winter, mainly from inorganic species such as sulfate and nitrate, and is due to an increased need to domestic heating and different combustion processes. However, the largest mass concentrations are measured in summer, and those are ~80% organic, being SOA formed from the oxidation of the abundant BVOCs that are emitted from the forest. While some of the organics can result from anthropogenic activities, we were able to show that this is a very small (< 10%) contribution at this site (Heikkinen *et al.* 2021). These links were only made possible due to the wealth of supporting data available at the station, such as direct VOC measurements to identify biogenic sources, and black carbon and CO for identifying combustion sources.

Here, we focus in more detail into two specific aerosol components, primary biological aerosol particles and soot. Plant fragments, pollen, spores, algae, bacteria and viruses are typical constituents of primary biological aerosol particles (PBAPs, Després *et al.* 2012, Šantl-Temkiv *et al.* 2020). The amount and distribution of PBAPs in the atmosphere have gained more interest, mainly because of the possible underestimation of their levels and their atmospheric impact (Morris *et al.* 2011, Estillore *et al.* 2016). Globally, PBAPs constitute ca. 30% of the mass of particles larger than 1  $\mu\text{m}$  in urban and rural air (Fröhlich-Nowoisky *et al.* 2016), up to 65% in boreal forest air (Manninen *et al.* 2014), and up to 80% in tropical forest air (Elbert *et al.* 2007).

We have successfully determined chemical tracers (amino acids, saccharides, see Fig. 13) and gene copy numbers (16S and 18S for bacteria and fungi, respectively) to access bioaerosols in size-segregated aerosol samples collected at the SMEAR II station (Helin *et al.* 2017, Ruiz-Jimenez *et al.* 2021). According to our results (Helin *et al.* 2017), the spring pollen season influenced the levels of free amino acids as well as the bacterial abundances. Elevated PBAP abundances occurred during the pollen season (Manninen *et al.* 2014), and based on our estimation even up to 77% of the total particle mass may be of biological origin in the studied site. We also observed clear variations in the composition of bioaerosols as a function of the particle size (Ruiz-Jimenez *et al.* 2021). In most cases, the highest concentration values and gene copy numbers (in the case of microbes) were observed for 2.5–10  $\mu\text{m}$  particles, followed by > 10, 1–2.5, and < 1.0  $\mu\text{m}$  particles. Variables related to the air and soil temperature, UV radiation, and the amount of water in the soil all affected the composition of bioaerosols. Positive correlations were also observed between gas-phase VOCs (acetone, toluene, methanol, and 2-methyl-3-buten-2-ol) and the gene copy numbers of microbes in biogenic aerosols.

Notable ingredient in the urban atmospheric aerosols is soot, which originates from combustion processes and motor vehicle emissions (Harley *et al.* 2005). It may be referred to black carbon or elemental carbon (Bond and Bergstrom 2006). Although soot and aerosol particles in general have a short atmospheric lifetime, they contribute to both regional and global climate change (Jacobson 2001, Ramanathan and Carmichael 2008). More recently, various studies have been made to resolve the uncertainties related to the effect of soot/black carbon on cloud formation and global warming (e.g. Lohmann *et al.* 2020, Fierce *et al.* 2020). Using specifically developed laser desorption-ionization aerosol mass spectrometer we were able to quantify carbon clusters from  $C_{14}$  to  $C_{19}$  in 50 nm urban air particles. The average fraction of carbon clusters per sample was 7.2%, ranging from 0.01% to 30.8% (19 pg to 6465 pg). Fullerenes from  $C_{50}$  to  $C_{100}$  in the 50 nm urban air particles were also detected with this technique (Laitinen *et al.* 2014).



**Fig 13.** Average free amino acid (upper figure) and saccharides (lower figure) concentrations in different size fractions determined at the SMEAR II station during 2014 (blue) (1 Feb. 2014–1 Nov. 2014) and 2017 (orange) (4 Sep. 2017–22 Nov. 2017) campaigns. Note: no data available for average saccharides concentration from 2014 campaign (Helin *et al.* 2017 and Ruiz-Jimenez *et al.* 2021).

### Cloud formation

Aerosols acting as cloud condensation nuclei are capable of modulating cloud droplet number concentration, and therefore its radiative properties. Additionally, there is evidence that perturbation in aerosol concentrations cause changes in cloud cover or liquid water path. Given that clouds are a major part of the daily weather and the global climate system and that boreal forest acts as a source of biogenic aerosol particles that grow to CCN sizes, impact of these particles on cloud formation and evolution is a topic of current scientific interest. Representation of cloud feedbacks is a major source of uncertainty in climate models and accounts for a large inter-model variability in predicted climate scenarios (Coupled Model Intercomparison Project (CMIP) Phase 3 (Bony *et al.* 2006, Dufresne and Bony 2008), Phase 5 (Andrews *et al.* 2012) and Phase 6 (Zelinka *et al.* 2020)). Aerosol–cloud–precipitation interactions is one of the major reasons for this uncertainty.

## In situ measurements of cloud formation

CoE partner institutes maintain two stations with continuous in situ observations for aerosol–cloud interactions, SMEAR IV station in Kuopio is located at the top of the Puijo tower 306 m above sea level and 230 m above the surrounding lake level in a semi-urban environment and Pallas-Sodankylä Global Atmospheric Watch (GAW) station in northern Finland is located at the Sammaltunturi measurement site on top of a fell 300 m above the surrounding area. These two stations measure aerosol size distribution and number concentration, light extinction (scattering and absorption) by aerosol particles, cloud droplet size distribution, trace gas concentration, and several meteorological parameters. The aerosol size distribution is measured through two inlets allowing the sampling of the interstitial aerosol and total aerosol including both the interstitial particles and cloud droplet residuals. The difference between the total aerosol and interstitial aerosol gives then the fraction of activated particles as a function of particle size. These measurements enable detailed in situ studies of cloud droplet activation and the effect of aerosol properties on it (Komppula *et al.* 2005, Anttila *et al.* 2009, 2012, Portin *et al.* 2014).

Aerosol chemical composition plays a central role in cloud droplet activation. Väisänen *et al.* (2016) illustrated the sensitivity of cloud droplet formation to aerosol hygroscopicity by investigating activation efficiencies of externally mixed aerosol having high and less hygroscopic modes at size range relevant for activation. They showed that the less hygroscopic mode remained unactivated reducing the potential of particle population to activate cloud droplets by 70% compared to case where all particles would belong to high hygroscopic mode. Also Ruuskanen *et al.* (2021) investigated the on-cloud scavenging of scattering and absorbing aerosol particles. In their study, the absorbing aerosol consisted mostly of black carbon. Their analysis showed that the scavenging coefficients for scattering and absorbing aerosol particles were 0.85 and 0.55 respectively and higher fraction of black carbon is in smaller particle sizes so that at least 20–30% of interstitial particles within clouds consisted of absorbing material. Chem-

istry plays a role not only in activation, but also in other cloud processes as the aerosol particles may transform chemically in clouds due to aqueous phase chemistry (e.g. Ervens 2015). Hao *et al.* (2013) studied in more detail the effects of chemical composition on activation and further the effects of cloud processing on aerosol composition in low level stratus clouds. They observed higher fraction of low volatile oxygenated organic aerosol in cloud droplet residuals than in interstitial aerosol. Also clear differences in particle acidity were observed: cloud residues were clearly less acidic than interstitial aerosol. According to their analysis, these observations indicate possible joint effect of activation process and cloud processing.

## Radar measurements of cloud formation

Combining in-situ and ground-based remote-sensing measurements collected during Biogenic Aerosols–Effects on Clouds and Climate (BAECC) campaign at SMEAR II in 2014 (Petäjä *et al.* 2016b), allowed investigating the influence of biogenic aerosols on clouds (Petäjä *et al.* 2021a). Using a combination of comprehensive ground-based aerosol measurements it was found that the marine air transported over forested areas increase aerosol load by factors of about 2 to 8 for the air mass transport times of 20 hours and 75 hours, respectively. Corresponding cloud remote sensing observations detect an increase in the droplet number concentration, liquid water path and optical depth of warm, low-level clouds, which are staying connected to the ground, by factors of up to two (Petäjä *et al.* 2021a). This study shows that the boreal forest emissions may play an important role by modulating warm, low-level cloud properties and therefore affect cloud radiative effects.

In mid- to high-latitudes, majority of precipitation originates from ice clouds (Field and Heymsfield 2015). Given that a large fraction of these clouds contains supercooled liquid water, riming may have a significant impact on surface precipitation. Using surface-based observations collected in SMEAR II in Hyttiälä, Moisseev *et al.* (2017) have shown that 5–40% of snowfall mass is gained by riming. This is in line with



other geographical locations, i.e. 30%–40% in the Sierra Nevada (Mitchell *et al.* 1990), and more than 50% in Japan (Harimaya and Sato 1989). It was also shown that riming modifies snowflake shape, when the mass of accreted water exceeds 50% of the total particle mass ice particles become more spherical (Li *et al.* 2018). To further advance our knowledge of riming occurrence at different geographic location, a method to estimate riming fraction from Doppler cloud radar observations was derived (Kneifel and Moisseev 2020). This method was applied to cloud radar observations collected at several ACTRIS stations. It was found that riming occurs in 1–8% of the non-convective ice containing clouds. The dependence of riming on aerosol loading however was not as clear as was expected from previous studies.

We have also conducted long-term radar measurements in the city of Helsinki. Using 11 years of University of Helsinki, Kumpula campus radar observations, it was found that airplanes arriving to or departing from the Helsinki-Vantaa airport could in certain condition increase surface precipitation intensity (Moisseev *et al.* 2019). Adiabatic cooling of air behind airplane wings leads to the production of ice particles (Woodley *et al.* 2003), which seed lower mixed-phase cloud layer. This process leads to the formation of larger snowflakes, by aggregation, and result in heavier precipitation intensity. It was found that precipitation in the affected areas could be 6–14 times higher than in the background large-scale precipitation.

## Modelling of cloud formation

Cloud modelling covers a vast range of scales starting from the microphysical properties of a single cloud hydrometeor ending up to atmospheric cloud systems with varying cloud types. In the CoE ATM, cloud modelling concentrated mainly on the aerosol effect on the liquid phase clouds, where we first studied how different chemical compounds affect the droplet formation.

Semivolatile aerosol components produce an increase in cloud droplet number concentration in a similar manner as the classical Twomey

effect forecasts related to the changes in aerosol number concentration. In the CoE ATM, we have explained the enhanced activation through Köhler theory (Kokkola *et al.* 2003), estimated the effect in atmospheric clouds with parcel modeling framework, and finally, related to nitric acid, also parameterized the effect and produced the first estimate of  $-0.46 \text{ W m}^{-2}$  for global indirect radiative forcing (Romakaniemi *et al.* 2005, Makkonen *et al.* 2012a). Köhler theory also forecasts that certain surface active compounds lower the surface tension of liquid aerosol solute prior and during the cloud droplet formation process, and thus these compounds have potential also to enhance droplet concentration. However, accounting for different competing effects during the activation process, the effect is estimated to be small especially at a global scale (Sorjamaa *et al.* 2004, Prisle *et al.* 2012), although different results have been presented for some conditions (e.g. Ovadnaite *et al.* 2017).

During the CoE, we have taken steps towards simulating aerosol indirect effects at cloud resolving scale with a coupled aerosol-large-eddy model UCLALES-SALSA (Tonttila *et al.* 2017). The core of the model is based on the well-established large-eddy simulation platform (UCLALES) intended for idealized cloud studies. To account for aerosol it is coupled with SALSA aerosol microphysics (Kokkola *et al.* 2008), which is further updated to cover both liquid and solid hydrometeors of different sizes (Tonttila *et al.* 2017, Ahola *et al.* 2020). To this end UCLALES-SALSA has been employed in different applications including smog events, fog formation, warm and mixed phase boundary layer clouds, and also moderate convection. Common to all of these is the need for explicit representation of aerosol properties in different atmospheric processes, and interaction with cloud and atmospheric dynamics. We have shown that the employment of cloud droplet parameterization in fogs leads to an overestimate in fog droplet number concentration affecting the fog lifetime in numerical weather prediction and also estimates of aerosol radiative forcing caused through changes in fog properties (Boutle *et al.* 2018). Related to drizzle formation in marine stratocumulus, the role of aerosol size distribu-

tion and especially the giant CCN particles is shown to be evident (Tonttila *et al.* 2021).

## Dynamic meteorology

Meteorology is a branch of atmospheric sciences that operates on especially large scales. At the start of the CoE ATM, the link between in situ studies and meteorology was initially weak. At the planetary scale, it is obvious that the Earth system components, such as atmosphere and biosphere, are in perpetual interaction. However, when considering local scale processes, it can be quite hard to perceive and appreciate these large-scale couplings. Process studies, for instance, typically concentrate on some specific phenomena that are studied experimentally and theoretically (e.g. Viskari *et al.* 2012a, 2012b). At this scale, the process seems to be embedded in a large-scale environment that is given, thus easily masking the feedback to the processes controlling the environment. More concretely, dynamics and physics of global weather systems control the time evolution of atmospheric state. These provide the environment for aerosol microphysical processes and air chemistry where the key ambient variables are temperature, humidity, and intensity of solar and terrestrial radiation. In such process studies, the role of meteorology is weak since it only provides expertise regarding the environment — the curiosity is directed to the microphysical processes and their theoretical formulation, and less to the feedbacks affecting the large-scale environment and the large-scale system itself.

Widening the study scope can have an immediate impact on the curiosity towards the larger-scale environment. Roll vortices is a universal fluid dynamical phenomenon in convectively active boundary layers (Lampilahti *et al.* 2020). In the atmospheric boundary layer, the vortices ventilate near-surface air and enhance long-range transport, thus controlling trace gas and aerosol concentrations. The CoE organized a major measurement campaign which involved air-borne and surface in situ observations and produced complicated measurement data in four dimensions. In this case, data analysis and interpretation were equally rewarding both for scien-

tists involved in local processes and larger-scale flow dynamics — expertise in all disciplines were necessary to interpret the data, even though the impact of increased aerosol concentration in the ascending branches on the cloud formation and roll vortex intensity could not eventually be determined.

Core research objectives in microphysical process studies are the new formulations of theories that explain the observed phenomena (e.g. Kokkola *et al.* 2008). Long-term support of the CoE enabled development of large-scale models of the atmosphere and Earth system where these new microphysical process formulations can be implemented (Makkonen *et al.* 2009). On one hand, this enables us to test how general the theories are in explaining events outside the immediate surroundings of the in situ measurement sites. Even more importantly, these large-scale models open a direct route to investigate the feedbacks between, e.g., the aerosol population and the large-scale environment. These models can be used in very wide variety of research questions, and this is exactly what has been accomplished in the CoE ATM.

The CoE has enhanced inter-disciplinarity, and incorporation of weather system understanding to microphysical research. A shining example is related to deep convection which transports moisture to the upper troposphere where it has a major impact on the radiative transfer of the Earth system (Riuttanen *et al.* 2016). Aerosols have microphysical and thermo-dynamical impacts on deep convective clouds, and any changes in atmospheric aerosols can have direct climate feedback. Therefore, there is a need to detect the existence and understand the character of this feedback mechanism. The interdisciplinary approach fostered by the CoE has been instrumental in enabling feedback studies that were previously not possible.

In summary, a major benefit of this CoE is that participating scientists have learned to appreciate the importance of the mutual couplings between the Earth system components. Despite some interactions and feedbacks appearing to be beyond control in certain research contexts, the interactions and feedbacks do exist and their importance have been recognized.

## Remote sensing for investigating Earth System processes

Earth Observation data available from spaceborne remote sensing instruments can be used to investigate climate processes on a global scale. Daily data records from microwave radiometers start as early as 1978 providing brightness temperatures at a coarse spatial resolution of tens of kilometers (Njoku *et al.* 1980, Hollinger *et al.* 1990). We used these data sets to quantify hemispheric processes of the terrestrial cryosphere and to study their relation to carbon cycle. This was accomplished by fusing satellite data sets, in situ data and model predictions. The main investigated variables included snow cover and soil freeze-thaw status that both affect the seasonal cycle of CO<sub>2</sub> and CH<sub>4</sub> in the boreal and arctic region. Detailed comparison of remote sensing signatures and land-atmosphere coupling were carried out in the Sodankylä site that incorporates in situ sensor networks and a suite of satellite reference instruments monitoring both ground/vegetation and the properties of atmosphere, e.g. columnar concentrations of greenhouse gases (Rautiainen *et al.* 2014, Colliander *et al.* 2017, Hannula *et al.* 2020, Lorente *et al.* 2021). Based on these investigations, a novel method to monitor circum-polar soil freezing and thawing processes from L-band microwave radiometer satellite data was established and implemented in co-operation with the European Space Agency (Rautiainen *et al.* 2016).

The employment of microwave radiometer data together with global in situ observations of snow depth and snow mass (given as snow water equivalent in individual samples) led to a major advance in assessing Earth's snow mass and its trend for regional to hemispheric scales for the period 1980–2018 (Pulliainen *et al.* 2020). The obtained results indicate that in Eurasia the multi-decadal trend in the seasonal peak snow mass has been negligible, whereas a decreasing trend is evident in North America. However, regional differences are strong. For example, results for East Siberia indicate exceptionally high levels of snow mass for the years 2017 and 2018, possibly due to absence of sea ice on the East Siberian Sea during these years. Further, the earlier uncertainty in hemispheric snow mass

estimates was reduced from 33% to 7.4% (concerning hemispheric non-alpine areas). Another key finding was the estimation of advancement boreal forest spring recovery due to earlier snow melt by linking microwave radiometer data-derived snow melt information to carbon uptake (Pulliainen *et al.* 2017). This was carried out by the combined use of satellite data, EC measurements on CO<sub>2</sub> fluxes across Eurasia and North America, and simulations with a land ecosystem model coupled to a global circulation model (ECHAM/JSBACH). The results show that the spring recovery of photosynthesis advanced about two days per decade for the circum-polar boreal forest zone from 1979–2014. We estimated that this advance of spring has increased the carbon uptake of conifer-dominated boreal forests by 4–6% per decade (for the first half of the year) providing a negative feedback mechanism to ongoing global warming.

## Climate feedbacks

Climate feedbacks are defined as interactions in which a perturbation in one climate variable causes a change in the second, and the change in the second quantity ultimately leads to an additional change in the first (IPCC 2013, 2021). The Earth's climate system is affected by numerous feedback mechanisms that can either amplify (positive feedback) or suppress (negative feedback) the ongoing global warming (Bony *et al.* 2006, Heineman and Reichstein 2008, Ceppi *et al.* 2017, Williams *et al.* 2019). During our CoE, we have concentrated on climate feedbacks involving the continental biosphere, and introduced new potentially important feedback mechanisms, and we have investigated the strength of these feedbacks using both long-term observations and large-scale model simulations.

## Background to our feedback studies

The interest in climate feedbacks associated with biosphere-atmosphere interactions originates largely from the work by Charlson *et al.* (1987), who suggested that increased sulfur emissions from the oceans in a warming climate

would lead to increased aerosol concentrations and cloud albedos, causing a negative feedback that would slow down the warming of the climate. Kulmala *et al.* (2004c) hypothesized that a negative feedback mechanism involving natural aerosol particles would also operate in a continental biosphere. Central components of this feedback are increased emissions of biogenic volatile organic compounds (BVOCs) from the continental biosphere in a warming climate and enhanced formation of secondary organic aerosol (SOA) resulting from the atmospheric oxidations of these BVOCs, causing an increased atmospheric aerosol loading and larger negative radiative effect that would slow down the global warming (Fig. 1).

The potentially important role of continental ecosystems in the cycling of water, carbon and nitrogen in the Earth system, and thereby in climate feedbacks, were gradually recognized (e.g. Barth *et al.* 2005, Heineman and Reichstein 2008). Our CoE participated actively in constructing a review paper that summarized our understanding on feedback loops connecting terrestrial biogeochemical cycles, biosphere-atmosphere exchange, atmospheric composition and climate (Arnth *et al.* 2010). One of the main conclusions of that paper was that the strength of biogeochemical feedbacks, while highly uncertain, could be comparable to those of more widely-studied feedbacks in the physical climate system.

Higher atmospheric aerosol loadings increase the ratio of diffuse to total radiation reaching the Earth's surface, which in turn tends to enhance the carbon uptake by photosynthesis in many continental ecosystems (Gu *et al.* 2002, Mercado *et al.* 2009, Cirino *et al.* 2014, Ezhova *et al.* 2018). Kulmala *et al.* (2013a) combined this idea with the work by Kulmala *et al.* (2004c), and introduced the so-called continental biosphere-aerosol-cloud-climate (COBACC) feedback mechanism. This mechanism has two partly overlapping feedback loops, both initiated by higher atmospheric CO<sub>2</sub> concentrations, and both of them having a suppressing effect on global warming (Fig. 1). The overlapping part of the two loops is related to higher atmospheric aerosol loadings due to higher BVOC emissions in a world with higher CO<sub>2</sub> concentrations and ambient temperatures.

The latest development in our feedback work is the introduction of the concept CarbonSink+ (Kulmala *et al.* 2020). It builds on the idea of using forest management in climate change mitigation (e.g. Grassi *et al.* 2017), with a couple of new extensions. More specifically, CarbonSink+ aims to take into account: 1) the influences of changing atmospheric composition on the forest carbon uptake over time scales comparable to typical afforestation or reforestation activities; and 2) the combined climatic effects by which forests act as a carbon sink and change either the surface albedo or atmospheric aerosol loading. Using the boreal forest environment as an illustrative example, Kulmala *et al.* (2020) and Kalliokoski *et al.* (2020) demonstrated the importance of considering all these factors when mitigating the climate change through forest management.

### Lessons from long-term observations

Our CoE has vast experience in using observational data for investigating the different parts of the COBACC feedback mechanism discussed in the previous section. Using several years of particle number size distribution measurements from three sites, Tunved *et al.* (2006) were able to establish a firm link between summer-time aerosol concentrations inside the boreal forest zone and SOA formation associated with BVOC emissions from the forest. Later we showed that, due to the strong response of BVOC emissions to the ambient temperature, higher temperatures lead to larger aerosol loadings in a boreal forest environment (Paasonen *et al.* 2013, Liao *et al.* 2014, Lihavainen *et al.* 2015).

Closing the original branch of the COBACC feedback mechanism requires estimating the radiative effect associated with biogenic SOA formation and its response to increasing ambient temperatures. We have estimated this radiative effect due to both aerosol-cloud and aerosol-radiation interactions using different measurement data sets (Kurtén *et al.* 2003, Lihavainen *et al.* 2009, Paasonen *et al.* 2013). For the cloud albedo feedback due to biogenic secondary organic aerosol, Paasonen *et al.* (2013) derived local estimates in the range from  $-0.4 \text{ W m}^{-2} \text{ K}^{-1}$

to  $-0.7 \text{ W m}^{-2} \text{ K}^{-1}$  at four boreal forest sites, and the global value of about  $-0.01 \text{ W m}^{-2} \text{ K}^{-1}$ . Lihavainen *et al.* (2015) investigated the feedback due aerosol-radiation interactions in a boreal forest site, and derived a feedback strength that was clearly smaller than the corresponding cloud albedo feedback.

The strength of the feedback loop related to carbon uptake in the COBACC feedback mechanism was estimated first by Kulmala *et al.* (2014). They found a potentially large gain for this feedback in the boreal forest environment, however with a large uncertainty range. In SMEAR II, a 10% increase in ecosystem GPP driven by increased atmospheric  $\text{CO}_2$  concentration led to a significant positive feedback to GPP by increasing atmospheric particle growth rate due to organic vapours (+7.3%), the amount of biogenic secondary organic aerosols measured with condensation sink (+6.5%), the ratio between the diffuse and global radiation (+8.5%) and finally the GPP (+3%, Kulmala *et al.* 2014). However, in a more recent analysis Launiainen *et al.* (2022) found that only 30–40% of the observed ecosystem GPP increase over 2001–2017 could be attributed to  $\text{CO}_2$  fertilization at SMEAR II. Ezhova *et al.* (2018) used measurement data from five boreal and hemi-boreal sites, and found that the presence of atmospheric aerosols can increase the carbon uptake by photosynthesis by up to 10–15% under clear sky conditions. Recently, Yli-Juuti *et al.* (2021) presented direct evidence on the COBACC feedback mechanism utilizing long term in situ aerosol composition measurements and remote sensing on aerosol and cloud properties. Their results show a significant negative feedback of  $-0.63 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$  from temperature-dependent BSOA formation via strengthening of both direct and cloud albedo effects of aerosols. The cooling effect of the feedback equals to  $\sim 18\%$  of the current effective radiative forcing of anthropogenic aerosols over boreal forest area in summer (Yli-Juuti *et al.* 2021).

Quantification of the different parts of this feedback loop using measurement data alone, or the overall strength of this feedback, has turned out to be difficult. The main reason for this are challenges in controlling the influences of factors other than those originally ascribed to this

feedback, including the presence of clouds or anthropogenic pollutants, and possible synergistic effects caused by the ambient temperature or some other meteorological variables.

## Model investigations

Model simulations have been used widely to study climate feedbacks (e.g. Carslaw *et al.* 2010, Webb *et al.* 2013, Hu *et al.* 2020). The advantage of this approach over observations is a better control of the factors and processes influencing the studied feedback, and a possibility to make future predictions. The drawback is that models include only a subset of all the processes operating in the Earth system, so it is possible that a model simulation could miss some factor having an important influence on a feedback.

The first global modeling effort by our CoE ATM was related to the COBACC feedback mechanism and was conducted by Makkonen *et al.* (2012b), who demonstrated that the radiative effect caused by biogenic SOA is sensitive to BVOC emissions and atmospheric new particle formation under both present-day conditions and in the future. Scott *et al.* (2014) diagnosed climate feedbacks caused by terrestrial natural aerosols from global model simulations. Their global estimate on the climate feedback caused by biogenic SOA was  $-0.03 \text{ W m}^{-2} \text{ K}^{-1}$ , dominated by aerosol-radiation interactions, while the part of this feedback caused by the cloud albedo effect was similar to the observation-based estimate by Paasonen *et al.* (2013) (see Sect. 3.7.2). Using a global aerosol-climate model, Arneth *et al.* (2016) found a global cloud radiative forcing of  $-0.03 \text{ W m}^{-2}$  due to about 40% increase of BVOC, although the forcing was much stronger ( $-0.50 \text{ W m}^{-2}$ ) over the Eastern Siberian study region. In Boy *et al.* (2019), a coupled atmosphere-ocean-land model was used to quantify BVOC-aerosol feedback in an idealized doubled  $\text{CO}_2$  concentration. Over boreal forest, monoterpene emissions increased from 18 to 28  $\text{Tg yr}^{-1}$  leading to increased aerosol and cloud droplet number concentrations. Sporre *et al.* (2019) used an Earth system model to investigate the whole COBACC feedback mechanism and found it to have a significant impact on climate. They did

not find any boost in the global carbon uptake by photosynthesis (GPP) associated with the lower branch of the COBACC feedback, probably because BSOA effects on clouds seemed to dominate the simulated changes in GPP. Finally, using three Earth system models, Sporre *et al.* (2020) showed that the radiative effects by biogenic SOA are sensitive to how BVOC and resulting SOA treated in the models.

In addition to biogenic SOA, concentrations and thereby radiative effects of many other natural aerosol types change with changing climate (Carslaw *et al.* 2010). Model simulations by Korhonen *et al.* (2010) indicate that the increased wind speeds associated with the observed acceleration of the westerly jet in the Southern Hemisphere have caused higher sea spray aerosol flux from the Southern Ocean to the atmosphere since 1980's, resulting in a substantial negative climate feedback. Scott *et al.* (2014) estimated that in a warming climate, the climate feedback due to increased forest fire aerosol emissions could be even higher than the feedback due to increased biogenic SOA formation.

Anthropogenic contribution to the future atmospheric aerosol load is very likely to decrease as a result of air pollution control, which is likely to have strong climatic implications (Brasseur and Roeckner 2005, Partanen *et al.* 2018, Samset 2018). Our CoE was among the first ones to show that air pollution control can cause accelerated warming in the future, and that this effect is coupled with the future behavior of the natural aerosol system (Makkonen *et al.* 2012c). We also investigated how different air pollution control strategies would influence near-future changes in aerosol radiative effects (Pietikäinen *et al.* 2015). The results showed that from a climate warming point of view, targeted emission reduction measures would be a much better choice than overall high reductions globally.

Global model studies provide insight that there is potential for strong Earth system feedbacks via biogenic aerosols influencing climate projections of the 21st century. Strong BVOC emission increases are predicted in at least some global emission models of gases and aerosols from nature (MEGAN-based models, e.g. Sporre

*et al.* 2019), although the response in some process-based dynamic vegetation-terrestrial ecosystem models (e.g. LPJ-GUESS) or other model approaches might yield lower emission response under future pathways (e.g. Makkonen *et al.* 2012b). While models agree fairly well in aerosol concentration and optical depth responses to simple BVOC perturbations (Sporre *et al.* 2020), results remain mixed when analyzing the changes in aerosol size distributions, CCN concentrations or cloud properties. Hence, the radiative flux perturbation related to BVOC increase varies significantly between models and can even be of opposite sign.

## Conclusions and future outlook

Feedback mechanisms are essential components of our climate system, as they either accelerate or slow down changes in climate-related quantities in the presence of external forcings. During the nearly two decades of CoE ATM work, combining the gained process level understanding with comprehensive, long-term field measurement enabled us to provide the first quantitative estimates regarding the COBACC feedback in boreal and hemi-boreal environments (Kulmala *et al.* 2014, Ezhova *et al.* 2018, Yli-Juuti *et al.* 2021). This feedback loop demonstrates how important biospheric processes are not only for carbon and aerosol budgets, but also for the whole climate system, as the COBACC feedback mitigates global warming, thereby giving the mankind a window of opportunity to reduce global carbon emissions. It is important to find out how important this feedback loop is globally and particularly in the boreal and arctic environments. The strength of the COBACC feedback is connected tightly with the functioning of the biosphere, including the observed yet poorly understood greening and other vegetation changes currently taking place in boreal and arctic environments (Buermann *et al.* 2014, Pearson *et al.* 2013, Reich *et al.* 2015). Therefore, more long-term measurements are needed globally to understand and quantify the COBACC feedback loop in different climate regions and ecosystem types, and to predict how the ecosystem and atmosphere interaction

will change in the future. Our analysis demonstrated the power of using comprehensive field measurements in investigating the complicated couplings between the biosphere and atmosphere on one hand, and on the other hand, the need for complementary approaches relying on the combination of field data, satellite observations and model simulations.

Results from atmospheric research can also be directly applied to human health (Mielonen *et al.* 2015, Yang *et al.* 2018); in Finland the small particles in the atmosphere shorten the average lifetime expectancy by few months, but e.g. in China the effect is several years (Lelieveld *et al.* 2015). Climate change and poor air quality form a pair of problems that must be mitigated simultaneously in the coming decades. Changes in climate and air quality depend on both natural and man-made emissions, as well as various physical, chemical and biological processes occurring in the atmosphere, biosphere and at their interface. Air quality, trace gases, aerosols, and climate are tightly linked via atmospheric processes — e.g. reduction of aerosol emissions causes additional warming due to a reduction in scattering of radiation and changes in cloud properties (Kulmala 2015). On the other hand, absorbing and toxic carbonaceous aerosols increase warming and simultaneously cause health effects. Poor understanding of the atmospheric interactions may thus lead to unwanted climate impacts and various negative health effects (Fiore *et al.* 2012, Fuzzi *et al.* 2015, Kulmala 2015). The fact that new particle formation does occur in polluted Chinese megacities like Beijing and Shanghai (Chu *et al.* 2019, Kulmala *et al.* 2021a) suggests that there are several major physical and chemical mechanisms in a heavily-polluted atmosphere that have not been recognized before and may not even operate in clean or moderately-polluted environments. This requires contributions from a new type of science that links disciplines, knowledge systems and societal partners to support a more agile innovation system. Thus, we are directing increasing efforts to study air quality and its feedbacks with atmospheric processes in the era after the CoE ATM. The work of the CoE ATM community continues in a new Atmosphere and Climate Competence Center (ACCC) flagship.

*Acknowledgements:* We warmly acknowledge the work of the whole Center of Excellence community and our collaborators in producing the research that was reviewed in the article. We thank the scientific advisory board of the Center of Excellence: Ruprecht Jaenicke, Anna Rutgersson and Ronald C Cohen. We thank Timo Tuomivaara for his contribution in the science philosophy section of the review. The work was funded by the Academy of Finland Centre of Excellence (grant no. 307331) and Research Flagship (grants no. 337549, 337550, 337551, 337552) programs.

## References

- Aalto J., Kolari P., Hari, P. Kerminen V. -M., Schiestl-Aalto P., Aaltonen H., Levula J., Siivola E., Kulmala M. & Bäck J. 2014. New foliage growth is a significant, unaccounted source for volatiles in boreal evergreen forests. *Biogeosciences* 11:5: 1331-1344.
- Aalto J., Porcar-Castell A., Atherton J., Kolari P., Pohja T., Hari P., Nikinmaa E., Petäjä T. & Bäck J. 2015. Onset of photosynthesis in spring speeds up monoterpene synthesis and leads to emission bursts. *Plant, Cell and Environment* 38:11: 2299-2312.
- Aalto P., Hämeri K., Becker E., Weber R., Salm J., Mäkelä J. M., Hoell C., O'Dowd C. D., Karlsson H., Hansson H. C., Väkevä M., Koponen I. K., Buzorius G. & Kulmala M. 2001. Physical characterization of aerosol particles during nucleation events. *Tellus B* 53: 344-358.
- Aaltonen H., Aalto J., Kolari P., Pihlatie M., Pumpanen J., Kulmala M., Nikinmaa E., Vesala T. & Bäck J. 2013. Continuous VOC flux measurements on boreal forest floor. *Plant and Soil* 369: 241-256.
- Agazzi, E. (2019) Systemic thinking. In: Mario Bunge: A Centenary Festschrift, ed. M.R. Matthews. Springer, Cham, Switzerland. p. 219-240.
- Agazzi, E. (2014) Scientific Objectivity and Its Contexts. Springer. 482 pp.
- Ahola J., Korhonen H., Tonttila J., Romakkaniemi S., Kokkola H. & Raatikainen T. 2020. Modelling mixed-phase clouds with the large-eddy model UCLALES-SALSA. *Atmos. Chem. Phys.* 20: 11639-11654.
- Alekseychik P., Mammarella I., Launiainen S., Rannik Ü. & Vesala T. 2013. Evolution of the nocturnal decoupled layer in the pine forest canopy. *Agricultural and Forest Meteorology* 174-175: 15-27.
- 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 Yu., Ding A., Guo H., Park S., Lavric J.V., Reum F., Panov A., Prokushkin A. & Kulmala M. 2016. Ground-based station network in arctic and subarctic Eurasia: An overview. *Geography, Environment, Sustainably* 9:2: 75-88.
- Alekseychik P., Katul G., Korpela I. & Launiainen, S. 2021a. Eddies in motion: visualizing boundary-layer turbulence above an open boreal peatland using UAS thermal videos. *Atmos. Meas. Tech.* 14: 3501-3521.

- Alekseychik P., Korrensalo A., Mammarella I., Launiainen S., Tuittila E.-S., Korpela I. & Vesala T. 2021b. Carbon balance of a Finnish bog: temporal variability and limiting factors based on 6 years of eddy-covariance data. *Biogeosciences* 18: 4681–4704.
- Almeida J., Schobesberger S., Kuerten A., Ortega Colomer I. K., Kupiainen O., Praplan A. P., Adamov A., Amorim A., Bianchi F., Breitenlechner M., David A., Dommen J., Donahue N. M., Downard A., Dunne E., Duplissy J., Ehrhart S., Flagan R. C., Franchin A., Guida R., Hakala J., Hansel A., Heinritzi M., Henschel H., Jokinen T., Junninen H., Kajos M., Kangasluoma J., Keskinen H., Kupc A., Kurten T., Kvashin A. N., Laaksonen A., Lehtipalo K., Leiminger M., Leppä J., Loukonen V., Makhmutov V., Mathot S., McGrath M. J., Nieminen T., Olenius T., Onnela A., Petäjä T., Riccobono F., Riipinen I., Rissanen M., Rondo L., Ruuskanen T., Santos F. D., Sarnela N., Schallhart S., Schnitzhofer R., Seinfeld J. H., Simon M., Sipilä M., Stozhkov Y., Stratmann F., Tome A., Troestl J., Tsagkogeorgas G., Vaattovaara P., Viisanen Y., Virtanen A., Vrtala A., Wagner P. E., Weingartner E., Wex H., Williamson C., Wimmer D., Ye P., Yli-Juuti T., Carslaw K. S., Kulmala M., Curtius J., Baltensperger U., Worsnop D. R., Vehkamäki H. & Kirkby J. 2013. Molecular understanding of sulphuric acid-amine particle nucleation in the atmosphere. *Nature* 502: 359–363.
- Altimir N., Kolari P., Tuovinen J.-P., Vesala T., Bäck J., Suni T., Kulmala M. & Hari P. 2006. Foliage surface ozone deposition: a role for surface moisture? *Biogeosciences* 3: 209–228.
- Anttila T., Vaattovaara P., Komppula M., Hyvärinen A.-P., Lihavainen H., Kerminen V.-M. & Laaksonen A. 2009. Size-dependent activation of aerosols into cloud droplets at a subarctic background site during the second Pallas Cloud Experiment (2nd PaCE): method development and data evaluation. *Atmos. Chem. Phys.* 9: 4841–4854.
- Anttila T., Brus D., Jaatinen A., Hyvärinen A.-P., Kivekäs N., Romakkaniemi S., Komppula M. & Lihavainen H. 2012. Relationships between particles, cloud condensation nuclei and cloud droplet activation during the third Pallas Cloud Experiment (PaCE-3). *Atmos. Chem. Phys.* 12: 11435–11450.
- Arneth A., Harrison S. P., Zaehe S., Tsigaridis K., Menon S., Bartlein P. J., Feichter J., Korhola A., Kulmala M., O'Donnell D., Schurgers G., Sorvari S. & Vesala T. 2010. Terrestrial biogeochemical feedbacks in the climate system. *Nature Geosci.* 3: 525–532.
- Arneth A., Makkonen R., Olin S., Paasonen P., Holst T., Kajos M. K., Kulmala M., Maximov T., Miller P. A. & Schurgers G. 2016. Future vegetation–climate interactions in Eastern Siberia: an assessment of the competing effects of CO<sub>2</sub> and secondary organic aerosols. *Atmos. Chem. Phys.* 16: 5243–5262.
- Arneth A., Unger N., Kulmala M. & Andreae M.O. 2009. Clean the air, heat the planet? *Science* 326: 672–673.
- Artaxo P., Hansson H.-C., Andreae M.O., Bäck J., Alves E.G., Barbosa H.M.J., Bender F., Bourtsoukidis E., Carbone S., Chi J., Decesari S., Després V.R., Ditas F., Ezhova E., Fuzzi S., Hasselquist N.J., Heintzenberg J., Holanda B.A., Guenther A., Hakola H., Heikkinen L., Kerminen V.-M., Kontkanen J., Krejci R., Kulmala M., Lavric J.V., de Leeuw G., Lehtipalo K., Machado L.A.T., McFiggans G., Franco M.A.M., Meller B.B., Morais F.G., Mohr C., Morgan W., Nilsson M.B., Peichl M., Petäjä T., Praß M., Pöhlker C., Pöhlker M.L., Pöschl U., Von Randow C., Riipinen I., Rinne J., Rizzo L.V., Rosenfeld D., Silva Dias M.A.F., Sogacheva L., Stier P., Swietlicki E., Sörgel M., Tunved P., Virkkula A., Wang J., Weber B., Yáñez-Serrano A.M., Zieger P., Mikhailov E., Smith J.N. & Kesselmeier J. 2022. Tropical and Boreal Forest–Atmosphere Interactions: A Review. *Tellus B: Chemical and Physical Meteorology* 74: 24–163.
- Asmi E., Sipilä M., Manninen H. E., Vanhanen J., Lehtipalo K., Gagné S., Neitola K., Mirme A., Mirme S., Tamm E., Uin J., Komsaare K., Attoui M. & Kulmala M. 2009. Results of the first air ion spectrometer calibration and intercomparison workshop. *Atmos. Chem. Phys.* 9: 141–154.
- Asmi E., Kivekäs N., Kerminen V.-M., Komppula M., Hyvärinen A.-P., Hatakka J., Viisanen Y. & Lihavainen H. 2011. Secondary new particle formation in Northern Finland Pallas site between the years 2000 and 2010. *Atmos. Chem. Phys.* 11: 12959–12972.
- Asmi E., Kondratyev V., Brus D., Laurila T., Lihavainen H., Backman J., Vakkari V., Aurela M., Hatakka J., Viisanen Y., Uttal T., Ivakhov V. & Makshtas A. 2016. Aerosol size distribution seasonal characteristics measured in Tiksi, Russian Arctic. *Atmospheric Chemistry and Physics* 16: 1271–1287.
- Atherton J., Nichol C.J. & Porcar-Castell A. 2016. Using spectral chlorophyll fluorescence and the photochemical reflectance index to predict physiological dynamics. *Remote Sensing of Environment* 176: 17–30.
- Atherton J., Olascoaga B., Alonso L. & Porcar-Castell A. 2017. Spatial variation of leaf optical properties in a boreal forest is influenced by species and light environment. *Frontiers in Plant Science* 8: 309.
- Atherton J., Liu W. & Porcar-Castell A. 2019. Nocturnal Light Emitting Diode Induced Fluorescence (LEDIF): A new technique to measure the chlorophyll a fluorescence emission spectral distribution of plant canopies in situ. *Remote Sensing of Environment* 231: 111137. <https://doi.org/10.1016/j.rse.2019.03.030>
- Aubinet M., Vesala T. & Papale D. (Eds.). 2012. Eddy covariance—A practical guide to measurement and data analysis. Springer, Dordrecht. 978-94-007-2350-4
- Aurela M., Riutta T., Laurila T., Tuovinen J.-P., Vesala T., Tuittila E.-S., Rinne J., Haapanala S. & Laine J. 2007. CO<sub>2</sub> exchange of a sedge fen in southern Finland - the impact of a drought period. *Tellus B: Chemical and Physical Meteorology* 59:5: 826–837.
- Aurela M., Lohila A., Tuovinen J.-P., Hatakka J., Penttilä T. & Laurila T. 2015a. Carbon dioxide and energy flux measurements on four different northern boreal ecosystems at Pallas. *Boreal Environment Research* 20: 455–473.
- Aurela M., Laurila T., Tuovinen J.-P., Hatakka J., Linkosalmi M., Virtanen T., Mikola J., Asmi E., Ivakhov V., Kondratyev V., Uttal T. & Makshtas A. 2015b. CH<sub>4</sub> and CO<sub>2</sub>



- exchange on permafrost tundra in Tiksi, Siberia. In: Kulmala M., Zilitinkevich S., Lappalainen H.K., Kyrö E.-M. & Kontkanen J. (eds.), Proceedings of the 1st Pan-Eurasian Experiment (PEEX) Conference and the 5th PEEX Meeting, *Report Series in Aerosol Science* 163: 60-62.
- Auvinen M., Järvi L., Hellsten A., Rannik Ü. & Vesala T. 2017. Numerical framework for the computation of urban flux footprints employing large-eddy simulation and Lagrangian stochastic modelling. *Geoscientific Model Development* 10: 4187-4205.
- Adamczyk B., Ahvenainen A., Sietiö O.-M., Kanerva S., Kieloaho A.-J., Smolander A., Kitunen V., Saranpää P., Laakso T., Strakova P. & Heinonsalo J. 2016. The contribution of ericoid plants to soil nitrogen chemistry and organic matter decomposition in boreal forest soil. *Soil Biology & Biochemistry* 103: 394-404.
- Adamczyk B., Sietiö O.-M., Biasi C. & Heinonsalo J. 2019a. Interaction between tannins and fungal necromass stabilizes fungal residues in boreal forest soils. *New Phytologist* 223: 16-21.
- Adamczyk B., Sietiö O.-M., Straková P., Prommer J., Wild N., Hagner M., Pihlatie M., Fritze H., Richter A. & Heinonsalo J. 2019b. Plant roots increase both decomposition and stable organic matter formation in boreal forest soil. *Nature Comm.* 10: 3982.
- Bäck J., Aalto J., Henriksson M., Hakola H., He Q. & Boy M. 2012. Chemodiversity of a Scots pine stand and implications for terpene air concentrations. *Biogeosciences* 9: 689-702.
- Bacour C., Maignan F., MacBean N., Porcar-Castell A., Flexas J., Frankenberg C., Peylin P., Chevallier F., Vuichard N. & Bastrikov V. 2019. Improving estimates of gross primary productivity by assimilating solar-induced fluorescence satellite retrievals in a terrestrial biosphere model using a process-based SIF model. *Journal of Geophysical Research: Biogeosciences* 124: 3281-3306.
- Bandy A. R. & Ianni J. C. 1998. Study of hydrates of H<sub>2</sub>SO<sub>4</sub> using density functional theory. *J. Phys. Chem. A* 102: 6533-6539.
- Barreira L. M. F., Duporté G., Parshintsev J., Hartonen K., Jussila M., Aalto J., Bäck J., Kulmala M. & Riekkola M.-L. 2017. Emissions of biogenic volatile organic compounds from the boreal forest floor and understory: a study by solid-phase microextraction and portable gas chromatography-mass spectrometry. *Boreal Env. Res.* 22: 393-413.
- Barth M., McFadden J. P., Sun J., Wiedinmayer C., Chuang P., Collins D., Griffin R., Hannigan M., Karl T., Kim S.-W., Lasher-Trapp S., Levis S., Litvak M., Mahowald N., Moore K., Nandi S., Nemitz E., Nenes A., Potosnak M., Raymod T. M., Smith J., Still C. & Stroud C. 2005. Coupling between land ecosystems and the atmospheric hydrologic cycle through biogenic aerosol pathways. *Bull. Am. Meteor. Soc.* 86:12: 1738-1742.
- Beck L., Sarnela N., Junninen H., Hoppe C. J. M., Garmash O., Bianchi F., Riva M., Rose C., Peräkylä O., Wimmer D., Kausiala O., Jokinen T., Ahonen L., Mikkilä J., Hakala J., He H.-U., Kontkanen J., Wolf K. K. E., Capelletti D., Mazzola M., Traversi R., Petroselli C., Viola A. P., Vitale V., Lange R., Massling A., Nojgaard J. K., Krejci R., Karlsson L., Zieger P., Jang S., Lee K., Vakkari V., Lampilahti J., Thakur R. C., Leino K., Kangasluoma J., Duplissy E.-M., Siivola E., Marbouti M., Tham Y. J., Saiz-Lopez A. Petäjä T., Ehn M., Worsnop D. R., Skov H., Kulmala M., Kerminen V.-M. & Sipilä M. 2021. Differing mechanisms of new particle formation at two arctic sites. *Geophys. Res. Lett.* 48: e2020GL091334.
- Beichert P. & Schrems O. 1998. Complexes of Sulfuric Acid with Hydrogen Chloride, Water, Nitric Acid, Chlorine Nitrate, and Hydrogen Peroxide: An ab Initio Investigation. *J. Phys. Chem. A* 102: 10540-10544.
- Beniston M. 2013. Grand challenges in climate research. *Frontiers in Environmental Science* 1:1 <https://doi.org/10.3389/fenvs.2013.00001>
- Besel V., Kubecka J., Kurten T. & Vehkamäki H. 2020. Impact of Quantum Chemistry Parameter Choices and Cluster Distribution Model Settings on Modeled Atmospheric Particle Formation Rates. *Journal of Physical Chemistry A* 124:28: 5931-5943.
- Bianchi F., Kurtén T., Riva M., Mohr C., Rissanen M.P., Roldin P., Berndt T., Crounse J.D., Wennberg P.O., Mentel T.F., Wildt J., Junninen H., Jokinen T., Kulmala M., Worsnop D.R., Thornton J.A., Donahue N., Kjaergaard H.G. & Ehn M. 2019. Highly oxygenated organic molecules (HOM) from gas-phase autoxidation involving peroxy radicals: a key contributor to atmospheric aerosol. *Chem. Rev.* 119:6: 3472-3509.
- Bianchi F., Junninen H., Bigi A., Sinclair V. A., Dada L., Hoyle C. R., Zha Q., Yao L., Ahonen L. R., Bonasoni P., Buenrostro Mazon S., Hutterli M., Laj P., Lehtipalo K., Kangasluoma J., Kerminen V.-M., Kontkanen J., Marinoni A., Mirme S., Molteni U., Petäjä T., Riva M., Rose C., Sellegri K., Yan C., Worsnop D. R., Kulmala M., Baltensperger U. & Dommen, J. 2021. Biogenic particles formed in the Himalaya as an important source of free tropospheric aerosols. *Nature Geosci.* 14: 4-9.
- Bond T.C. & Bergstrom R.W. 2006. Light absorption by carbonaceous particles: an investigative review. *Aerosol Sci. Technol.* 40: 27-67.
- Bony S., Colman R., Kattsov V. M., Allan R. P., Bretherton C. S., Dufresne J.-L., Hall A., Hallegatte S., Holland M. M., Ingram W., Randall D. A., Soden B. J., Tselioudis G. & Webb M. J. 2006. How well do we understand and evaluate climate change feedback processes? *J. Climate* 19: 3445-3482.
- Boutle I., Price J., Kudzotsa I., Kokkola H. & Romakkaniemi S. 2018. Aerosol-fog interaction and the transition to well-mixed radiation fog. *Atmos. Chem. Phys.* 18: 7827-7840.
- Boy M., Thomson E. S., Acosta Navarro J.-C., Arnalds O., Batchvarova E., Bäck J., Berninger F., Bilde M., Brasseur Z., Dagsson-Waldhauserova P., Castarède D., Dalirian M., de Leeuw G., Dragosics M., Duplissy E.-M., Duplissy J., Ekman A. M. L., Fang K., Gallet J.-C., Glasius M., Gryning S.-E., Grythe H., Hansson H.-C., Hansson M., Isaksson E., Iversen T., Jonsdottir I., Kasurinen V., Kirkevåg I., Korhola A., Krejci R., Krist-

- jansson J. E., Lappalainen H., Lauri A., Leppäranta M., Lihavainen H., Makkonen R., Massling A., Meinander O., Nilsson E. D., Olafsson H., Pettersson J. B. C., Prisle N. L., Riipinen I., Roldin P., Ruppel M., Salter M., Sand M., Seland Ø., Seppä H., Skov H., Soares J., Stohl A., Ström J., Svensson J., Swietlicki E., Tabakova K., Thorsteinsson T., Virkkula A., Weyhenmeyer G. A., Wu Y., Zieger P. & Kulmala M. 2019. Interactions between the atmosphere, cryosphere and ecosystems at northern high latitudes. *Atmos. Chem. Phys.* 19: 2015-2061.
- Brando, P. M. Balch J. K., Nepstad D. C., Morton D. C., Putz F. E., Coe M. T., Silvério D., Macedo M. N., Davidson E. A., Nóbrega C. C., Alencar A. & Soares-Filho B. S. 2014. Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proc. Natl. Acad. Sci.* 111:17: 6347-6352.
- Brasseur G. P. & Roeckner E. 2005. Impact of improved air quality on the future evolution of climate. *Geophys. Res. Lett.* 32: L23704. doi:10.1029/2005GL023902
- Brodribb T.J., Powers J., Cochard H., Choat B. 2020. Hanging by a thread? Forests and drought. *Science* 368: 261-266.
- Brus D., Hyvärinen A.-P., Wedekind J., Viisanen Y., Kulmala M., Zdimal V., Smolik J. & Lihavainen H. 2008. The homogeneous nucleation of 1-pentanol in a laminar flow diffusion chamber: The effect of pressure and kind of carrier gas. *J. Chem. Phys.* 128, 134312.
- Brus D. Hyvärinen A.-P., Viisanen Y., Kulmala M. & Lihavainen H. 2010. Homogeneous nucleation of sulfuric acid and water mixture: experimental setup and first results. *Atmos. Chem. Phys.* 10: 2631-2641.
- Buermann W., Parida B., Jung M., MacDonald G.M., Tucker C.J. & Reichstein M. 2014. Recent shift in Eurasian boreal forest greening response may be associated with warmer and drier summers. *Geophysical Research Letters* 41: 1995-2002.
- Bunge, M. (2018) From a scientific point of view: Reasoning and evidence beat improvisation across fields. Cambridge Scholars Publishing, UK. 169 pp.
- Bunge, M. (2006) Chasing reality: Strife over realism. University of Toronto press, Canada. 384 pp.
- Cai R., Yan C., Yang D., Yin R., Lu Y., Deng C., Fu Y., Ruan J., Li X., Kontkanen J., Zhang Q., Kangasluoma J., Ma Y., Hao J., Worsnop D. R. Bianchi F., Paasonen P., Kerminen V.-M., Liu Y., Wang L., Zheng J., Kulmala M. & Jian J. 2021. Sulfuric acid-amine nucleation in urban Beijing. *Atmos. Chem. Phys.* 21: 2457-2468.
- Carslaw K. S., Boucher O., Spracklen D. V., Mann G. W., Rae J. G. L., Woodward S. & Kulmala M. 2010. A review of natural aerosol interactions and feedbacks within the Earth system. *Atmos. Chem. Phys.* 10: 1701-1737.
- Ceppi P., Briant F., Zelinka M. D. & Hartmann D. L. 2017. Cloud feedback mechanisms and their representation in global climate models. *WIREs Clim. Change* 8: e465. <https://doi.org/10.1002/wcc.465>
- Chan T., Hölttä T., Berninger F., Mäkinen H., Nöjd P., Mencuccini M. & Nikinmaa E. 2016. Separating water-potential induced swelling and shrinking from measured radial stem variations reveals a cambial growth and osmotic concentration signal. *Plant, Cell & Environment* 39:2: 233-244.
- Chan T., Berninger F., Koları P., Nikinmaa E. & Hölttä T. 2018. Linking stem growth respiration to the seasonal course of stem growth and GPP of Scots pine. *Tree Physiology* 38: 1356-1370.
- Charlson, R. J., Lovelock J. E., Andreae M. O. & Warren S. G. 1987. Oceanic phytoplankton, atmospheric Sulphur, cloud albedo and climate. *Nature* 326: 655-661.
- Chu B., Kerminen V.-M., Bianchi F., Yan C., Petäjä T. & Kulmala M. 2019. Atmospheric new particle formation in China. *Atmos. Chem. Phys.* 19: 115-138.
- Cirino G. G. Souza, R. A. F., Adams D. K. & Artaxo P. 2014. The effect of atmospheric aerosol particles and clouds on net ecosystem exchange in the Amazon. *Atmos. Chem. Phys.* 14: 6523-6543.
- Colliander A., Jackson T., Bindlish R., Chan S., Das N., Kim S., Cosh M., Dunbar R., Dang L., Pashaian L., Asanuma J., Aida K., Berg A., Rowlandson T., Bosch D., Caldwell T., Caylor K., Goodrich D., al Jassar H., Lopez-Baeza E., Martínez-Fernández J., González-Zamora A., Livingston S., McNairn H., Pacheco A., Moghaddam M., Montzka C., Notarnicola C., Niedrist G., Pellarin T., Prueger J., Pulliainen J., Rautiainen K., Ramos J., Seyfried M., Starks P., Su Z., Zeng Y., van der Velde R., Thibeault M., Dorigo W., Vreugdenhil M., Walker J., Wu X., Moneris A., O'Neill P., Entekhabi D., Njoku E., Yueh S. 2017. Validation of SMAP surface soil moisture products with core validation sites. *Remote Sensing of Environment* 191: 215-231.
- Crouse J.D., Nielsen L.B., Jørgensen S., Kjaergaard H.G. & Wennberg P.O. 2013. Autoxidation of organic compounds in the atmosphere. *J. Phys. Chem. Lett.* 4: 3513-3520.
- Dada L., Chellapermal R., Buenrostro Mazon S., Paasonen P., Lampilahti J., Manninen H. E., Junninen H., Petäjä T., Kerminen V.-M. & Kulmala M. 2018. Refined classification and characterization of atmospheric new-particle formation events using air ions. *Atmos. Chem. Phys.* 18: 17883-17893.
- Dal Maso M., Kulmala M., Riipinen I., Wagner R., Hussein T., Aalto P. P. & Lehtinen K. E. J. 2005. Formation and growth of fresh atmospheric aerosol: eight years of aerosol size distribution data from SMEAR II, Hyytiälä, Finland. *Boreal Env. Res.* 10: 323-336.
- DePalma J. W., Doren D. J. & Johnston M.V. 2014. Formation and growth of molecular clusters containing sulfuric acid, water, ammonia, and dimethylamine. *J. Phys. Chem. A* 118: 5464-5473.
- Després V., Huffman J. A., Burrows S. M., Hoose C., Safatov A., Buryak G., Fröhlich-Nowoisky J., Elbert W., Andreae M., Pöschl U. & Jaenicke R. 2012. Primary biological aerosol particles in the atmosphere: a review. *Tellus B: Chemical and Physical Meteorology* 64: 15598.
- Ding A.J., Fu C.B., Yang X.Q., Sun J.N., Petäjä T., Kerminen V.-M., Wang T., Xie Y., Herrmann E., Zheng L.F., Nie W., Liu Q., Wei X.L. & Kulmala M. 2013a. Intense atmospheric pollution modifies weather: a case of mixed biomass burning with fossil fuel combustion pollution

- in eastern China. *Atmos. Chem. Phys.* 13: 10545-10554.
- Ding A.J., Fu C. B., Yang X. Q., Sun J. N., Zheng L. F., Xie Y. N., Herrmann E., Nie W., Petäjä T., Kerminen V.-M. and Kulmala M. 2013b. Ozone and fine particle in the western Yangtze River Delta: and overview of 1 yr data at the SORPES station. *Atmos. Chem. Phys.* 13: 5813-5830.
- Ding A.J., Huang X., Nie W., Sun J.N., Kerminen V.-M., Petäjä T., Su H., Cheng 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. & Fu C.B. 2016a. Enhanced haze pollution by black carbon in megacities in China. *Geophysical Research Letters* 43: 2873-2879.
- Ding A.J., Nie W., Huang X., Chi. X., Sun J., Kerminen V.-M., Xu Z., Guo W., Petäjä T., Yang X., Kulmala M. & Fu G. 2016b. Long-term observation of pollution-weather/climate interactions at the SORPES station: a review and outlook. *Front. Environ. Sci. Eng.* 10: 15.
- Ding Y., Schiestl-Aalto P., Helmisari H.-S., Makita N., Ryhti K. & Kulmala L. 2020. Temperature and moisture dependence of daily growth of Scots pine (*Pinus sylvestris* L.) roots in Southern Finland. *Tree Physiology* 40:2: 272-283.
- Dufresne J. & Bony S. 2008. An assessment of the primary sources of spread of global warming estimates from coupled atmosphere-ocean models. *Journal of Climate* 21: 5135-5144.
- Dunne E., Gordon H., Kürten A., Almeida J., Duplissy J., Williamson C., Ortega I.K., Pringle K.J., Adamov A., Baltensperger U., Barmet P., Benduhn F., Bianchi F., Breitenlechner M., Clarke A., Curtius J., Dommen J., Donahue N.M., Erhart S., Flagan R.C., Franchin A., Guida R., Hakala J., Hansel A., Heinrzi M., Jokinen T., Kangasluoma J., Kirkby J., Kulmala M., Kupc A., Lawler M.J., Lehtipalo K., Makhmutov V., Mann G., Mathot S., Merikanto J., Miettinen P., Nenes A., Onnela A., Rap A., Reddington C.L.S., Riccobono F., Richards N.A.D., Rissanen M., Rondo L., Sarnela N., Schobesberger S., Sengupta K., Simon M., Sipilä M., Smith J.N., Stozkhov Y., Tomé A., Tröstl J., Wanger P.E., Wimmer D., Winkler P.M., Worsnop D.R. & Carslaw K.S. 2016. Global atmospheric particle formation from CERN CLOUD measurements. *Science* 6316: 1119-1124.
- Duporté G., Parshintsev J., Barreira L. M. F., Hartonen K., Kulmala M. & Riekkola M.-L. 2016. Nitrogen-Containing Low Volatile Compounds from Pinonaldehyde-Dimethylamine Reaction in the Atmosphere: A Laboratory and Field Study. *Environ. Sci. Technol.* 50: 4693-4700.
- Duporté G., Riva M., Parshintsev J., Heikkinen E., Barreira L. M. F., Myllys N., Heikkinen L., Hartonen K., Kulmala M., Ehn M. & Riekkola M.-L. 2017. Chemical Characterization of Gas- and Particle-Phase Products from the Ozonolysis of  $\alpha$ -Pinene in the Presence of Dimethylamine. *Environ. Sci. Technol.* 51: 5602-5610.
- Duursma R., Kolari P., Perämäki M., Nikinmaa E., Hari P., Delzon S., Loustau D., Ilvesniemi H., Pumpanen J., Mäkelä A. 2008. Predicting the decline in daily maximum transpiration rate of two pine stands during drought based on constant minimum leaf water potential and plant hydraulic conductance. *Tree Physiology* 28: 265-276.
- Ehn M., Junninen H., Petäjä T., Kurtén T., Kerminen V.-M., Schobesberger S., Manninen H.E., Ortega I.K., Vehkamäki H., Kulmala M. & Worsnop D.R. 2010. Composition and temporal behavior of ambient ions in the boreal forest. *Atmos. Chem. Phys.* 10: 8513-8530.
- Ehn M., Thornton J. A., Kleist E., Sipilä M., Junninen H., Pullinen I., Springer M., Rubach F., Tillmann R., Lee B., Lopez-Hilfiker F., Andres S., Acir I-H. , Rissanen M. P., Jokinen T., Schobesberger S., Kangasluoma J., Kontkanen J., Nieminen T., Kurtén T., Nielsen L. B., Jorgensen S., Kjaergaard H. G., Canagaratna M., Dal Maso M., Berndt T., Petäjä T., Wahner A., Kerminen V.-M., Kulmala M., Worsnop D. R., Wildt J. & Mentel T. F. 2014. A large source of low-volatility secondary organic aerosol. *Nature* 506: 476-479.
- Elbert W., Taylor P. E., Andreae M. O. & Pöschl U. 2007. Contribution of fungi to primary biogenic aerosols in the atmosphere: wet and dry discharged spores, carbohydrates, and inorganic ions. *Atmos. Chem. Phys.* 7: 4569-4588.
- Elm J. 2019. Unexpected growth coordinate in large clusters consisting of sulfuric acid and C<sub>8</sub>H<sub>2</sub>O<sub>6</sub> tricarboxylic acid. *J. Phys. Chem. A* 123: 3170-3175.
- Elm J., Kubečka J., Besel V. Jääskeläinen M. J., Halonen R., Kurtén T. & Vehkamäki H. 2020. Modelling the Formation and Growth of Atmospheric Molecular Clusters: A Review. *J. Aerosol Sci.* 149: 105621.
- Erkkilä K.-M., Ojala A., Bastviken D., Biermann T., Heiskanen J. J., Lindroth A., Peltola O., Rantakari M., Vesala T. & Mammarella I. 2018. Methane and carbon dioxide fluxes over a lake: comparison between eddy covariance, floating chambers and boundary layer method. *Biogeosciences* 15:2: 429-445.
- Ervens B. 2015. Modeling the processing of aerosol and trace gases in clouds and fogs. *Chem. Rev.* 115: 4157-4198.
- 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. & Kulmala M. 2018. Direct effect of aerosols on solar radiation and gross primary production in boreal and hemiboreal forests. *Atmos. Chem. Phys.* 18: 17863-17881.
- Ezhova E., Orlov D., Suhonen E., Kaverin D., Mahura A., Gennadinik V., Kukkonen I., Drozdov D., Lappalainen H. K., Melnikov V., Petäjä T., Kerminen V.-M., Zilitinkevich S., Malkhazova S. M., Christensen T. R. & Kulmala M. 2021. Climatic Factors Influencing the Anthrax Outbreak of 2016 in Siberia, Russia. *EcoHealth* 18:2: 217-228.
- Estillore A. D., Trueblood J. V. & Grassian V. H. 2016. Atmospheric chemistry of bioaerosols: heterogeneous and multiphase reactions with atmospheric oxidants and other trace gases. *Chem. Sci.* 7: 6604-6616.
- Field P. R. & Heymsfield A. J. 2015. Importance of snow to global precipitation. *Geophys. Res. Lett.* 42: 9512-9520.
- Fierce L., Onasch T. B., Cappa C. D., Mazzoleni C., China

- S., Bhandari J., Davidovits P., Fischer D. A., Helgestad T., Lambe A. T., Sedlacek III A. J., Smith G. D. & Wolff L. 2020. Radiative absorption enhancements by black carbon controlled by particle-to-particle heterogeneity in composition. *PNAS* 117: 5196–5203.
- Fiore A.M., Naik V., Spracklen D.M., Steiner A., Unger N., Prather M., Bergmann D., Cameron-Smith P.J., Cionni L., Collins W.J., Dalsøren S., Eyring V., Folberth G.A., Ginoux P., Horowitz L.W., Josse B., Lamarque J.-F., MacKenzie I.A., Nagashima T., O'Connor F.M., Righi M., Rumbold S.T., Shindell D.T., Skeie R.B., Sudo K., Szopa S., Takemura T. & Zeng G. 2012. Global air quality and climate. *Chem. Soc. Rev.* 41: 6663–6683.
- Franz D., Acosta M., Altimir N., Arriga N., Arrouays D., Aubinet M., Aurela M., Ayres E., López-Ballesteros A., Barbaste M., Berveiller D., Biraud S., Boukir H., Brown T., Brümmner C., Buchmann N., Burba G., Carrara A., Cescatti A., Ceschia E., Clement R., Cremonese E., Crill P., Darenova E., Dengel S., D'Odorico P., Gianluca F., Fleck S., Fratini G., Fuß R., Gielen B., Gogo S., Grace J., Graf A., Grellé A., Gross P., Grünwald T., Haapanala S., Hehn M., Heinesch B., Heiskanen J., Herbst M., Herschlein C., Hörtnagl L., Hufkens K., Ibrom A., Jolivet C., Joly L., Jones M., Kiese R., Klemmedtsson L., Kljun N., Klumpp K., Kolari P., Kolle O., Kowalski A., Kutsch W., Laurila T., De Ligne A., Linder S., Lindroth A., Lohila A., Longdoz B., Mammarella I., Manise T., Marañon-Jimenez S., Matteucci G., Mauder M., Meier P., Merbold L., Mereu S., Metzger S., Migliavacca M., Mölder M., Montagnani L., Moureaux C., Nelson D., Nemitz E., Nicolini G., Nilsson M.B., Op de Beek M., Osborne B., Ottosson Löfvenius M., Pavelka M., Peichl M., Peltola O., Pihlatie M., Pitacco A., Pokorný R., Pumpanen J., Ratié C., Schrumpf M., Sedláč P., Serrano Ortiz P., Siebicke L., Šigut L., Silvennoinen H., Simioni G., Skiba U., Sonntag O., Soudani K., Soulé P., Steinbrecher R., Tallec T., Thimonier A., Tuittila E., Tuovinen J., Vestin P., Vincent G., Vincke C., Vitale D., Waldner P., Weslien P., Wingate L., Wohlfahrt G., Zahniser M. & Vesala T. 2018. Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe's terrestrial ecosystems: a review. *Int. Agrophys.* 32: 439–455.
- Franchin A., Ehrhart S., Leppä J., Nieminen T., Gagné S., Schobesberger S., Wimmer D., Duplissy J., Riccobono F., Dunne E. M., Rondo L., Downard A., Bianchi F., Kupc A., Tsakogeorgas G., Lehtipalo K., Manninen H. E., Almeida J., Amorim A., Wagner P. E., Hansel A., Kirkby J., Kürten A., Donahue N. M., Makhmutov V., Mathot S., Metzger A., Petäjä T., Schnitzhofer R., Sipilä M., Stozhkov Y., Tomé A., Kerminen V.-M., Carslaw K., Curtius J., Baltensperger U. & Kulmala M. 2015. Experimental investigation of ion-ion recombination under atmospheric conditions. *Atmos. Chem. Phys.* 15: 7203–7216.
- Friedlingstein P., O'Sullivan M., Jones M. W., Andrew R. M., Hauck J., Olsen A., Peters G. P., Peters W., Pongratz J., Sitch S., Le Quéré C., Canadell J. G., Ciais P., Jackson R. B., Alin S., Aragão L. E. O. C., Arneeth A., Arora V., Bates N. R., Becker M., Benoit-Cattin A., Bittig H. C., Bopp L., Bultan S., Chandra N., Chevallier F., Chini L. P., Evans W., Florentie L., Forster P. M., Gasser T., Gehlen M., Gilfillan D., Gkritzalis T., Gregor L., Gruber N., Harris I., Hartung K., Haverd V., Houghton R. A., Ilyina T., Jain A. K., Joetjzer E., Kadono K., Kato E., Kitidis V., Korsbakken J. I., Landschützer P., Lefèvre N., Lenton A., Lienert S., Liu Z., Lombardozzi D., Marland G., Metzl N., Munro D. R., Nabel J. E. M. S., Nakaoka S.-I., Niwa Y., O'Brien K., Ono T., Palmer P. I., Pierrot D., Poulter B., Resplandy L., Robertson E., Rödenbeck C., Schwinger J., Séférian R., Skjelvan I., Smith A. J. P., Sutton A. J., Tanhua T., Tans P. P., Tian H., Tilbrook B., van der Werf G., Vuichard N., Walker A. P., Wanninkhof R., Watson A. J., Willis D., Wiltshire A. J., Yuan W., Yue X. & Zaehle S. 2020. Global Carbon Budget 2020. *Earth Syst. Sci. Data* 12: 3269–3340.
- Fröhlich-Nowoisky J., Kampf C. J., Weber B., Huffman J. A., Pöhlker C., Andreae M. O., Lang-Yona N., Burrows S. M., Gunthe S. S., Elbert W., Su H., Hoor P., Thines E., Hoffmann T., Després V. R. & Pöschl U. 2016. Bioaerosols in the earth system: climate, health, and ecosystem interactions. *Atmospheric Research.* 182: 346–376.
- Fuzzi S., Baltensperger U., Carslaw K., Decesari S., van der Gon H.D., Facchini M.C., Fowler D., Koren I., Langford B., Lohmann U., Nemitz E., Pandis S., Riipinen I., Rudich Y., Schaap M., Slowik J.G., Spracklen D.V., Vignati E., Wild M., Williams M. & Gilardoni S. 2015. Particulate matter, air quality and climate: lessons learned and future needs. *Atmos. Chem. Phys.* 15: 8217–8299.
- Gagne S., Lehtipalo K., Manninen H. E., Nieminen T., Schobesberger S., Franchin A., Yli-Juuti T., Boulon J., Sonntag A., Mirme S., Mirme A., Horrak U., Petäjä T., Asmi E. & Kulmala M. 2011. Intercomparison of air ion spectrometers: an evaluation of results in varying conditions. *Atmos. Meas. Tech.* 4: 805–822.
- Gea-Izquierdo G., Mäkelä A., Margolis H., Bergeron Y., Black A.T., Dunn A., Hadley J., Pa U. K.T., Falk M., Wharon S., Monson R., Hollinger D.Y., Laurila T., Aurela M., McCaughey H., Bourque C., Vesala T. & Berninger F. 2010. Modeling acclimation of photosynthesis to temperature in evergreen conifer forests. *New Phytologist* 188: 175–186.
- Ghirardo A., Koch K., Taipale R., Zimmer I., Schnitzler J.-P. & Rinne J. 2010. Determination of de novo and pool emissions of terpenes from four common boreal/alpine trees by <sup>13</sup>CO<sub>2</sub> labeling and PTR-MS analysis. *Plant, Cell & Environment* 33: 781–792.
- Golub M., Desai A.R., Vesala T., Mammarella I., Ojala A. et al. 2021. New insights into diel to interannual variation in carbon dioxide emissions from lakes and reservoirs. *Earth and Space Science Open Archive ESSOAr*; Jun 17, 2021. DOI:10.1002/essoar.10507313.1
- Gordon H., Kirkby J., Baltensperger U., Bianchi F., Breitenlechner M., Curtius J., Dias A., Dommen J., Donahue N. M., Dunne E. M., Duplissy J., Ehrhart S., Flagan R. C., Frege C., Fuchs C., Hansel A., Hoyle C. R., Kulmala M., Kürten A., Lehtipalo K., Makhmutov V., Molteni U., Rissanen M. P., Stozhkov Y., Tröstl J., Tsakogeorgas G., Wagner R., Williamson C., Wimmer D., Winkler P. M., Yan C. & Carslaw K. S. 2017. Causes and impor-

- tance of new particle formation in the present-day and preindustrial atmospheres. *J. Geophys. Res. Atmos.* 122: 8739–8760.
- Görke H., Neitola K., Hyvärinen A.-P., Lihavainen H., Wölk J., Strey R. & Brus D. 2014. Homogenous nucleation rates of n-propanol measured in the Laminar Flow Diffusion Chamber at different total pressures. *The Journal of Chemical Physics* 140: 174301. doi: 10.1063/1.4872364
- Gotz A., Petzold A., Asmi A., Blomberg N., Lamanna G. & Dekker Ron. 2020. ESFRI cluster projects - Position papers on expectations and planned contributions to the EOSC. Zenodo. <http://doi.org/10.5281/zenodo.3675081>
- Grassi G., House J., Dentener F., Federici S., den Elzen M. & Penman J. 2017. The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Clim. Change* 4: 3227–3230.
- Green J.K., Konings A.G., Alemohammad S.H., Berry J., Entekhabi D., Kolassa J., Lee J.E. & Gentine P. 2017. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. *Nature Geoscience* 10: 410–414.
- Gu L., Baldocchi D., Verma S. B., Black T. A., Vesala T., Falge E. M. & Dowty P. R. 2002. Advantages of diffuse radiation for terrestrial ecosystem productivity. *J. Geophys. Res.* 107: D6. doi: 10.1029/2001JD001242
- Guo S., Hu M., Zamora M. L., Peng J., Shang D., Zheng J., Du Z., Wu Shao M., Zeng L., Molina M. J. & Zhang R. 2014. Elucidating severe urban haze formation in China. *Proc. Natl. Acad. Sci.* 111: 17373–17378.
- Haapanala S., Rinne J., Pystynen K.-H., Hellén H., Hakola H. & Riutta T. 2006. Measurements of hydrocarbon emissions from a boreal fen using the REA technique. *Biogeosciences* 3: 103–112.
- Hakola H., Tarvainen V., Bäck J., Ranta H., Bonn B., Rinne J. & Kulmala M. 2006. Seasonal variation of mono- and sesquiterpene emission rates of Scots pine. *Biogeosciences* 3: 93–101.
- Hakola H., Tarvainen V., Praplan A. P., Jaars K., Hemmilä M., Kulmala M., Bäck J. & Hellén, H. 2017. Terpenoid and carbonyl emissions from Norway spruce in Finland during the growing season. *Atmos. Chem. Phys.* 17: 3357–3370.
- Halmmeenmäki E., Heinonsalo J., Putkinen A., Santalahti M., Fritze H. & Pihlatie M. 2017. Above- and belowground fluxes of methane from boreal dwarf shrubs and *Pinus sylvestris* seedlings. *Plant Soil* 420: 361–373.
- Halonen R., Zapadinsky E., Kurtén T., Vehkamäki H. & Reischl B. 2019. Rate enhancement in collisions of sulfuric acid molecules due to long-range intermolecular forces. *Atmos. Chem. Phys.* 19: 13355–13366.
- Hannula H.-R., Heinilä K., Böttcher K., Mattila O.-P., Salminen M. & Pulliainen J. 2020. Laboratory, field, mast-borne and airborne spectral reflectance measurements of boreal landscape during spring. *Earth System Science Data* 12: 719–740.
- Hamed A., Joutsensaari J., Mikkonen S., Sogacheva L., Dal Maso M., Kulmala M., Cavalli F., Fuzzi S., Facchini M.C., Decesari S., Mírcea M., Lehtinen K.E.J. & Laaksonen A. 2007. Nucleation and growth of new particles in Po Valley, Italy. *Atmos. Chem. Phys.* 7: 355–376.
- Hao L., Romakkaniemi S., Kortelainen, A., Jaatinen A., Portin H., Miettinen P., Komppula M., Leskinen A., Virtanen A., Smith J. N., Sueper D., Worsnop D. R., Lehtinen K. E. J. & Laaksonen A. 2013. Aerosol Chemical Composition in Cloud Events by High Resolution Time-of-Flight Aerosol Mass Spectrometry. *Environ. Sci. Technol.* 47: 2645–2653.
- Hari P., Mäkelä A., Korpilähti E. & Holmberg M. 1986. Optimal control of leaf gas exchange. *Tree physiol.* 2: 169–175.
- Hari P., Kulmala M., Pohja T., Lahti T., Siivola E., Palva L., Aalto P., Hämeri K., Vesala T., Luoma S. & Pulliainen E. 1994. Air pollution in eastern Lapland: challenge for an environmental measurement station. *Silva Fennica* 28: 29–39.
- Hari P., Mäkelä A., Berninger F. & Pohja T. 1999a. Field evidence for the optimality hypothesis of gas exchange in plants. *Functional Plant Biology* 26:3: 239–244.
- Hari P., Keronen P., Bäck J., Altimir N., Linkosalo T., Pohja T., Kulmala M. & Vesala, T. 1999b. An improvement of the method for calibrating measurements of photosynthetic CO<sub>2</sub> flux. *Plant, Cell & Environment* 22:10: 1297–1301.
- Hari P. & Kulmala M. 2005. Station for Measuring Ecosystem-Atmosphere Relations II (SMEAR II). *Boreal Environ. Res.* 10: 315–322.
- Hari P. & Kulmala L. (Eds). 2008. *Boreal forest and climate change*. Adv. Global Change Res. 34, Springer, 582. pp., <http://doi.org/10.1007/978-1-4020-8718-9>.
- Hari P., Bäck J., Heliövaara K., Kerminen V.-M., Kulmala L., Mäkelä A., Nikinmaa E., Petäjä T. & Kulmala M. 2014. Towards quantitative ecology: Newton’s principia revisited. *Boreal Environ. Res.* 19: 142–152
- Hari P., Petäjä T., Bäck J., Kerminen V.-M., Lappalainen H.K., Vihma T., Laurila T., Viisanen Y., Vesala T. & Kulmala M. 2016. Conceptual design of a measurement network of the global change. *Atmos. Chem. Phys.* 16: 21063–21093.
- Hari P., Aakala T., Aalto J., Bäck J., Hollmén J., Jögiste K., Kabiri Koupaei K., Kähkönen M. A., Korpela M., Kulmala L., Nikinmaa E., Pumpanen J., Salkinoja-Salonen M., Schiestl-Aalto P., Simojoki A. & Havimo M. 2017a. Newtonian boreal forest ecology: The Scots pine ecosystem as an example. *PLoS ONE* 12: e0177927. <https://doi.org/10.1371/journal.pone.0177927>
- Hari P., Kerminen V.-M., Kulmala L., Kulmala M., Noe S., Petäjä T., Vanhatalo A. & Bäck J. 2017b. Annual cycle of Scots pine photosynthesis. *Atmos. Chem. Phys.* 17: 15045–15053.
- Hari P., Noe S., Dengel S., Elbers J., Gielen B., Kerminen V.-M., Kruijt B., Kulmala L., Lindroth A., Mammarella I., Petäjä T., Schurgers G., Vanhatalo A., Kulmala M. & Bäck J. 2018. Prediction of photosynthesis in Scots pine ecosystems across Europe by a needle-level theory. *Atmos. Chem. Phys.* 18: 13321–13328.
- Harimaya T. & Sato M. 1989. Measurement of the riming amount on snowflakes. *Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics)* 8: 355–366.
- Harley R.A., Marr L.C., Lehner J.K., Giddings S.N. 2005. Changes in motor vehicle emissions on diurnal to

- decadal time scales and effects on atmospheric composition. *Environ. Sci. Technol.* 39: 5356–5362.
- Hatakka J., Aalto T., Aaltonen V., Aurela M., Hakola H., Komppula M., Laurila T., Lihavainen H., Paatero J., Salminen K. & Viisanen Y. 2003. Overview of the atmospheric research activities and results at Pallas GAW station. *Boreal Environ. Res.* 8: 365–383.
- He X.-C., Tham Y. J., Dada L., Wang M., Finkenzeller H., Stolzenburg D., Iyer S., Simon M., Kürten A., Shen J., Rörup B., Rissanen M., Schobesberger S., Baalbaki Wang D. S., Koenig T. K., Jokinen T., Sarnela N., Beck L., Almeida J., Amanatidis S., Amorim A., Ataei F., Baccharini A., Bertozzi B., Bianchi F., Brilke S., Caudillo L., Chen D., Chiu R., Chu B., Dias A., Ding A., Dommen J., Duplissy J., El Haddad I., Carracedo L. G., Granzin M., Hansell A., Heinritzi M., Hofbauer V., Junninen H., Kangasluoma J., Kempainen D., Kim C., Kong W., Krechmer J. E., Kvashin A., Laitinen T., Lamkaddam H., Lee C. P., Lehtipalo K., Leiminger M., Li Z., Makhamutov V., Manninen H. E., Marie G., Marten R., Mathot S., Mauldin R. L., Mentler B., Möhler O., Müller T., Nie W., Onnela A., Petäjä T., Pfeifer J., Philippov M., Ranjithkumar A., Saiz-Lopez A., Salma I., Scholz W., Schuchmann S., Schulze B., Steiner G., Stozhkov Y., Tauber C., Tomé A., Thakur R. C., Väisänen O., Vazquez-Pufleau M., Wagner A. C., Wang Y., Weber S. K., Winkler P. M., Wu Y., Xiao M., Yan C., Ye Q., Ylisirniö A., Zauner-Wieczorek M., Zha Q., Zhou P., Flagan R. C., Curtius J., Baltensperger U., Kulmala M., Kerminen V.-M., Kurtén T., Donahue N. M., Volkamer R., Kirkby J., Worsnop D. R. & Sipilä M. 2021. Role of iodine oxoacids in atmospheric aerosol nucleation. *Science* 371: 589–595.
- Heikkinen L., Äijälä M., Riva M., Luoma K., Dällenbach K., Aalto J., Aalto P., Aliaga D., Aurela M., Keskinen H., Makkonen U., Rantala P., Kulmala M., Petäjä T., Worsnop D. & Ehn M. 2020. Long-term sub-micrometer aerosol chemical composition in the boreal forest: inter- and intra-annual variability. *Atmos. Chem. Phys.* 20: 3151–3180.
- Heikkinen L., Äijälä M., Daellenbach K.R., Chen G., Garmash O., Aliaga D., Graeffe F., Rätty M., Luoma K., Aalto P., Kulmala M., Petäjä T., Worsnop D. & Ehn M. 2021. Eight years of sub-micrometre organic aerosol composition data from the boreal forest characterized using a machine-learning approach. *Atmos. Chem. Phys.* 21: 10081–10109.
- Heimlich L., Lohila A., Tuovinen J.-P., Vekuri H., Heinonsalo J., Nevalainen O., Korkiakoski M., Liski J., Laurila T. & Kulmala L. 2021. Carbon dioxide fluxes and carbon balance of an agricultural grassland in southern Finland. *Biogeosciences* 18: 3467–3483.
- Heineman M. & Reichstein M. 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* 451: 289–292.
- Helin A., Rönkkö T., Parshintsev J., Hartonen K., Schilling B., Läubli T. & Riekkola M.-L. 2015. Solid phase micro-extraction Arrow for the sampling of volatile amines in wastewater and atmosphere. *J. Chromatogr. A* 1426: 56–63.
- Helin A., Sietiö O.-M., Heinonsalo J., Bäck J., Riekkola M.-L. & Parshintsev J. 2017. Characterization of free amino acids, bacteria and fungi in size-segregated atmospheric aerosols in boreal forest: seasonal patterns, abundances and size distributions. *Atmos. Chem. Phys.* 17: 13089–13101.
- Helin A., Hakola H. & Hellén, H. 2020. Optimisation of a thermal desorption–gas chromatography–mass spectrometry method for the analysis of monoterpenes, sesquiterpenes and diterpenes. *Atmos. Meas. Tech.* 13: 3543–3560.
- Hellén H., Hakola H., Pystynen K.-H., Rinne J. & Haapanala S. 2006. C<sub>2</sub>-C<sub>10</sub> hydrocarbon emissions from a boreal wetland and forest floor. *Biogeosciences* 3: 167–174.
- Hellén H., Kuronen P. & Hakola H. 2012. Heated stainless steel tube for ozone removal in the ambient air measurements of mono- and sesquiterpenes. *Atmospheric Environment* 57: 35–40.
- Hellén H., Praplan A. P., Tykkä T., Ylivinkka I., Vakkari V., Bäck J., Petäjä T., Kulmala M. & Hakola H. 2018. Long-term measurements of volatile organic compounds highlight the importance of sesquiterpenes for the atmospheric chemistry of a boreal forest. *Atmos. Chem. Phys.* 18:19: 13839–13863.
- Hellén H., Schallhart S., Praplan A. P., Tykkä T., Aurela M., Lohila A. & Hakola H. 2020. Sesquiterpenes dominate monoterpenes in northern wetland emissions. *Atmos. Chem. Phys.* 20: 7021–7034.
- Hellén H., Praplan A. P., Tykkä T., Helin A., Schallhart S., Schiestl-Aalto P. P., Bäck J. & Hakola H. 2021. Sesquiterpenes and oxygenated sesquiterpenes dominate the VOC (C<sub>5</sub>-C<sub>20</sub>) emissions of downy birches. *Atmos. Chem. Phys.* 21: 8045–8066.
- Henschel H., Navarro J. C.A., Yli-Juuti T., Kupiainen-Määttä O., Olenius T., Ortega I. K., Clegg S. L., Kurtén T., Riipinen I. & Vehkamäki H. 2014. Hydration of atmospherically relevant molecular clusters: Computational chemistry and classical thermodynamics. *J. Phys. Chem. A* 118: 2599–2611.
- Herb J., Nadykto A. B. & Yu F. 2011. Large ternary hydrogen-bonded pre-nucleation clusters in the Earth's atmosphere. *Chem. Phys. Lett.*, 518: 7–14.
- Hollinger J., Peirce J. & Poe G. 1990. SSM/I instrument evaluation. *IEEE Transactions on Geoscience and Remote Sensing* 28: 781–790.
- Hölttä T. & Kolari P. 2009. Interpretation of stem CO<sub>2</sub> efflux measurements. *Tree Physiology* 29: 1447–1456.
- Hölttä T., Mäkinen H., Nöjd P., Mäkelä A. & Nikinmaa E. 2010. A physiological model of cambial growth. *Tree Physiology* 30: 1235–1252.
- Hölttä T., Lintunen A., Chan T., Mäkelä A. & Nikinmaa E. 2017. A steady state stomatal model of balanced leaf gas exchange, hydraulics and maximal source-sink flux. *Tree Physiology* 37: 851–868.
- Hu X., Fan H., Cai M., Sejas S. A., Taylor P. & Yang S. 2020. A less cloudy picture of the inter-model spread in future global warming projections. *Nature Com.* 11:4472 <https://doi.org/10.1038/s41467-020-18227-9>
- Hu L., Montzka S., Kaushik A., Andrews A., Sweeney C., Miller J., Baker I., Denning S., Campbell E., Shiga Y.,

- Tans P., Siso M., Crotwell M., McKain K., Thoning K., Hall B., Vimont I., Elkins J., Whelan M. & Suntharalingam P. 2021. COS-derived GPP relationships with temperature and light help explain high-latitude atmospheric CO<sub>2</sub> seasonal cycle amplification. *Proc. Natl. Acad. Sci.* 118:33:e2103423118. 10.1073/pnas.2103423118
- Huotari J., Ojala A., Peltomaa E., Nordbo A., Launiainen S., Pumpanen J., Rasilo T., Hari P. & Vesala T. 2011. Long-term direct CO<sub>2</sub> flux measurements over a boreal lake: Five years of eddy covariance data. *Geophysical Research Letters* 38: L18401, <http://dx.doi.org/10.1029/2011GL048753>
- Hyvärinen A.-P., Lihavainen H., Viisanen Y. & Kulmala M. 2004. Homogeneous nucleation rates of higher *n* -alcohols measured in a laminar flow diffusion chamber. *J. Chem. Phys.* 120:24: 11621.
- Hyvärinen A.-P., Raatikainen T., Laaksonen A., Viisanen Y. & Lihavainen H. 2005. Surface tensions and densities of H<sub>2</sub>SO<sub>4</sub> + NH<sub>3</sub> + water solutions. *Geophys. Res. Lett.* 32:16: L16807.
- Hyvärinen A.-P., Lihavainen H., Gaman A., Vairila L., Ojala H., Kulmala M. & Viisanen Y. 2006. Surface tensions and densities of oxalic-, malonic-, succinic-, maleic-, malic-, and cis-pinonic acid. *J. Chem. Eng. Data* 51: 255-260.
- Ianni J. C. & Bandy A. R. 1999. A density functional theory study of the hydrates of NH<sub>3</sub>\*H<sub>2</sub>SO<sub>4</sub> and its implications for the formation of new atmospheric particles. *J. Phys. Chem. A* 103: 2801–2811.
- Ianni J. C. & Bandy A. R. 2000. A theoretical study of the hydrates of (H<sub>2</sub>SO<sub>4</sub>)<sub>2</sub> and its implications for the formation of new atmospheric particles. *J. Molec. Struct. THEOCHEM.* 497: 19-37.
- Iivesniemi H., Levula J., Ojansuu R., Kolari P., Kulmala L., Pumpanen J., Launiainen S., Vesala T., Nikinmaa E. 2009. Long-term measurements of the carbon balance of a boreal Scots pine dominated forest ecosystem. *Boreal Env. Res.* 14: 731–753.
- Iivesniemi H., Pumpanen J., Duursma R., Hari P., Keronen P., Kolari P., Kulmala M., Mammarella I., Nikinmaa E., Rannik Ü., Pohja T., Siivola E. & Vesala T. 2010. Water balance of a boreal Scots pine forest. *Boreal Env. Res.* 15: 375–396.
- IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.
- IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.
- Ivakhov V.M., Paramonova N.N., Privalov V.I., Zinchenko A.V., Loskutova M.A., Makshtas A.P., Kustov V.Y., Laurila T., Aurela M. & Asmi E. 2019. atmospheric concentration of carbon dioxide at tiksi and cape baranov stations in 2010–2017. *Russian Meteorology and Hydrology* 44: 291-299.
- Jacobson M.Z. 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* 409: 695–697.
- Järvi L., Hannuniemi H., Hussein T., Junninen H., Aalto P.P., Hillamo R., Mäkelä T., Keronen P., Siivola E., Vesala T. & Kulmala M. 2009a. The urban measurement station SMEAR III: continuous monitoring of air pollution and surface-atmosphere interactions in Helsinki, Finland. *Boreal Env. Res.* 14, Suppl. A: 86–109.
- Järvi L., Rannik Ü., Mammarella I., Sogachev A., Aalto P.P., Keronen P., Siivola E., Kulmala M. & Vesala T. 2009b. Annual particle flux observations over a heterogeneous urban area. *Atmos. Chem. Phys.* 9: 7847-7856.
- Järvi L., Nordbo A., Junninen H., Riikonen A., Moilanen J., Nikinmaa E. & Vesala T. 2012. Seasonal and annual variation of carbon dioxide surface fluxes in Helsinki, Finland, in 2006-2010. *Atmos. Chem. Phys.* 12: 8475-8489.
- Järvi L., Rannik Ü., Kokkonen T.V, Kurppa M., Karppinen A., Kouznetsov R.D., Rantala P. Vesala T. and Wood C.R. (2018). Uncertainty of eddy covariance flux measurements over an urban area based on two towers. *Atmospheric Measurement Techniques* 11, 5421-5438.
- Järvi L., Havu M., Ward H.C., Bellucco V., McFadden J.P., Toivonen T., Heikinheimo V., Kolari P., Riikonen A. & Grimmond C.S.B. 2019. Spatial Modeling of Local-Scale Biogenic and Anthropogenic Carbon Dioxide Emissions in Helsinki. *Journal of Geophysical Research: Atmospheres* 124: 8363-8384.
- Jokinen T., Sipilä M., Junninen H., Ehn M., Lönn G., Hakala J., Petäjä T., Mauldin III R. L., Kulmala M. & Worsnop D. R. 2012. Atmospheric sulphuric acid and neutral cluster measurements using CI-API-TOF. *Atmos. Chem. Phys.* 12: 4117–4125.
- Jokinen T., Sipilä M., Richters S., Kerminen V.-M., Paasonen P., Stratmann F., Worsnop D., Kulmala M., Ehn M., Herrmann H. & Berndt T. 2014. Rapid autoxidation forms highly oxidized RO<sub>2</sub> radicals in the atmosphere. *Angew. Chem.* 53: 14596-14600.
- Jokinen T., Berndt T., Makkonen R., Kerminen V.-M., Junninen H., Paasonen P., Stratmann F., Herrmann H., Guenther A., Worsnop D. R., Kulmala M., Ehn M. & Sipilä M. 2015 Production of extremely low-volatile organic compounds from biogenic emissions: measured yields and atmospheric implications. *Proc. Nat. Acad. Sci.* 112: 7123-7128.
- Jokinen T., Sipilä M., Kontkanen J., Vakkari V., Tisler P., Duplissy E.-M., Junninen H., Kangasluoma J., Manninen H. E., Petäjä T., Kulmala M., Worsnop D. R., Kirkby J., Virkkula A. & Kerminen V.-M. 2018. Ion induced sulfuric acid-ammonia nucleation drives particle formation in coastal Antarctica. *Sci. Adv.* 4: eaat9744.
- Jokinen T., Kausiala O., Garmash O., Peräkylä O., Junninen H., Schobesberger S., Yan C., Sipilä M. & Rissanen M.P.

2016. Production of highly oxidized organic compounds from ozonolysis of beta-caryophyllene: laboratory and field measurements. *Boreal Environ. Res.* 21: 262-273.
- Jokinen T., Lehtipalo K., Thakur R.C., Ylivinkka I., Neitola K., Sarnela N., Laitinen T., Kulmala M., Petäjä T. & Sipilä M. 2022. Measurement report: Long-term measurements of aerosol precursor concentrations in the Finnish subarctic boreal forest. *Atmos. Chem. Phys.* 22: 2237-2254.
- Joutsensaari J., Ozon M., Nieminen T., Mikkonen S., Lähi-vaara T., Decesari S., Facchini M.C., Laaksonen A. & Lehtinen K.E.J. 2018. Identification of new particle formation events with deep learning. *Atmos. Chem. Phys.* 18: 9597-9615.
- Junninen H., Lauri A., Keronen P., Aalto P., Hiltunen V., Hari P. & Kulmala M. 2009. Smart-SMEAR: on-line data exploration and visualization tool for SMEAR stations. *Boreal Environ. Res.* 14: 447-457.
- Junninen H., Ehn M., Petäjä T., Luosujärvi L., Kotiaho T., Kostianen R., Rohner U., Gonin M., Fuhrer K., Kulmala M. & Worsnop D. R. 2010. A high-resolution mass spectrometer to measure atmospheric ion composition. *Atmos. Meas. Tech.* 3: 1039-1053.
- Juottonen H., Tuittila E-S., Juutinen S., Fritze, H. & Yrjälä K. 2008. Seasonality of rDNA- and rRNA-derived archaeal communities and methanogenic potential in a boreal mire. *ISME J.* 2: 157-1168.
- Juutinen S., Virtanen T., Kondratyev V., Laurila T., Linkosalmi M., Mikola J., Nyman J., Räsänen A., Tuovinen J.-P. & Aurela M. 2017. Spatial variation and seasonal dynamics of leaf-area index in the arctic tundra—implications for linking ground observations and satellite images. *Environmental Research Letters* 12: 095002. <https://doi.org/10.1088/1748-9326/aa7f85>.
- Kalivitis N., Kerminen V.-M., Kouvarikis G., Stavroulas I., Tzitzikalaki E., Kalkavouras P., Daskalakis N., Myriokefalitakis S., Bougiatioti A., Manninen H. E., Roldin P., Petäjä T., Boy M., Kulmala M., Kanakidou M. & Mihailopoulos N. 2019. Formation and growth of atmospheric nanoparticles in the eastern Mediterranean: results from long-term measurements and process simulation. *Atmos. Chem. Phys.* 19: 2671-2686.
- Kalliokoski T., Bäck J., Boy M., Kulmala M., Kuusinen N., Mäkelä A., Minkinen K., Minunno F., Paasonen P., Peltoniemi M., Taipale D., Valsta L., Vanhatalo A., Zhou L., Zhou P., Berninger F. 2020. Mitigation impact of different harvest scenarios of Finnish forests that account for albedo, aerosols, and trade-offs of carbon sequestration and avoided emissions. *Front. For. Glob. Change* 3: 562044. doi: 10.3389/ffgc.2020.562044
- Kangasluoma J., Kuang C., Wimmer D., Rissanen M. P., Lehtipalo K., Ehn M., Worsnop D. R., Wang J., Kulmala M. & Petäjä T. 2014. Sub-3 nm particle size and composition dependent response of a nano-CPC battery. *Atmos. Meas. Tech.* 7: 689-700.
- Kangasluoma J., Attoui M., Korhonen F., Ahonen L., Siivola E. & Petäjä T. 2016. Characterization of a Herrmann-type high-resolution differential mobility analyzer. *Aerosol Science and Technology* 50: 222-229.
- Kangasluoma J., Hering S., Picard D., Lewis G., Enroth J., Korhonen F., Kulmala M., Sellegri K., Attoui M. & Petäjä T. 2017. Characterization of three new condensation particle counters for sub-3 nm particle detection during the Helsinki CPC workshop: the ADI versatile water CPC, TSI 3777 nano enhancer and boosted TSI 3010. *Atmos. Meas. Tech.* 10: 2271-2281.
- Kangasluoma J., Ahonen L. R., Laurila T., Cai R., Enroth J., Mazon S., Korhonen F., Aalto P., Kulmala M., Attoui M. & Petäjä T. 2018. Laboratory verification of a new high flow differential mobility particle sizer, and field measurements in Hyytiälä. *J. Aerosol Sci.* 124: 1-9.
- Kangasluoma J., Cai R. L., Jiang J. K., Deng C. J., Stolzenburg D., Ahonen L. R., Chan T., Fu Y. Y., Kim C., Laurila T. M., Zhou Y., Dada L., Sulo J., Flagan R. C., Kulmala M., Petäjä T. & Lehtipalo K. 2020. Overview of measurements and current instrumentation for 1-10 nm aerosol particle number size distributions. *J. Aerosol Sci.* 148: 105584.
- Karl T. G., Spirig C., Rinne J., Stroud C., Prevost P., Greenberg J., Fall R. & Guenther A. 2002. Virtual disjunct eddy covariance measurements of organic compound fluxes from a subalpine forest using proton transfer reaction mass spectrometry. *Atmos. Chem. Phys.* 2: 279-291.
- Karttunen S., Kurppa M., Auvinen M., Hellsten A. & Järvi L. 2020. Large-eddy simulation of the optimal street-tree layout for pedestrian-level aerosol particle concentrations — A case study from a city-boulevard. *Atmospheric Environment. X* 6:15: 100073.
- Kazil J., Stier P., Zhang K., Quaas J., Kinne S., O'Donnell D., Rast S., Esch M., Ferrachat S., Lohmann U. & Feichter J. 2010. Aerosol nucleation and its role for clouds and Earth's radiative forcing in the aerosol-climate model ECHAM5-HAM. *Atmos. Chem. Phys.* 10: 10733-10752.
- Kerminen V.-M., Chen X., Vakkari V., Petäjä T., Kulmala M. & Bianchi F. 2018. Atmospheric new particle formation and growth: review of field observations. *Environ. Res. Lett.* 13: 103003.
- Kerminen V.-M. & Kulmala M. 2002. Analytical formulae connecting the “real” and the “apparent” nucleation rate and the nuclei number concentration for atmospheric nucleation events. *J. Aerosol Sci.* 33: 609-622.
- Kerminen V.-M., Paramonov M., Anttila T., Riipinen I., Fountoukis C., Korhonen H., Asmi E., Laakso L., Lihavainen H., Swietlicki E., Svenningsson B., Asmi A., Pandis S. N., Kulmala M. & Petäjä T. 2012. Cloud condensation nuclei production associated with atmospheric nucleation: a synthesis based on existing literature and new results. *Atmos. Chem. Phys.* 12: 12037-12059.
- Kerminen V.-M., Petäjä T., Manninen H.E., Paasonen P., Nieminen T.J., Sipilä M., Junninen H., Ehn M., Gagne S., Laakso L., Riipinen I., Vehkamäki H., Kurten T., Ortega I.K., Dal Maso M., Brus D., Hyvärinen A., Lihavainen H., Leppä J., Lehtinen, K.E.J., Mirme A., Mirme S., Hörrak U., Berndt T., Stratmann F., Birmili W., Wiedensohler A., Metzger A., Dommnen J., Baltensperger U., Kiendler-Scharr A., Mentel T.F., Wildt J., Winkler P.M., Wagner P.E., Petzold A., Minikin A., Plass-Dülmer C., Pöschl U., Laaksonen A. & Kulmala M. 2010. Atmospheric nucleation: highlights of the EUCAARI project



- and future directions. *Atmospheric Chemistry and Physics* 10: 10829-10848.
- Keskinen H., Virtanen A., Joutsensaari J., Tsagkogeorgas G., Duplissy J., Schobesberger S., Gysel M., Riccobono F., Slowik J. G., Bianchi F., Yli-Juuti T., Lehtipalo K., Rondo L., Breitenlechner M., Kupc A., Almeida J., Amorim A., Dunne E. M., Downard A. J., Ehrhart S., Franchin A., Kajos M.K., Kirkby J., Kürten A., Nieminen T., Makhmutov V., Mathot S., Miettinen P., Onnela A., Petäjä T., Praplan A., Santos F. D., Schallhart S., Sipilä M., Stozhkov Y., Tomé A., Vaattovaara P., Wimmer D., Prevot A., Dommen J., Donahue N. M., Flagan R.C., Weingartner E., Viisanen Y., Riipinen I., Hansel A., Curtius J., Kulmala M., Worsnop D. R., Baltensperger U., Wex H., Stratmann F. & Laaksonen A. 2013. Evolution of particle composition in CLOUD nucleation experiments. *Atmos. Chem. Phys.* 13: 5587-5600.
- Kieloaho A.-J., Hellén H., Hakola H. & Pihlatie M. 2013. Gas-phase alkylamines in a boreal Scots pine forest air. *Atmospheric Environment* 80: 369-377.
- Kieloaho A.-J., Pihlatie M., Dominguez Carrasco M., Kanerva S., Parshintsev J., Riekkola M.-L., Pumpanen J. & Heinonsalo J. 2016. Stimulation of soil organic nitrogen pool: the effect of plant and soil organic matter degrading enzymes. *Soil Biology & Biochemistry* 96: 97-106.
- Kieloaho A.-J., Pihlatie M., Launiainen S., Kulmala M., Riekkola M.-L., Parshintsev J., Mammarella I., Vesala T. & Heinonsalo J. 2017. Soil concentrations and soil-atmosphere exchange of alkylamines in a boreal Scots pine forest. *Biogeosciences* 14: 1075-1091.
- Kilkki J., Aalto T., Hatakka J., Portin H. & Laurila T. 2015: Atmospheric CO<sub>2</sub> observations at Finnish urban and rural sites. *Boreal Environmental Research* 20: 227-242.
- Krinner G., Viovy N., de Noblet-Ducoudré N., Ogée J., Polcher J., Friedlingstein P., Ciais P., Sitch S. & Prentice I.C. 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochem. Cycles*, 19, GB1015, doi:10.1029/2003GB002199
- Kirkby J., Curtius J., Almeida J., Dunne E., Duplissy J., Erhart S., Franchin A., Gagné S., Ickes L., Kürten A., Kupc A., Metzger A., Riccobono F., Rondo L., Schobesberger S., Tsagkogeorgas G., Wimmer D., Amorim A., Bianchi F., Breitenlechner M., David A., Dommen J., Downard A., Ehn M., Flagan R.C., Haidler S., Hansel A., Hauser D., Jud W., Junninen H., Kazil J., Kreissl F., Kvashin A., Laaksonen A., Lehtipalo K., Lima J., Lovejoy E.R., Makhmutov V., Mathot S., Mikkilä J., Minginette P., Mogo S., Nieminen T., Onnela A., Pereira P., Petäjä T., Schnitzhofer R., Seinfeld J.H., Sipilä M., Stozhkov Y., Stratmann F., Tome A., Vanhanen J., Viisanen Y., Vrtala A., Wagner P.E., Walther H., Weingartner E., Wex H., Winkler P.M., Carslaw K.S., Worsnop D.R., Baltensperger U. & Kulmala M. 2011. The role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature* 476: 429-433.
- Kirkby J., Duplissy J., Sengupta K., Frege C., Gordon H., Williamson C., Heinritzi M., Simon M., Yan C., Almeida J., Tröstl J., Nieminen T., Ortega I. K., Wagner R., Adamov A., Amorim A., Bernhammer A.-K., Bianchi F., Breitenlechner M., Brilke S., Chen X., Craven J., Dias A., Ehrhart S., Flagan R. C., Franchin A., Fuchs C., Guida R., Hakala J., Hoyle C. R., Jokinen T., Junninen H., Kangasluoma J., Kim J., Krapf M., Kurten A., Laaksonen A., Lehtipalo K., Makhmutov V., Mathot S., Molteni U., Onnela A., Peräkylä O., Piel F., Petäjä T., Praplan A. P., Pringle K., Rap A., Richards N. A. D., Riipinen I., Rissanen M. P., Rondo L., Sarnela N., Schobesberger S., Scott C. E., Seinfeld J. H., Sipilä M., Steiner G., Stozhkov Y., Stratmann G., Tome A., Virtanen A., Vogel A. L., Wagner A. C., Wagner P. E., Weingartner E., Wimmer D., Winkler P. M., Ye P., Zhang X., Hansel A., Dommen J., Donahue N. M., Worsnop D. R., Baltensperger U., Kulmala M., Carslaw K. S. & Curtius J. 2016. Ion-induced nucleation of pure biogenic particles. *Nature* 533: 521-526.
- Clump J., Wyborn L., Downs R., Asmi A., Wu M., Ryder G. & Martin J. 2020. Principles and best practices in data versioning for all data sets big and small. Version 1.1. Research Data Alliance. doi: 10.15497/RDA00042.
- Kneifel S. & Moisseev D. 2020. Long-Term Statistics of Riming in Nonconvective Clouds Derived from Ground-Based Doppler Cloud Radar Observations. *J. Atmos. Sci.* 77: 3495-3508.
- Kohonen K.-M., Kolari P., Kooijmans L.M.J., Chen H., Seibt U., Sun W. & Mammarella I. 2020. Towards standardized processing of eddy covariance flux measurements of carbonyl sulfide. *Atmos. Meas. Tech.* 13: 3957-3975.
- Kohonen K.-M., Dewar R., Tramontana G., Mauranen A., Kolari P., Kooijmans L.M.J., Papale D., Vesala T. & Mammarella I. 2022. Intercomparison of methods to estimate gross primary production based on CO<sub>2</sub> and COS flux measurements. *Biogeosci.* 19: 4067-4088.
- Kokkola H., Romakkaniemi S. & Laaksonen A. 2003. Köhler theory for a polydisperse droplet population in the presence of a soluble trace gas, and an application to stratospheric STS droplet growth. *Atmos. Chem. Phys.* 3: 2139-2146.
- Kokkola H., Korhonen H., Lehtinen K. E. J., Makkonen R., Asmi A., Järvenoja S., Anttila T., Partanen A.-I., Kulmala M., Järvinen H., Laaksonen A. & Kerminen V.-M. 2008. SALSA — a Sectional Aerosol module for Large Scale Applications. *Atmos. Chem. Phys.* 8: 2469-2483.
- Kolari P., Pumpanen J., Kulmala L., Ilvesniemi H., Nikinmaa E., Grönholm T. & Hari P. 2006. Forest floor vegetation plays an important role in photosynthetic production of boreal forests. *Forest Ecology and Management* 221: 241-248.
- Kolari P., Lappalainen H.K., Hänninen H. & Hari P. 2007. Relationship between temperature and the seasonal course of photosynthesis in Scots pine at northern timberline and in southern boreal zone. *Tellus B: Chemical and Physical Meteorology* 59:3: 542-552.
- Kolari P., Kulmala L., Pumpanen J., Launiainen S., Ilvesniemi H., Hari P. & Nikinmaa E. 2009. CO<sub>2</sub> exchange and component CO<sub>2</sub> fluxes of a boreal Scots pine forest. *Boreal Env. Res.* 14: 761-783.
- Kolari P., Bäck J., Taipale R., Ruuskanen T.M., Kajos M.K.,

- Rinne J., Kulmala M. & Hari P. 2012. Evaluation of accuracy in measurements of VOC emissions with dynamic chamber system. *Atmospheric Environment* 62: 344-351.
- Kolb T.E., Fehsenfeld G.J., Ayres M.P., Bentz B.J., Hickey J.A., Mathiasen R., Stewart J.E., & Weeden A.S. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. *For. Ecol. Manage.* 380: 321–334.
- Komppula M., Lihavainen H., Kerminen V.-M., Kulmala M. & Viisanen Y. 2005. Measurements of cloud droplet activation of aerosol particles at a clean subarctic background site. *J. Geophys. Res.* 110: D06204. doi:10.1029/2004JD005200
- Kontkanen J., Olenius T., Kulmala M. & Riipinen I. 2018. Exploring the potential of nano-Köhler theory to describe the growth of atmospheric molecular clusters by organic vapors using cluster kinetics simulations. *Atmos. Chem. Phys.* 18: 13733-13754.
- Koponen I., Virkkula A., Hillamo R., Kerminen V.-M. & Kulmala M. 2003. Number size distributions and concentrations of the continental summer aerosols in Queen Maud Land, Antarctica. *J. Geophys. Res.* 108:D18: 4587.
- Korhonen H., Carslaw K. S., Forster P. M., Mikkonen S., Gordon N. D & Kokkola H. 2010. Aerosol climate feedback due to decadal increases in Southern Hemisphere wind speeds. *Geophys. Res. Lett.* 37: L02805. doi:10.1029/2009GL041320
- Korhonen H., Kerminen V.-M., Kokkola H. & Lehtinen K. E. J. 2014. Estimating atmospheric nucleation rates from size distribution measurements: Analytical equations for the case of size dependent growth rates. *J. Aerosol Sci.* 69: 13-20.
- Korhonen J., Pihlatie M., Pumpanen J., Aaltonen H., Hari P., Levula J., Kieloaho A.-J., Nikinmaa E., Vesala T. & Ilvesniemi H. 2013. Nitrogen balance of a boreal Scots pine forest. *Biogeosciences* 10: 1083-1095.
- Korkiakoski M., Minkkinen K., Ojanen P., Penttilä T., Koskinen M., Laurila T., & Lohila A. 2017. Methane exchange at the peatland forest floor—automatic chamber system exposes the dynamics of small fluxes. *Biogeosciences* 14: 1947-1967.
- Korkiakoski M., Tuovinen J.-P., Penttilä T., Sarkkola S., Ojanen P., Minkkinen K., Rinne J., Laurila T. & Lohila A. 2019. Greenhouse gas and energy fluxes in a boreal peatland forest after clearcutting. *Biogeosciences* 16: 3703-3723.
- Korkiakoski M., Ojanen P., Penttilä T., Minkkinen K., Sarkkola S., Rainne J., Laurila T. & Lohila A. 2020. Impact of partial harvest on CH<sub>4</sub> and N<sub>2</sub>O balances of a drained boreal peatland forest. *Agricultural and Forest Meteorology* 295: 108168. <https://doi.org/10.1016/j.agrformet.2020.108168>
- Korkiakoski M., Määttä T., Peltoniemi K., Penttilä T. & Lohila, A. 2021. Excess soil moisture and fresh carbon input are prerequisites for methane production in podzolic soil. *Biogeosciences* 19: 2025-2041.
- Korrensalo A., Männistö E., Alekseychik P., Mammarella I., Rinne J., Vesala T. & Tuittila E.-S. 2018. Small spatial variability in methane emission measured from a wet patterned boreal bog. *Biogeosciences* 15: 1749-1761.
- Koskinen M., Minkkinen K., Ojanen P., Kämäräinen M., Laurila T. & Lohila A. 2014. Measurements of the CO<sub>2</sub> exchange with an automated chamber system throughout the year: challenges in measuring the nighttime respiration in porous peat soil. *Biogeosciences* 11: 347-363.
- Köster E., Köster K., Berninger F. & Pumpanen J. 2015a. Carbon dioxide, methane and nitrous oxide fluxes from podzols of a fire chronosequence in the boreal forests in Väriö, Finnish Lapland. *Geoderma Regional* 5: 181-187.
- Köster K., Berninger F., Lindén A. & Pumpanen J. 2014. Recovery in fungal biomass is related to decrease in soil organic matter turnover time in a boreal fire chronosequence. *Geoderma* 235–236: 74–82.
- Köster K., Berninger F., Köster E. & Pumpanen J. 2015b. Influences of reindeer grazing on above- and below-ground biomass and soil carbon dynamics. *Arctic, Antarctic and Alpine Research* 47:3: 495-503.
- Köster K., Köster E., Orumaa A., Parro K., Jögiuste K., Berninger F.A., Pumpanen J.S. & Metsläid M. 2016. How time since forest fire affects stand structure, soil physical-chemical properties and soil CO<sub>2</sub> efflux in hemiboreal Scots pine forest fire chronosequence? *Forests* 7: 201.
- Köster K., Köster E., Kulmala L., Berninger F. & Pumpanen J. 2017. Are the climatic factors combined with reindeer grazing affecting the soil CO<sub>2</sub> emissions in subarctic boreal pine forest? *CATENA* 149: 616-622.
- Köster K., Köster E., Berninger F., Heinonsalo J. & Pumpanen J. 2018. Contrasting effects of reindeer grazing on CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O fluxes originating from the northern boreal forest floor. *Land Degradation and Development* 29: 374-381.
- Kubečka J., Besel V., Kurtén T., Myllys N. & Vehkamäki H. 2019. Configurational sampling of noncovalent (atmospheric) molecular clusters: Sulfuric acid and guanidine. *J. Phys. Chem. A* 123: 6022–6033.
- Kulmala L., Launiainen S., Pumpanen J., Lankreijer H., Lindroth A., Hari P. & Vesala T. 2008. H<sub>2</sub>O and CO<sub>2</sub> fluxes at the floor of a boreal pine forest. *Tellus B: Chemical and Physical Meteorology* 60: 167-178.
- Kulmala L., Pumpanen J., Hari P. & Vesala T. 2011a. Photosynthesis of ground vegetation in different aged pine forests: Effect of environmental factors predicted with a process-based model. *Journal of Vegetation Science* 22: 96-110.
- Kulmala L., Pumpanen J., Kolari P., Muukkonen P., Hari P. & Vesala T. 2011b. Photosynthetic production of ground vegetation in different-aged Scots pine (*Pinus sylvestris*) forests. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 41: 2020-2030.
- Kulmala L., Žliobaite I., Nikinmaa E., Nöjd P., Kolari P., Kabiri Koupaie K., Hollmén J. & Mäkinen H. 2016b. Environmental control of growth variation in a boreal Scots pine stand — a data-driven approach. *Silva Fennica* 50: 1680.
- Kulmala L., Read J., Nöjd P., Rathgeber C.B.K., Cuny H.E., Hollmén J. & Mäkinen H. 2017a Identifying the main

- drivers for the production and maturation of Scots pine tracheids along a temperature gradient. *Agricultural and Forest Meteorology* 232: 210–224.
- Kulmala L., Pumpanen J., Kolari P., Dengel S., Berninger F., Köster K., Matkala L., Vanhatalo A., Vesala T. & Bäck J. 2019. Inter- and intra-annual dynamics of photosynthesis differ between forest floor vegetation and tree canopy in a subarctic Scots pine stand. *Agricultural and Forest Meteorology* 271: 1–11.
- Kulmala M., Hämeri K., Aalto P., Mäkelä J. M., Pirjola L., Nilsson E. D., Buzorius G., Rannik U., Dal Maso M., Seidl W., Hoffman T., Janson R., Hansson H.-C., Viisanen Y., Laaksonen A. & O'Dowd C. D. 2001a. Overview of the international project on biogenic aerosol formation in the boreal forest (BIOFOR). *Tellus B* 53: 324–343.
- Kulmala M., Dal Maso M., Mäkelä J. M., Pirjola L., Väkevä M., Aalto P., Miikkulainen P., Hämeri K. & O'Dowd C. D. 2001b. On the formation, growth and composition of nucleation mode particles. *Tellus B* 53: 479–490.
- Kulmala M., Vehkamäki H., Petäjä T., Dal Maso M., Lauri A., Kerminen V.-M., Birmili W. & McMurry P. H. 2004a. Formation and growth rates of ultrafine atmospheric particles: A review of observations. *J. Aerosol Sci.* 35: 143–176.
- Kulmala M., Kerminen V.-M., Anttila T., Laaksonen A. & O'Dowd C. D. 2004b. Organic aerosol formation via sulphate cluster activation. *J. Geophys. Res.* 109: D04205. doi: 10.1029/2003JD003961
- Kulmala M., Suni T., Lehtinen K. E. J., Dal Maso M., Boy M., Reissell A., Rannik U., Aalto P., Keronen P., Hakola H., Bäck J., Hoffmann T., Vesala T. & Hari P. 2004c. A new feedback mechanism linking forests, aerosols, and climate. *Atmos. Chem. Phys.* 4: 557–562.
- Kulmala M., Hari P., Laaksonen A., Vesala T. & Viisanen Y. 2005. Research unit of physics, chemistry and biology of atmospheric composition and climate change: overview of recent results. *Boreal Environ. Res.* 10: 459–477.
- Kulmala M., Mordas G., Petäjä T., Grönholm T., Aalto P., Vehkamäki H., Hienola A.I., Herrmann E., Sipilä M.J., Riipinen I., Manninen H.E., Hämeri K., Stratmann F., Bilde M., Winkler P.M., Birmili W. & Wagner P.E. 2007a. The condensation particle counter battery (CPCB): a new tool to investigate the activation properties of nanoparticles. *Journal of Aerosol Science* 38: 289–304.
- Kulmala M., Riipinen I., Sipilä M., Manninen H. E., Petäjä T., Junninen H., Dal Maso M., Mordas G., Mirme A., Vana M., Hirsikko A., Laakso L., Harrison R. M., Hanson I., Leung C., Lehtinen K. E. J. & Kerminen V.-M. 2007b. Toward direct measurement of atmospheric nucleation. *Science* 318: 89–92.
- Kulmala M., Asmi A., Lappalainen H.K., Carslaw K.S., Pöschl U., Baltensperger U., Hov Ø., Brenquier J.-L., Pandis S.N., Facchini M.C., Hansson H.-C., Wiedensohler A. & O'Dowd C.D. 2009a. Introduction: European Integrated Project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI) — integrating aerosol research from nano to global scales. *Atmos. Chem. Phys.* 9: 2825–2841.
- Kulmala M., Bäck J. & Kerminen V.-M. 2009b. Preface to physics, chemistry and biology of atmospheric composition and climate change. *Boreal Environ. Res.* 14: 439–441.
- Kulmala M., Nieminen T., Chellarpermal R., Makkonen R., Bäck J. & Kerminen V.-M. 2013a. Climate feedbacks linking the increasing atmospheric CO<sub>2</sub> concentration, BVOC emissions, aerosols and clouds in forest ecosystems. In: Niinemets Ü. & Monson R.K. (eds.), *Biology, Controls and Models of Tree Volatile Organic Compound Emissions*, Springer, 489–508.
- Kulmala M., Kontkanen J., Junninen H., Lehtipalo K., Manninen H. E., Nieminen T., Petäjä T., Sipilä M., Schobesberger S., Rantala P., Franchin A., Jokinen T., Järvinen E., Äijälä M., Kangasluoma J., Hakala J., Aalto P. P., Paasonen P., Mikkilä J., Vanhanen J., Aalto J., Hakola H., Makkonen U., Ruuskanen T., Mauldin R. L., Duplissy J., Vehkamäki H., Bäck J., Kortelainen A., Riipinen I., Kurtén T., Johnston M. V., Smith J. N., Ehn M., Mentel T. F., Lehtinen K. E. J., Laaksonen A., Kerminen V.-M. & Worsnop D. R. 2013b. Direct observations of atmospheric aerosol nucleation. *Science* 33: 943–946.
- Kulmala M., Nieminen T., Nikandrova A., Lehtipalo K., Manninen H. E., Kajos M. K., Kolari P., Lauri A., Petäjä T., Krejci, R., Hansson H.-C., Swietlicki E., Lindroth A., Christensen T. R., Arneth A., Hari P., Bäck J., Vesala T. & Kerminen V.-M. 2014. CO<sub>2</sub>-induced terrestrial climate feedback mechanism: From carbon sink to aerosol source and back. *Boreal Env. Res.* 19, Suppl. B: 122–131.
- Kulmala M. 2015. China's choking cocktail. *Nature* 526: 497–499.
- Kulmala M., Lappalainen H.K., Petäjä T., Kurten T., Kerminen V.-M., Viisanen Y., Hari P., Bondur V., Kasimov N., Kotlyakov V., Matvienko G., Baklanov A, Guo H., Ding A., Hansson H.-C., & Zilitinkevich S. 2015. Introduction: The Pan-Eurasian Experiment (PEEX) — multi-disciplinary, multi-scale and multi-component research and capacity building initiative. *Atmos. Chem. Phys.* 15: 13085–13096.
- Kulmala M., Hörrak U., Manninen H.E., Mirme S., Noppel M., Lehtipalo K., Junninen H., Vehkamäki H., Kerminen V.-M., Noe S.M. & Tamm H. 2016a. The legacy of Finnish–Estonian air ion and aerosol workshops. *Boreal Env. Res.* 21:3: 181–206.
- Kulmala M., Kerminen V.-M., Petäjä T., Ding A. J. & Wang L. 2017b. Atmospheric gas-to-particle conversion: why NPF events are observed in megacities? *Faraday Discuss.* 200: 271–288.
- Kulmala M. 2018. Build a global Earth observatory. *Nature* 553: 21–22.
- Kulmala M., Ezhova E., Kalliokoski T., Noe S., Vesala T., Lohila A., Liski J., Makkonen R., Bäck J., Petäjä T. & Kerminen V.-M. 2020. CarbonSink+ -accounting for multiple feedbacks from forests. *Boreal Env. Res.* 25: 145–149.
- Kulmala M., Dada L., Daellenbach K. R., Yan C., Stolzenburg D., Kontkanen J., Ezhova E., Hakala S., Tuovinen S., Kokkonen T. V., Kurppa M., Cai R., Zhou Y., Yin R., Baalbaki R., Chan T., Chu B., Deng C., Fu Y., Ge

- M., He H., Heikkinen L., Junninen H., Liu Y., Lu Y., Nie W., Rusanen A., Vakkari V., Wang Y., Yang G., Yao L., Zheng J., Kujansuu J., Kangasluoma J., Petäjä T., Paasonen P., Järvi L., Worsnop D., Ding A., Liu Y., Wang L., Jiang J., Bianchi F. & Kerminen V.-M. 2021a. Is reducing new particle formation a plausible solution to mitigate particulate air pollution in Beijing and other Chinese megacities? *Faraday Discuss.* 226: 334-347.
- Kulmala M., Lintunen A., Ylivinkka I., Mikkala J., Rantanen R., Kujansuu J., Petäjä T., & Lappalainen H.K. 2021b. Atmospheric and ecosystem big data providing key contributions in reaching United Nations' sustainable development goals. *Big Earth Data* 5, 3: 277-305. doi: 10.1080/20964471.2021.1936943
- Kukkonen I., Suhonen E., Ezhova E., Lappalainen H. K., Gennadinik V., Ponomareva O., Gravis A., Miles V., Kulmala M., Melnikov V. & Drozdov, D. 2020. Observations and modelling of ground temperature evolution in the discontinuous permafrost zone in Nady, North-West Siberia. *Permafrost and Periglacial Processes* 31:2: 264-280.
- Kurdi L. & Kochanski E. 1989. Theoretical studies of sulfuric acid monohydrate: Neutral or ionic complex? *Chem. Phys. Lett.* 158: 111-115.
- Kurtén T., Kulmala M., Dal Maso M., Suni T., Reissel A., Vehkamäki H., Hari P., Laaksonen A., Viisanen Y. & Vesala T. 2003. Estimation of different forest-related contributions to the radiative balance using observations in southern Finland. *Boreal Env. Res.* 8: 275–285.
- Kurtén T., Loukonen V., Vehkamäki H. & Kulmala M. 2008. Amines are likely to enhance neutral and ion-induced sulfuric acid-water nucleation in the atmosphere more effectively than ammonia. *Atmos. Chem. Phys.* 8: 4095–4103.
- Kurtén T., Möller K.H., Nguyen T.B., Schwantes R.H., Misztal P.K., Su L., Wennberg P.O., Fry J.L. & Kjaergaard H.G. 2017. Alkoxy radical bond scissions explain the anomalously low secondary organic aerosol and organonitrate yields from  $\alpha$ -pinene + NO<sub>3</sub>. *Phys. Chem. Lett.* 8:13: 2826–2834.
- Kyrö E.-M., Väänänen R., Kerminen V.-M., Virkkula A., Petäjä T., Dal Maso M., Nieminen T., Juhola S., Shcherbinin A., Riipinen I., Lehtipalo K., Keronen P., Aalto P. P., Hari P. & Kulmala M. 2014. Trends in new particle formation in eastern Lapland, Finland: effect of decreasing sulfur emissions from Kola Peninsula. *Atmos. Chem. Phys.* 14: 4383-4396.
- Laakso L., Petäjä T., Lehtinen K. E. J., Kulmala M., Paatero J., Horrak U., Tammet H. & Joutsensaari J. 2004. Ion production rate in a boreal forest based on ion, particle and radiation measurements. *Atmos. Chem. Phys.* 4: 1933-1943.
- Laitinen T., Petäjä T., Backman J., Hartonen K., Junninen H., Ruiz-Jiménez J., Worsnop D., Kulmala M. & Riekkola M.-L. 2014. Carbon clusters in 50 nm urban air aerosol particles quantified by laser desorption–ionization aerosol mass spectrometer. *Int. J. Mass Spectrom.* 358: 17-24.
- Lampilahti J., Manninen H. E., Nieminen T., Mirme S., Ehn M., Pullinen I., Leino K., Schobesberger S., Kangasluoma J., Kontkanen J., Järvinen E., Väänänen R., Yli-Juuti T., Krejci R., Lehtipalo K., Levula J., Mirme A., Decesari S., Tillmann R., Worsnop D. R., Rohrer F., Kiendler-Scharr A., Petäjä T., Kerminen V.-M., Mentel T. F. & Kulmala M. 2021. Zeppelin-led study on the onset of new particle formation in the planetary boundary layer. *Atmos. Chem. Phys.* 21: 12649–12663.
- Lampilahti J., Manninen H. E., Leino K., Väänänen R., Manninen A., Buenrostro Mazon S., Nieminen T., Leskinen M., Enroth J., Bister M., Zilitinkevich S., Kangasluoma J., Järvinen H., Kerminen V.-M., Petäjä T. & Kulmala M. 2020. Roll vortices induce new particle formation bursts in the planetary boundary layer. *Atmos. Chem. Phys.* 20: 11841-11854.
- Lan H., Zhang W., Smätt J.-H., Koivula R., Hartonen K. & Riekkola M.-L. 2019a. Selective extraction of aliphatic amines by functionalized mesoporous silica-coated solid phase microextraction. *Microchim. Acta* 186: 412. <https://doi.org/10.1007/s00604-019-3523-5>
- Lan H., Holopainen J., Hartonen K., Jussila M., Ritala M. & Riekkola M.-L. 2019b. Fully Automated Online Dynamic In-Tube Extraction for Continuous Sampling of Volatile Organic Compounds in Air. *Anal. Chem.* 91: 8507-8515.
- Lan H., Ruiz-Jimenez J., Leleev Y., Demaria G., Jussila M., Hartonen K. & Riekkola M.-L. 2021. Quantitative analysis and spatial and temporal distribution of volatile organic compounds in atmospheric air by utilizing drone with miniaturized samplers. *Chemosphere* 282: 131024. <https://doi.org/10.1016/j.chemosphere.2021.131024>
- Lappalainen H.K., Petäjä T., Kujansuu J., Kerminen V.-M., 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. & Kulmala M. 2014. 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: 13-48.
- Lappalainen H.K., Kulmala M. & Zilitinkevich S. (eds.) 2015. Pan- Eurasian experiment (PEEX) science plan. 307 p. [https://www.atm.helsinki.fi/peex/images/PEEX\\_Science\\_Plan.pdf](https://www.atm.helsinki.fi/peex/images/PEEX_Science_Plan.pdf)
- Lappalainen H.K., Kerminen V.-M., Petäjä T., Kurtén 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., Hörrak 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., Lísitzin

- A., Mahura A., Makshtas A., Mareev E., Mazon S., Matishov D., Melnikov V., Mikhailov E., Moiseev 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., Spracklen D.V., Su H., Subetto D.A., Sun J., Terzhvik A.Y., Timofeyev Y., Troitskaya Y., Tynkkynen V.-P., Kharuk V.I., Zaytseva N., Zhang J., Viisanen Y., Vesala T., Hari P., Hansson H.C., Matvienko G.G., Kasimov N.S., Guo H., Bondur V., Zilitinkevich S. & Kulmala M. 2016. Pan-Eurasian Experiment (PEEX): towards a holistic understanding of the feedbacks and interactions in the land–atmosphere–ocean–society continuum in the northern Eurasian region. *Atmos. Chem. Phys.* 16: 14421–14461.
- Lappalainen H.K., Kulmala M., Kujansuu J., Petäjä T., Mahura A., de Leeuw G., Zilitinkevich S., Juustila M., Kerminen V.-M., Bornstein B., Jiahua Z., Yong X., Yubao Q., Dong L., Jie L. & Huadong G. 2018. The Silk Road agenda of the Pan-Eurasian Experiment (PEEX) program. *Big Earth Data* 2:1: 8–35.
- Lappalainen H.K., Altimir N., Kerminen V., Petäjä T., Makkonen R., Alekseychik P., Zaitseva N., Bashmakova I., Kujansuu J., Lauri A., Haapanala P., Mazon S.B., Borisova A., Konstantinov P., Chalov S., Laurila T., Asmi E., Lihavainen H., Bäck J., Arshinov M., Mahura A., Arnold S., Vihma T., Uotila P., de Leeuw G., Kukkonen I., Malkhazova S., Tynkkynen V., Fedorova I., Hansson H.C., Dobrolyubov S., Melnikov V., Matvienko G., Baklanov A., Viisanen Y., Kasimov N., Guo H., Bondur V., Zilitinkevich S. & Kulmala M. 2019. Pan-Eurasian Experiment (PEEX) program: An overview of the first 5 years in operation and future prospects. *Geography, environment, sustainability* 11: 6–19.
- Lappalainen H.K., Petäjä T., Vihma T., Räisänen J., Baklanov A., Chalov S., Esau I., Ezhova E., Leppäranta M., Pozdnyakov D., Pumpanen J., Andreae M.O., Arshinov M., Asmi E., Bai J., Bashmachnikov I., Belan B., Bianchi F., Biskaborn B., Boy M., Bäck J., Cheng B., Chubarova N., Duplissy J., Dyukarev E., Eleftheriadis K., Forsius M., Heimann M., Juhola S., Kononov V., Kononov I., Konstantinov P., Köster K., Lapshina E., Lintunen A., Mahura A., Makkonen R., Malkhazova S., Mammarella I., Mammola S., Buenrostro Mazon S., Meinander O., Mikhailov E., Miles V., Myslenkov S., Orlov D., Paris J.-D., Pirazzini R., Popovicheva O., Pulliaainen J., Rautiaainen K., Sachs T., Shevchenko V., Skorokhod A., Stohl A., Suhonen E., Thomson E.S., Tsidilina M., Tynkkynen V.-P., Uotila P., Virkkula A., Voropay N., Wolf T., Yasunaka S., Zhang J., Qiu Y., Ding A., Guo H., Bondur V., Kasimov N., Zilitinkevich S., Kerminen V.-M. & Kulmala M. 2022a. Overview: Recent advances in the understanding of the northern Eurasian environments and of the urban air quality in China — a Pan-Eurasian Experiment (PEEX) programme perspective. *Atmos. Chem. Phys.* 22: 4413–4469.
- Lappalainen H., Petäjä T., Lintunen A. & Kulmala M. 2022b. Institute for Atmospheric and Earth System Research (INAR): Showcases for making science diplomacy. *Polar Record* 58, E15. doi:10.1017/S0032247421000760
- Launiainen S., Vesala T., Möllder M., Mammarella I., Smolander S., Rannik Ü., Kolari P., Hari P., Lindroth A. G. & Katul G. 2007. Vertical variability and effect of stability in turbulent characteristics and fluxes down to the floor of a pine forest. *Tellus B: Chemical and Physical Meteorology* 59, 5: 919–936.
- Launiainen S. 2010. Seasonal and inter-annual variability of energy exchange above a boreal Scots pine forest. *Biogeosciences* 7: 3921–3940.
- Launiainen S., Katul G.G., Leppä K., Kolari P., Aslan T., Grönholm T., Korhonen L., Mammarella I. & Vesala T. 2022. Does growing atmospheric CO<sub>2</sub> explain increasing carbon sink in a boreal coniferous forest?. *Global Change Biology* 28: 2910–2929.
- Lehtinen K. E. J., Dal Maso M., Kulmala M. & Kerminen V.-M. 2007. Estimating nucleation rates from apparent particle formation rates and vice-versa: Revised formulation of the Kerminen-Kulmala equation. *J. Aerosol Sci.* 38: 988–994.
- Lehtipalo K., Sipilä M., Riipinen I., Nieminen T. & Kulmala M. 2009. Analysis of atmospheric neutral and charged molecular clusters in boreal forest using pulse-height CPC. *Atmos. Chem. Phys.* 9: 4177–4184.
- Lehtipalo K., Rondo L., Kontkanen J., Schobesberger S., Jokinen T., Sarnela N., Kürten A., Ehrhart S., Franchin A., Nieminen T., Riccobono F., Sipilä M., Yli-Juuti T., Duplissy J., Adamov A., Ahlm L., Almeida J., Amorim A., Bianchi F., Breitenlechner M., Dommen J., Downard A. J., Dunne E. M., Flagan R. C., Guida R., Hakala J., Hansel A., Jud W., Kangasluoma J., Kerminen V.-M., Keskinen H., Kim J., Kirkby J., Kupc A., Kupiainen-Määttä O., Laaksonen A., Lawler M. J., Leiminger M., Mathot S., Olenius T., Ortega I. K., Onnela A., Petäjä T., Praplan A., Rissanen M. P., Ruuskanen T., Santos F. D., Schallhart S., Schnitzhofer R., Simon M., Smith J. N., Tröstl J., Tsagkogeorgas G., Tomé A., Vaattovaara P., Vehkamäki H., Vrtala A. E., Wagner P. E., Williamson C., Wimmer D., Winkler P. M., Virtanen A., Donahue N. M., Carslaw K. S., Baltensperger U., Riipinen I., Curtius J., Worsnop D. R. & Kulmala M. 2016. The effect of acid-base clustering and ions on the growth of atmospheric nano-particles. *Nat. Commun.* 7: 11594. doi: 10.1038/ncomms11594
- Lehtipalo K., Yan C., Dada L., Bianchi F., Xiao M., Wagner R., Stolzenburg D., Ahonen L.R., Amorim A., Baccarini A., Bauer P.S., Baumgartner B., Bergen A., Bernhammer A.-K., Breitenlechner M., Brilke S., Buchholz A., Buenrostro Mazon S., Chen D., Chen X., Dias A., Dommen J., Draper D.C., Duplissy J., Ehn M., Finkenzeller H., Fischer L., Frege C., Fuchs C., Garmash O., Gordon H., Hakala J., He X., Heikkinen L., Heinrizi M., Helm J., Hofbauer V., Hoyle C.R., Jokinen T., Kangasluoma J., Kerminen V.M., Kim C., Kirkby J., Kontkanen J., Kürten A., Lawler M.J., Mai H., Mathot S., Mauldin III R.L., Molteni U., Nichman L., Nie W., Nieminen T., Ojdanic A., Onnela A., Passananti M., Petäjä T., Piel F., Pospisilova V., Quéléver L.L.J., Rissanen M.P., Rose C., Sarnela N., Schallhart S., Schuchmann S., Sengupta K., Simon M., Sipilä M., Tauber C., Tomé A., Tröstl J.,

- Väisänen O., Vogel A.L., Volkamer R., Wagner A.C., Wang M., Weitz L., Wimmer D., Ye P., Ylisirniö A., Zha Q., Carslaw K.S., Curtius J., Donahue N.M., Flagan R.C., Hansel A., Riipinen I., Virtanen A., Winkler P.M., Baltensperger U., Kulmala M. & Worsnop D.R. 2018. Multi-component new particle formation from sulfuric acid, ammonia, and biogenic vapors. *Science Adv.* 12: eaau5363. DOI: 10.1126/sciadv.aau5363
- Lehtipalo K., Ahonen L.R., Baalbaki R., Sulo J., Chan T., Laurila T., Dada L., Duplissy J., Miettinen E., Vanhanen J., Kangasluoma J., Kulmala M., Petäjä T. & Jokinen T. 2022. The standard operating procedure for Airmodus Particle Size Magnifier and nano-Condensation Nucleus Counter. *J. Aerosol Sci.* 159: 105896.
- Leino K., Nieminen T., Manninen H. E., Petäjä T., Kerminen V.-M. & Kulmala M. 2016. Intermediate ions as a strong indicator of new particle formation bursts in boreal forest. *Boreal Env. Res.* 21: 274-286.
- Lelieveld J., Evans J.S., Fnais M., Giannadaki D. & Pozzer A. 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525: 367-371.
- Leskinen A., Portin H., Komppula M., Miettinen P., Arola A., Lihavainen H., Hatakka J., Laaksonen A. & Lehtinen K. E. J. 2009. Overview of the research activities and results at Puijo semi-urban measurement station. *Boreal Env. Res.* 14: 576-590.
- Li H. & Moisseev D. 2020. Two Layers of Melting Ice Particles Within a Single Radar Bright Band: Interpretation and Implications. *Geophysical Research Letters* 47:13:e2020GL087499.
- Li H., Moisseev D. & von Lerber A. 2018. How does riming affect dual-polarization radar observations and snowflake shape? *J. Geophys. Res. Atmos.* 123: 6070-6081.
- Liao L., Dal Maso M., Taipale R., Rinne J., Ehn M., Junninen H., Äijälä M., Nieminen T., Alekseychik P., Hulkkonen M., Worsnop D. R., Kerminen V.-M. & Kulmala M. 2011. Monoterpene pollution episodes in a forest environment: indication of anthropogenic origin and association with aerosol particles. *Boreal Env. Res.* 16: 288-303.
- Liao L., Kerminen V.-M., Boy M., Kulmala M. & Dal Maso M. 2014. Temperature influence on the natural aerosol budget over boreal forests. *Atmos. Chem. Phys.* 14: 8295-8308.
- Lihavainen H., Viisanen Y. & Kulmala M. 2000. Homogeneous nucleation of n-pentanol in a laminar flow diffusion chamber. *J. Chem. Phys.* 114: 10031-10038.
- Lihavainen H., Kerminen V.-M., Komppula M., Hatakka J., Aaltonen V., Kulmala M. & Viisanen Y. 2003. Production of "potential" cloud condensation nuclei associated with atmospheric new-particle formation in northern Finland. *J. Geophys. Res.* 108:D24: 4782. doi:10.1029/2003JD003887
- Lihavainen H., Kerminen V.-M., Tunved P., Aaltonen V., Arola A., Hatakka J., Hyvärinen A. & Viisanen Y. 2009. Observational signature of the direct radiative effect by natural boreal forest aerosols and its relation to the corresponding first indirect effect. *J. Geophys. Res.* 114: D20206. doi:10.1029/2009JD012078
- Lihavainen H., Asmi E., Aaltonen V., Makkonen U. & Kerminen V.-M. 2015. Direct radiative feedback due to biogenic secondary organic aerosol estimated from boreal forest site observations. *Environ. Res. Lett.* 10: 104005. doi:10.1088/1748-9326/10/10/104005
- Lindfors L., Hölttä T., Lintunen A., Porcar-Castell A., Nikinmaa E. & Juurola E. 2015. Dynamics of leaf gas exchange, chlorophyll fluorescence and stem diameter changes during freezing and thawing of Scots pine seedlings. *Tree Physiol.* 35: 1314-1324.
- Lindroth A., Holst J., Linderson M.-L., Aurela M., Biermann T., Heliasz M., Chi J., Ibrom A., Kolari P., Klemmedtsson L., Krasnova A., Laurila T., Lehner I., Lohila A., Mammarella I., Mölder M., Löfvenius M., Ottosson, P. M., Pilegaard K., Soosaar K., Vesala T., Vestin P., Weslien P. & Nilsson M. 2020. Effects of drought and meteorological forcing on carbon and water fluxes in Nordic forests during the dry summer of 2018. *Phil. Trans. R. Soc. B* 375:20190516. <http://doi.org/10.1098/rstb.2019.0516>
- Lintunen A., Lindfors L., Kolari P., Juurola E., Nikinmaa E. & Hölttä T. 2014. Bursts of CO<sub>2</sub> released during freezing offer a new perspective on avoidance of winter embolism in trees. *Annals of Botany*, 114:8: 1711-1718.
- Lintunen A., Paljakka T., Salmon Y., Dewar R., Riikonen A. & Hölttä T. 2020. 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.
- Lintunen A., Preisler Y., Oz I., Yakir D., Vesala T. & Hölttä T. 2021. Bark transpiration rates can reach needle transpiration rates under dry conditions in a semi-arid forest. *Front. Plant Sci.* 12. doi:10.3389/fpls.2021.790684
- Liu W., Atherton J., Möttöus M., Gastellu-Etchegorry J.-P., Malenovsky Z., Raunonen P., Åkerblom M., Mäkipää R. & Porcar-Castell A. 2019. Simulating solar-induced chlorophyll fluorescence in a boreal forest stand reconstructed from terrestrial laser scanning measurements. *Remote Sensing of Environment* 232: 111274. <https://doi.org/10.1016/j.rse.2019.111274>
- Liu Y.C., Yan C., Feng Z., Zheng F., Fan X., Zhang Y., Li C., Zhou Y., Lin Z., Guo Y., Zhang Y., Ma L., Zhou W., Liu Z., Dada L., Dällenbach K., Kontkanen J., Cai R., Chan T., Chu B., Du W., Yao L., Wang Y., Cai J., Kangasluoma J., Kokkonen T., Kujansuu J., Rusanen A., Deng C., Fu Y., Yin R., Li X., Lu Y., Liu Y., Lian C., Yang D., Wang W., Ge M., Wang Y., Worsnop D.R., Junninen H., He H., Kerminen V.-M., Zheng J., Wang L., Jiang J., Petäjä T., Bianchi F. & Kulmala M. 2020. Continuous and comprehensive atmospheric observation in Beijing: a station to understand the complex urban atmospheric environment. *Big Earth Data* 4: 295-321.
- Lohmann U., Friebel F., Kanji Z. A., Mahrt F., Mensah A. A. & Neubauer D. 2020. Future warming exacerbated by aged-soot effect on cloud formation. *Nature Geoscience* 13: 674-680.
- Lohila A., Tuovinen J.-P., Hatakka J., Aurela M., Vuorenmaa J., Haakana M., & Laurila T. 2015. Carbon dioxide and energy fluxes over a northern boreal lake. *Boreal Environment Research* 20: 474-488.
- Lohila A., Aalto T., Aurela M., Hatakka J., Tuovinen J.-P.,

- Kilikki J., Penttilä T., Vuorenmaa J., Hänninen P., Sutinen R., Viisanen Y. & Laurila T. 2016. Large contribution of boreal upland forest soils to a catchment-scale CH<sub>4</sub> balance in a wet year. *Geophysical Research Letters* 43: 2946–2953.
- Lopez-Hilfiker F. D., Mohr C., Ehn M., Rubach F., Kleist E., Wildt J., Mentel Th. F., Lutz A., Hallquist M., Worsnop D. & Thornton J. A. 2014. A novel method for online analysis of gas and particle composition: description and evaluation of a Filter Inlet for Gases and AEROSols (FIGAERO). *Atmos. Meas. Tech.* 7: 983–1001.
- Lorente A., Borsdorff T., Butz A., Hasekamp O., de Brugh J., Schneider A., Wu L., Hase F., Kivi R., Wunch D., Pollard D., Shiomi K., Deutscher N., Velasco V., Roehl C., Wennberg P., Warneke T. & Landgraf J. 2021. Methane retrieved from TROPOMI: Improvement of the dataproduct and validation of the first 2 years of measurements. *Atmos. Meas. Tech.* 14: 665–684.
- Machacova K., Bäck J., Vanhatalo A., Halmeenmäki E., Kolari P., Mammarella I., Pumpanen J., Acosta M., Urban O. & Pihlatie M. 2016. Pinus sylvestris as a missing source of nitrous oxide and methane in boreal forest. *Scientific Reports* 6: 23410. doi: 10.1038/srep23410
- Machacova K., Vainio E., Urban O. & Pihlatie M. 2019. Seasonal dynamics of stem N<sub>2</sub>O exchange follow the physiological activity of boreal trees. *Nature Comm.* 10: 4989. <https://doi.org/10.1038/s41467-019-12976-y>
- Mahowald N. 2011. Aerosol indirect effect on biogeochemical cycles and climate. *Science* 334: 794–796.
- Mäkelä A., Hari P., Berninger F., Hänninen H. & Nikinmaa E. 2004. Acclimation of photosynthetic capacity in Scots pine to the annual cycle of temperature. *Tree Physiology* 24: 369–376.
- Mäkelä A., Kolari P., Karimäki J., Nikinmaa E., Perämäki M. & Hari P. 2006. Modelling five years of weather-driven variation of GPP in a boreal forest. *Agricultural and Forest Meteorology* 139: 382–398.
- Mäkelä A., Pulkkinen M., Kolari P., Lagergren F., Lindroth A., Loustau D., Nikinmaa E., Vesala T., Hari P. 2008. Developing an empirical model of stand GPP with LUE approach: results from an analysis of eddy covariance data at five contrasting conifer sites in Europe. *Global Change Biology* 14: 92–108.
- Mäkelä J., Aalto P., Jokinen V., Pohja T., Nissinen A., Palmroth S., Markkanen T., Seitsonen K., Lihavainen H. & Kulmala M. 1997. Observations of ultrafine aerosol particle formation and growth in boreal forest. *Geophys. Res. Lett.* 21: 1219–1222.
- Mäki M., Heinonsalo J., Hellén H. & Bäck J. 2017. Contribution of understory vegetation and soil processes to boreal forest isoprenoid exchange. *Biogeosciences* 14: 1055–1073.
- Mäki M., Aalto J., Hellén H., Pihlatie M. & Bäck J. 2019a. Interannual and seasonal dynamics of volatile organic compound fluxes from the boreal forest floor. *Frontiers in Plant Science* 10: 191. <https://doi.org/10.3389/fpls.2019.00191>
- Mäki M., Aaltonen H., Heinonsalo J., Hellén H., Pumpanen J. & Bäck J. 2019b. Boreal forest soil is a significant and diverse source of volatile organic compounds. *Plant and Soil* 441: 89–110.
- Mäki M., Krasnov D. J., Hellén H., Noe S. N. & Bäck, J. 2019c. Stand type affects fluxes of volatile organic compounds from the forest floor in hemiboreal and boreal climates. *Plant and Soil* 441: 363–381.
- Makkonen R., Asmi A., Korhonen H., Kokkola H., Järvenoja S., Räisänen P., Lehtinen K. E. J., Laaksonen A., Kerminen V.-M., Järvinen H., Lohmann U., Bannartz R., Feichter J. & Kulmala M. 2009. Sensitivity of aerosol concentrations and cloud properties to nucleation and secondary organic distribution in ECHAM5-HAM global circulation model. *Atmos. Chem. Phys.* 9: 1747–1766.
- Makkonen R., Romakkaniemi S., Kokkola H., Stier P., Räisänen P., Rast S., Feichter J., Kulmala M. & Laaksonen A. 2012a. Brightening of the global cloud field by nitric acid and the associated radiative forcing. *Atmos. Chem. Phys.* 12: 7625–7633.
- Makkonen R., Asmi A., Kerminen V.-M., Boy M., Arneth A., Guenther A. & Kulmala M. 2012b. BVOC-aerosol-climate interactions in the global aerosol-climate model ECHAM5.5-HAM2. *Atmos. Chem. Phys.* 12: 10077–10096.
- Makkonen R., Asmi A., Kerminen V.-M., Boy M., Arneth A., Hari P. & Kulmala M. 2012c. Air pollution control and decreasing new particle formation lead to strong climate warming. *Atmos. Chem. Phys.* 12: 1515–1524.
- Mäli T., Mäki M., Hellén H., Heinonsalo J., Bäck J. & Lundell T. 2019. Decomposition of spruce wood and release of volatile organic compounds depend on decay type, fungal interactions and enzyme production patterns. *FEMS Microbiology Ecology* 95:9: fiz135. <https://doi.org/10.1093/femsec/fiz135>
- Malila J. 2018. On the early studies recognizing the role of sulphuric acid in the atmospheric haze and new particle formation. *Tellus B* 70: 1471913.
- Mammarella I., Kolari P., Rinne J., Keronen P., Pumpanen J. & Vesala T. 2007. Determining the contribution of vertical advection to the net ecosystem exchange at Hyytiälä forest, Finland. *Tellus B: Chemical and Physical Meteorology* 59:5: 900–909.
- Mammarella I., Launiainen S., Grönholm T., Keronen P., Pumpanen J., Rannik Ü. & Vesala T. 2009. Relative Humidity Effect on the High-Frequency Attenuation of Water Vapor Flux Measured by a Closed-Path Eddy Covariance System. *Journal of Atmospheric and Oceanic Technology* 26:9: 1856–1866.
- Mammarella I., Nordbo A., Rannik U., Haapanala S., Levula J., Laakso H., Ojala A., Peltola O., Heiskanen J., Pumpanen J. & Vesala T. 2015. Carbon dioxide and energy fluxes over a small boreal lake in Southern Finland. *Journal of Geophysical Research: Biogeosciences* 120: 1296–1314.
- Mammarella I., Peltola O., Nordbo A., Järvi L. & Rannik Ü. 2016. Quantifying the uncertainty of eddy covariance fluxes due to the use of different software packages and combinations of processing steps in two contrasting ecosystems. *Atmos. Meas. Tech.* 9: 4915–4933.
- Manka A., Brus D., Hyvärinen A.-P., Lihavainen H., Wölk J. & Strey R. 2010. Homogeneous water nucleation in

- a laminar flow diffusion chamber. *J. Chem. Phys.* 132: 244505.
- Manninen H. E., Petäjä T., Asmi E., Riipinen I., Nieminen T., Mikkilä J., Hörrak U., Mirme A., Mirme S., Laakso L., Kerminen V.-M. & Kulmala M. 2009. Long-term field measurements of charged and neutral clusters using Neutral cluster and Air Ion Spectrometer (NAIS). *Boreal Env. Res.* 14: 591-605.
- Manninen H. E., Nieminen T., Asmi E., Gagné S., Häkinen S., Lehtipalo K., Aalto P., Vana M., Mirme A., Mirme S., Hörrak U., Plass-Dülmer C., Stange G., Kiss G., Hoffer A., Törö N., Moerman M., Henzing B., de Leeuw G., Brinkenberg M., Kouvarakis G.N., Bougiatioti A., Mihalopoulos N., O'Dowd C., Ceburnis D., Arneth A., Svenningsson B., Swietlicki E., Tarozzi L., Decesari S., Facchini M.C., Birmili W., Sonntag A., Wiedensohler A., Boulou J., Sellegri K., Laj P., Gysel M., Bukowicki N., Weingartner E., Wehrle G., Laaksonen A., Hamed A., Joutsensaari J., Petäjä T., Kerminen V.-M. & Kulmala M. 2010. EUCAARI ion spectrometer measurements at 12 European sites — analysis of new particle formation events. *Atmos. Chem. Phys.* 10: 7907-7927.
- Manninen H., Bäck J., Sihto-Nissilä S.-L., Huffman J., Pessi A.-M., Hiltunen V., Aalto P., Hidalgo P., Hari P., Saarto A., Kulmala M. & Petäjä T. 2014. Patterns in airborne pollen and other primary biological aerosol particles (PBAP), and their contribution to aerosol mass and number in a boreal forest. *Boreal Env. Res.* 19: 383-405.
- Männistö E., Korrensalo A., Alekseychik P., Mammarella I., Peltola O., Vesala T. & Tuittila E.-S. 2019. Multiyear methane ebullition measurements from water and bare peat surfaces of a patterned boreal bog. *Biogeosciences* 16: 2409-2421.
- Marttila H., Aurela M., Büngener L., Rossi P.M., Lohila A., Postila H., Saari M., Penttilä T. & Kløve B. 2021. Quantifying groundwater fluxes from an aapa mire to a river-side esker formation. *Hydrology Research*, nh2021064, <https://doi.org/10.2166/nh.2021.064>
- Matkala L., Kulmala L., Kolari P., Aurela M. & Bäck J. 2021. Resilience of carbon dioxide and water exchange to extreme weather events in subarctic Scots pine and Norway spruce stands. *Agricultural and Forest Meteorology* 296: 108239. <https://doi.org/10.1016/j.agrformet.2020.108239>
- McGrath M. J., Olenius T., Ortega I. K., Loukonen V., Paasonen P., Kurten T., Kulmala M. & Vehkamäki H. 2012. Atmospheric Cluster Dynamics Code: a flexible method for solution of the birth-death equations. *Atmos. Chem. Phys.* 12: 2345-2355.
- McMurry P. H. & Friedlander S. K. 1979. New particle formation in the presence of an aerosol. *Atmos. Environ.* 13: 1635-1651.
- McMurry P.H. 1983. New particle formation in the presence of an aerosol: rates, time scales, and sub-0.01  $\mu\text{m}$  size distributions. *J. Colloid Interface Sci.* 78: 513-527.
- Mercado L. M., Bellouin N., Sitch S., Bourcher O., Huntingford C., Wild M. & Cox P. M. 2009. Impact of changes in diffuse radiation on the global land carbon sink. *Nature* 458: 1014-1017.
- Merikanto J., Spracklen D. V., Mann G. W., Pickering S. J. & Carslaw K. S. 2009. Impact of nucleation on global CCN. *Atmos. Chem. Phys.* 9: 8601-8616.
- Mielonen T., Laakso A., Karhunen A., Kokkola H., Partanen A.-I., Korhonen H., Romakkaniemi S. & Lehtinen K.E.J. 2015. From nuclear power to coal power: Aerosol-induced health and radiative effects. *Journal of Geophysical Research: Atmospheres* 120: 12631-12643.
- Mikkonen S., Korhonen H., Romakkaniemi S., Smith J.N., Joutsensaari J., Lehtinen K.E.J., Hamed A., Breider T.J., Birmili W., Spindler G., Plass-Duelmer C., Facchini M.C. & Laaksonen A. 2011. Meteorological and trace gas factors affecting the number concentration of atmospheric Aitken ( $D_p=50$  nm) particles in the continental boundary layer: parameterization using a multivariate mixed effects model. *Geosci. Model Dev.* 4: 1-13.
- Mikkonen S., Laine M., Mäkelä H. M., Gregow H., Tuomenvirta H., Lahtinen M., & Laaksonen A. 2015. Trends in the average temperature in Finland, 1847-2013. *Stochastic Environmental Research and Risk Assessment* 29: 1521-1529.
- Mikkonen S., Németh Z., Varga V., Weidinger T., Leinonen V., Yli-Juuti T. & Salma I. 2020. Decennial time trends and diurnal patterns of particle number concentrations in a central European city between 2008 and 2018. *Atmos. Chem. Phys.* 20: 12247-12263.
- Minunno F., Peltoniemi M., Launiainen S., Aurela M., Mammarella I., Lindroth A., Lohela A., Minkinen K., Mäkelä A. 2016. Calibration and validation of a semi-empirical flux ecosystem model for coniferous forests in the Boreal region. *Ecological Modelling* 341: 37-52.
- Mirme S. & Mirme A. 2013. The mathematical principles and design of the NAIS — a spectrometer for the measurement of cluster ion and nanometer aerosol size distributions. *Atmos. Meas. Tech.* 6: 1061-1071.
- Mirme A., Tamm E., Mordas G., Vana M., Uin J., Mirme S., Bernotas T., Laakso L., Hirsikko A. & Kulmala M. 2007. Wide-range multi-channel Air Ion Spectrometer. *Boreal Env. Res.* 12: 247-264.
- Mitchell D.L., Zhang R. & Pitter R.L. 1990. Mass-dimensional relationships for ice particles and the influence of riming on snowfall rates. *Journal of Applied Meteorology and Climatology* 29: 153-163.
- Mogensen D., Gierens R., Crowley J.N., Keronen P., Smolander S., Sogachev A., Nölscher A.C., Zhou L., Kulmala M., Tang M.J., Williams J. & Boy M. 2015. Simulations of atmospheric OH, O<sub>3</sub> and NO<sub>3</sub> reactivities within and above the boreal forest. *Atmos. Chem. Phys.* 15: 3909-3932.
- Moisseev D., von Lerber A. & Tiira J. 2017. Quantifying the effect of riming on snowfall using ground-based observations. *J. Geophys. Res. Atmos.* 122: 4019-4037.
- Moisseev D., Lautaportti S., Alku L., Tabakova K., O'Connor E. J., Leskinen M. & Kulmala M. 2019. Inadvertent localized intensification of precipitation by aircraft. *J. Geophys. Res. Atmos.* 124: 2094-2104. <https://doi.org/10.1029/2018JD029449>
- Mordas G., Sipilä M. & Kulmala M. 2008a. Nanometer particle detection by the condensation particle counter



- UF-02proto. *Aerosol Sci. Tech.* 42: 521-527.
- Mordas G., Manninen H. E., Petäjä T., Aalto P. P., Hämeri K. & Kulmala M. 2008b. On operation of the ultra-fine water-based CPC TSI3786 and comparison with other TSI models (TSI3776, TSI3772, TSI3025, TSI3010, TSI3007). *Aerosol Sci. Tech.* 42: 152-158.
- Morris C. E., Sands D. C., Bardin M., Jaenicke R., Vogel B., Leyronas C., Ariya P. A. & Psenner R. 2011. Microbiology and atmospheric processes: research challenges concerning the impact of airborne micro-organisms on the atmosphere and climate. *Biogeosciences* 8: 17–25.
- Motlagh H.N., Lagerspetz E., Nurmi P., Li X., Varjonen S., Mineraud J., Siekkinen M., Rebeiro-Hargrave A., Hussein T., Petäjä T., Kulmala M. & Tarkoma S. 2020. Toward Massive Scale Air Quality Monitoring. *IEEE Communications Magazine*. 58:2: 54-59.
- Neitola K., Brus D., Makkonen U., Sipilä M., Lihavainen H. & Kulmala M. 2014. Effect of addition of four base compounds on sulphuric-acid– water new-particle formation: a laboratory study. *Boreal Env. Res.* 19, suppl. B: 257–274.
- Nemitz E., Mammarella I., Ibrom A., Aurela M., Burba G., Dengel S., Gielen B., Grelle A., Heinesch B., Herbst M., Hörtnagl L., Klemmedtsson L., Lindroth A., Lohila A., McDermitt D.K., Meier P., Merbold L., Nelson D., Nicolini G., Nilsson M.P., Peltola O., Rinne J. & Zahniser M. 2018. Standardization of eddy covariance flux measurements of methane and nitrous oxide. *Int. Agrophys.* 32: 517-549.
- Nichman L., Järvinen E., Dorsey J., Connolly P., Duplissy J., Fuchs C., Ignatius K., Sengupta K., Stratmann F., Möhler O., Schnaiter M. & Gallagher M. 2017. Inter-comparison study and optical asphericity measurements of small ice particles in the CERN CLOUD experiment. *Atmos. Meas. Tech.*, 10: 3231–3248.
- Nieminen T., Asmi A., Dal Maso M., Aalto P. P., Keronen P., Petäjä T., Kulmala M. & Kerminen V.-M. 2014. Trends in atmospheric new-particle formation: 16 years of observations in a boreal-forest environment. *Boreal Env. Res.*, 19, suppl. B: 191-214.
- Nieminen T., Kerminen V.-M., Petäjä T., Aalto P. P., Arshinov M., Asmi E., Baltensperger U., Beddows D. S. C., Beukes J. P., Collins D., Ding A., Harrison R. M., Henzing B., Hooda R., Hu M., Horrak U., Kivekäs N., Komsaare K., Krejci R., Kristensson A., Laakso L., Laaksonen A., Leaitch W. R., Lihavainen H., Mihalopoulos N., Nemeth Z., Nie W., O'Dowd C. D., Salma I., Sellegri K., Svenninnson B., Swietlicki E., Tunved P., Ulevicijus V., Vakkari V., Vana M., Wiedensohler A., Wu Z., Virtanen A. & Kulmala M. 2018. Global analysis of continental boundary layer new particle formation based on long-term measurements. *Atmos. Chem. Phys.* 18: 14737-14756.
- Nikinmaa E., Hölttä T., Hari P., Kolari P., Mäkelä A., Sevanto S. & Vesala T. 2013. Assimilate transport in phloem sets conditions for leaf gas exchange. *Plant Cell and Environment* 36: 655–669.
- Njoku E., Stacey J. & Barath F. 1980. The Seasat scanning multichannel microwave radiometer (SMMR): Instrument description and performance. *IEEE Journal of Oceanic Engineering* 5:2: 100-115.
- Noe S.M., Niinemets Ü., Krasnova A., Krasnov D., Motallebi A., Kängsepp V., Jögiste K., Hörrak U., Komsaare K., Mirme S., Vana M., Tammet H., Bäck J., Vesala T., Kulmala M., Petäjä T., Kangur A. 2015. SMEAR Estonia: Perspectives of a large-scale forest ecosystem–atmosphere research infrastructure. — *Forestry Studies |Metsanduslikud Uurimused* 63: 56–84.
- Nölscher A. C., Williams J., Sinha V., Custer T., Song W., Johnson A. M., Axinte R., Bozem H., Fischer H., Povesle N., Phillips G., Crowley J. N., Rantala P., Rinne J., Kulmala M., Gonzales D., Valverde-Canossa J., Vogel A., Hoffmann T., Ouwersloot H. G., Vilà-Guerau de Arellano J. & Lelieveld J. 2012. Summertime total OH reactivity measurements from boreal forest during HUMPPA-COPEC 2010. *Atmos. Chem. Phys.* 12: 8257–8270.
- Nordbo A., Järvi L., Haapanala S., Wood C.R. & Vesala T. 2012. Fraction of natural area as main predictor of net CO<sub>2</sub> emissions from cities. *Geophysical Research Letters* 39: L20802. doi: 10.1029/2012GL053087
- Nordbo A., Järvi L., Haapanala S., Moilanen J. & Vesala T. 2013. Intra-city variation in urban morphology and turbulence structure in Helsinki, Finland. *Boundary-Layer Meteorology* 146:3: 469-496.
- Nordbo A., Kekäläinen P., Siivola E., Mammarella I., Timonen J. & Vesala T. 2014. Sorption-caused attenuation and delay of water vapor signals in eddy covariance sampling tubes and filters. *J. Atmos. Oceanic Technol.* 31: 2629–2649.
- O'Dowd C. D., Aalto P., Hämeri K., Kulmala M. & Hoffmann T. 2002. Aerosol formation - Atmospheric particles from organic vapours. *Nature* 416: 497-498.
- Okuyama K., Kousaka Y. & Motouchi T. 1984. Condensation Growth of Ultrafine Aerosol-Particles in a New Particle-Size Magnifier. *Aerosol Sci. Tech.* 3: 353-366.
- Olenius T., Schobesberger S., Kupiainen O., Franchin A., Junninen H., Ortega I. K., Kurtén T., Loukonen V., Worsnop D., Kulmala M. & Vehkamäki H. 2013. Comparing simulated and experimental molecular cluster distributions. *Faraday Discuss.* 6: 75-89.
- Ortega I. K., Kupiainen-Määttä O., Kurtén T., Olenius T., Wilkman O., McGrath M. J., Loukonen V. & Vehkamäki H. 2012. From quantum chemical formation free energies to evaporation rates. *Atmos. Chem. Phys.* 12: 225-235.
- Ovadnevaite J., Zuend A., Laaksonen A., Sanchez K.J., Roberts G., Ceburnis D., Decesari S., Rinaldi M., Hodas N., Facchini M.C., Seinfeld J.H. & O' Dowd C. 2017. Surface tension prevails over solute effect in organic-influenced cloud droplet activation. *Nature* 546: 637-641.
- Paasonen P., Nieminen T., Asmi E., Manninen H. E., Petäjä T., Plass-Dülmer C., Flentje H., Birmili W., Wiedensohler A., Horrak U., Metzger A., Hamed A., Laaksonen A., Facchini M. C., Kerminen V.-M. & Kulmala M. 2010. On the roles of sulphuric acid and low-volatility organic vapours in the initial steps of atmospheric new particle formation. *Atmos. Chem. Phys.* 10: 11223-11242.
- Paasonen P., Asmi A., Petäjä T., Kajos M. K., Äijälä M.,

- Junninen H., Holst T., Abbatt J. P. D., Arneth A., Birmili W., van der Gon H. D., Hamed A., Hoffer A., Laakso L., Laaksonen A., Leaitch W. R., Plass-Dülmer C., Pryor S. C., Räsänen P., Swietlicki E., Wiedensohler A., Worsnop D. R., Kerminen V.-M. & Kulmala M. 2013. Warming-induced increase in aerosol number concentration likely to moderate climate change. *Nature Geosci.* 6: 438-442.
- Paasonen P., Peltola M., Kontkanen J., Junninen H., Kerminen V.-M. & Kulmala M. 2018. Comprehensive analysis of particle growth rates from nucleation mode to cloud condensation nuclei in Boreal forest. *Atmos. Chem. Phys.* 18: 12085-12103.
- Paljakka T., Jyske T., Lintunen A., Aaltonen H., Nikinmaa E. & Hölttä T. 2017. Gradients and dynamics of inner bark and needle osmotic potentials in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.). *Plant, Cell & Environment* 40: 2160-2173.
- Palonen V., Pumpanen J., Kulmala L., Levin I., Heinonsalo J. & Vesala T. 2018 Seasonal and diurnal variations in atmospheric and soil air 14CO<sub>2</sub> in a boreal Scots pine forest. Radiocarbon, 1-15. <https://doi.org/10.1017/RDC.2017.95>
- Parshintsev J., Nurmi J., Kilpeläinen I., Hartonen K., Kulmala M. & Riekkola M.-L. 2008. Preparation of β-caryophyllene oxidation products and their determination in ambient aerosol samples. *Anal. Bioanal. Chem.* 390: 913-919.
- Parshintsev J., Rönkkö T., Helin A., Hartonen K. & Riekkola M.-L. 2015. Determination of atmospheric amines by on-fiber derivatization solid-phase microextraction, *J. Chromatogr. A* 1376: 46-52.
- Partanen A.-I., Landry J.-S. & Mathews J. D. 2018. Climate and health implications of future aerosol emission scenarios. *Environ. Res. Lett.* 13: 024028.
- Passananti M., Zapadinsky E., Zanca T., Kangasluoma J., Myllys N., Rissanen M. P., Kurtén T., Ehn M., Attoui M. & Vehkamäki H. 2019. How Well Can We Predict Cluster Fragmentation Inside a Mass Spectrometer? *Chem. Com.* 5: 5946-5949.
- Pearson R., Phillips S., Lorant M., Beck P.S.A., Damoulas T., Knight S.J. & Goetz S.J. 2013. Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Clim. Change* 3: 673-677.
- Peltoniemi M., Pulkkinen M., Aurela M., Pumpanen J., Kolari P. & Mäkelä A. 2015. A semi-empirical model of boreal forest gross primary production, evapotranspiration, and soil water-calibration and sensitivity analysis. *Boreal Env. Res.* 20: 151-171.
- Petäjä T., Mauldin III R. L., Kosciuch E., McGrath J., Nieminen T., Paasonen P., Boy M., Adamov A., Kotiaho T. & Kulmala M. 2009. Sulfuric acid and OH concentrations in a boreal forest site. *Atmos. Chem. Phys.* 9: 7435-7448.
- Petäjä T., Järvi L., Kerminen V.-M., Ding A.J., Sun J.N., Nie W., Kujansuu J., Virkkula A., Yang X., Fu C.B., Zilitinkevich S. & Kulmala M. 2016a. Enhanced air pollution via aerosol-boundary layer feedback in China. *Sci. Rep.* 6: 18998.
- Petäjä T., O'Connor E. J., Moisseev D., Sinclair V. A., Manninen A. J., Väänänen R., von Lerber A., Thornton J. A., Nicoll K., Petersen W., Chandrasekar V., Smith J. N., Winkler P. M., Krüger O., Hakola H., Timonen H., Brus D., Laurila T., Asmi E., Riekkola M., Mona L., Massoli P., Engelmann R., Komppula M., Wang J., Kuang C., Bäck J., Virtanen A., Levula J., Ritsche M. & Hickmon N. 2016b. BAECC: A Field Campaign to Elucidate the Impact of Biogenic Aerosols on Clouds and Climate, *Bulletin of the American Meteorological Society*, 97:10: 1909-1928.
- Petäjä T., Tabakova K., Manninen A., Ezhova E., O'Connor E., Moisseev D., Sinclair V.A., Backman J., Levula J., Luoma K., Virkkula A., Paramonov M., Rätty M., Äijälä M., Heikkinen L., Ehn M., Sipilä M., Yli-Juuti T., Virtanen A., Ritsche M., Hickmon N., Pulik G., Rosenfeld D. Worsnop D.R., Bäck J., Kulmala M. & Kerminen V.-M. 2021a. Influence of biogenic emissions from boreal forests on aerosol-cloud interactions. *Nature Geosci.* 15: 42-47.
- Petäjä T., Ganzei K. S., Lappalainen H. K., Tabakova K., Makkonen R., Räsänen J., Chalov S., Kulmala M., Zilitinkevich S., Baklanov P. Y., Shakhov R. B., Mishina N. V., Egidarev E. G., & Kondrat'ev I. I. 2021b. Research agenda for the Russian Far East and utilization of multi-platform comprehensive environmental observations. *International Journal of Digital Earth.* 14:3: 311-337.
- Petzold A. & Asmi A. 2020. ENVRI-FAIR EOSC Position Paper. Zenodo. <http://doi.org/10.5281/zenodo.3666806>
- Pietikäinen J.-P., Kupiainen K., Klimont Z., Makkonen R., Korhonen H., Karinkanta R., Hyvärinen A.-P., Karvosenoja N., Laaksonen A., Lihavainen H. & Kerminen V.-M. 2015. Impacts of emission reductions on aerosol radiative effects. *Atmos. Chem. Phys.* 15: 5501-5519.
- Pihlatie M., Pumpanen J., Rinne J., Ilvesniemi H., Simojoki A., Hari P. & Vesala T. 2007. Gas concentration driven fluxes of nitrous oxide and carbon dioxide in boreal forest soil. *Tellus B: Chemical and Physical Meteorology* 59:3: 458-469.
- Pihlatie M., Riis Christiansen J., Aaltonen H., Korhonen J., Nordbo A., Rasilo T., Rosa A.P., Benanti G., Giebels M., Helmy M., Schreiber P., Sheehy J., Juszczak R., Klefoth R., Vicca S., Dominique S., Jones S., Lobo do Vale R., Wolf B. & Pumpanen J. 2013. Comparison of static chambers to measure CH<sub>4</sub> emissions from soils. *Agricultural and Forest Meteorology* 124-136.
- Porcar-Castell A. 2011. A high-resolution portray of the annual dynamics in photochemical and non-photochemical quenching in needles of *Pinus sylvestris*. *Physiologia Plantarum* 143: 139-153.
- Porcar-Castell A., García-Plazaola J.I., Nichol C., Kolari P., Olascoaga B., Kuusinen N., Fernández-Marin B., Pulkkinen M., Juurola E., Nikinmaa E. 2012. Physiology of the seasonal relationship between photochemical reflectance index and photosynthetic light use efficiency. *Oecologia* 170: 313-323.
- Porcar-Castell A., Tyystjärvi E., Atherton J., van der Tol C., Pfündel E., Flexas J., Frankenberg C., Moreno J., Berry J.A. 2014. Linking chlorophyll fluorescence to photo-

- synthesis for remote sensing applications: mechanisms and challenges (Darwin Review). *Journal of Experimental Botany* 65: 4065–4095.
- Porcar-Castell A., Malenovsky Z., Magney T., Van Wittenbergh S., Fernández-Marín B., Maignan F., Zhang Y., Maseyk K., Atherton J., Albert L. P., Robson T., Zhao F., Garcia-Plazaola J.-I., Enslinger I., Rajewicz P. A., Grebe S., Tikkanen M., Kellner J. R., Ihalainen J. A., Rascher U. & Logan B. 2021. Chlorophyll a fluorescence illuminates a path connecting plant molecular biology to Earth-system science. *Nat. Plants* 7: 998–1009.
- Portin H., Leskinen A., Hao L., Kortelainen A., Miettinen P., Jaatinen A., Laaksonen A., Lehtinen K. E. J., Romakaniemi S. & Komppula M. 2014. The effect of local sources on particle size and chemical composition and their role in aerosol–cloud interactions at Puijo measurement station, *Atmos. Chem. Phys.* 14: 6021–6034.
- Praplan A.P., Pfannerstill E.Y., Williams J. & Hellén H. 2017. OH reactivity of the urban air in Helsinki, Finland, during winter. *Atmospheric Environment* 169: 150–161.
- Praplan A. P., Tykkä T., Chen D., Boy M., Taipale D., Vakari V., Zhou P., Petäjä T. & Hellén H. 2019. Long-term total OH reactivity measurements in a boreal forest. *Atmos. Chem. Phys.* 19: 14431–14453.
- Praplan A. P., Tykkä T., Schallhart S., Tarvainen V., Bäck J. & Hellén H. 2020. OH reactivity from the emissions of different tree species: investigating the missing reactivity in a boreal forest. *Biogeosciences* 17: 4681–4705.
- Prisle N. L., Asmi A., Topping D., Partanen A.-I., Romakaniemi S., Dal Maso M., Kulmala M., Laaksonen A., Lehtinen K. E. J., McFiggans G. & Kokkola H. 2012. Surfactant effects in global simulations of cloud droplet activation. *Geophys. Res. Lett.* 39: L05802. doi:10.1029/2011GL050467
- Pulliainen J., Aurela M., Laurila, T., Aalto T., Takala M., Salminen M., Kulmala M., Barr A., Heimann M., Lindroth A., Laaksonen A., Derksen C., Mäkelä A., Markkanen T., Lemmetyinen J., Susiluoto J., Dengel S., Mammarella I., Tuovinen J-P. & Vesala T. 2017. Early snowmelt significantly enhances boreal springtime carbon uptake. *PNAS* 114: 11081–11086.
- Pulliainen J., Luojus K., Derksen C., Mudryk L., Lemmetyinen J., Salminen M., Ikonen J., Takala M., Cohen J., Smolander T. & Norberg J. 2020. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature* 581: 294–298.
- Pumpanen J., Kolari P., Ilvesniemi H., Minkkinen K., Vesala T., Niinistö S., Lohila A., Larmola T., Morero M., Pihlatie M., Janssens I., Curiel Yuste J., Grünzweig J. M., Reth S., Subke J.-A., Savage K., Kutsch W., Østreng G., Ziegler W., Anthoni P., Lindroth A. & Hari P. 2004. Comparison of different chamber techniques for measuring soil CO<sub>2</sub> efflux. *Agricultural and Forest Meteorology* 123: 159–176.
- Pumpanen J., Ilvesniemi H., Kulmala L., Siivola E., Laakso H., Kolari P., Helenelund C., Laakso M., Uusimaa M. & Hari P. 2008. Respiration in boreal forest soil as determined from carbon dioxide concentration profile. *Soil Science Society of America Journal* 72: 1187–1196.
- Pumpanen J., Kulmala L., Linden A., Kolari P., Nikinmaa E. & Hari P. 2015. Seasonal dynamics of autotrophic respiration in boreal forest soil estimated by continuous chamber measurements. *Boreal Env. Res.* 20: 637–650.
- Putkinen A., Juottonen H., Juutinen S., Tuittila E.-S., Fritze H. & Yrjälä K. 2009. Archaeal rRNA communities and methane production in deep boreal peat. *FEMS Microbial Ecology* 70: 87–98.
- Quéléver L. L. J., Kristensen K., Jensen L. N., Rosati B., Teiwes R., Daellenbach K. R., Peräkylä O., Roldin P., Bossi R., Pedersen H. B., Glasius M., Bilde M. & Ehn M. 2019. Effect of temperature on the formation of highly oxygenated organic molecules (HOMs) from alpha-pinene ozonolysis. *Atmos. Chem. Phys.* 19: 7609–7625.
- Raczka B., Porcar-Castell A., Magney T., Lee J.E., Köhler P., Frankenberg C., Grossmann K., Logan B.A., Stutz J., Blanken D.B., Burns S.P., Duarte H., Yang X., Lin J.C. & Bowling D.R. 2019. Sustained nonphotochemical quenching shapes the seasonal pattern of solar-induced fluorescence at a high-elevation evergreen forest. *Journal of Geophysical Research: Biogeosciences* 124: 2005–2020.
- Raes F., Liao H., Chen W.-T. & Seinfeld J.H. 2010. Atmospheric chemistry-climate feedbacks. *Journal of Geophysical Research* 115: D12121, doi:10.1029/2009JD013300
- Raivonen M., Smolander S., Backman L., Susiluoto J., Aalto T., Markkanen T., Mäkelä J., Rinne J., Peltola O., Aurela M., Lohila A., Tomasic M., Li X., Larmola T., Juutinen S., Tuittila E.-S., Heimann M., Sevanto S., Kleinen T., Brovkin V. & Vesala T. 2017. HIMMELI v1.0: Helsinki Model of Methane buiLd-up and emISSION for peatlands. *Geosci. Model Dev.* 10: 4665–4691.
- Rajewicz P., Atherton J., Alonso L. & Porcar-Castell A. 2019. Leaf-level spectral fluorescence measurements: comparing methodologies for broadleaves and needles. *Remote Sensing* 11, 5: 532. <https://doi.org/10.3390/rs11050532>
- Ramanathan V. & Carmichael G. 2008. Global and regional climate changes due to black carbon. *Nat. Geosci.* 1: 221–227.
- Rannik Ü., Mammarella I., Keronen P. & Vesala T. 2009a. Vertical advection and nocturnal deposition of ozone over a Boreal pine forest. *Atmos. Chem. Phys.* 9: 2089–2095.
- Rannik Ü., Altimir N., Mammarella I., Bäck J., Rinne J., Ruuskanen T. M., Hari P., Vesala T. & Kulmala M. 2012. Ozone deposition into a boreal forest over a decade of observations: evaluating deposition partitioning and driving variables. *Atmos. Chem. Phys.* 12: 12165–12182.
- Rannik Ü., Peltola O. & Mammarella I. 2016. Random uncertainties of flux measurements by the eddy covariance technique. *Atmos. Meas. Tech.*, 9: 5163–5181. doi:10.5194/amt-9-5163-2016
- Rantala P., Taipale R., Aalto J., Kajos M. K., Patokoski J., Ruuskanen T. M. & Rinne J. 2014. Continuous flux measurements of VOCs using PTR-MS — reliability and feasibility of disjunct-eddy-covariance, surface-lay-

- er-gradient, and surface-layer-profile methods. *Boreal Env. Res.* 19, suppl. B: 87–107.
- Rantala P., Aalto J., Taipale R., Ruuskanen T. M. & Rinne J. 2015. Annual cycle of volatile organic compound exchange between a boreal pine forest and the atmosphere. *Biogeosciences* 12:19: 5753-5770.
- Rantanen M., Karpechko A.Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* 3, 168. <https://doi.org/10.1038/s43247-022-00498-3>
- Räsänen A., Korkiakoski M., Manninen T., Lohila A. & Virtanen T. 2021. Predicting catchment-scale methane fluxes with multi-source remote sensing. *Landscape Ecology* 36: 1177-1195.
- Rasilto T., Ojala A., Huotari J., Starr M. & Pumpanen J. 2015. Concentrations and quality of DOC along the terrestrial-aquatic continuum in a boreal forested catchment. *Freshwater Science* 34:2: 440-455.
- Rauber A., Asmi A., van Uytvanck D. & Proell S. 2015. Data Citation of Evolving Data: Recommendations of the Working Group on Data Citation (WGDC). <http://doi.org/10.15497/RDA00016>
- Rautiainen K., Lemmetyinen J., Schwank M., Kontu A., Ménard C.B., Mätzler C., Drusch M., Wiesmann A., Ikonen J. & Pulliainen J. 2014. Detection of soil freezing from L-band passive microwave observations. *Remote Sensing of Environment* 147: 206-218.
- Rautiainen K., Parkkinen T., Lemmetyinen J., Schwank M., Wiesmann A., Ikonen J., Derksen C., Davydov S., Davydova A., Boike J., Langer M., Drusch M. & Pulliainen J. 2016. SMOS prototype algorithm for detecting autumn soil freezing. *Remote Sensing of Environment* 180: 346-360.
- Re S., Osamura Y. K. & Morokuma K. 1999. Coexistence of Neutral and Ion-Pair Clusters of Hydrated Sulfuric Acid  $H_2SO_4(H_2O)_n$  ( $n = 1-5$ ) - A Molecular Orbital Study. *J. Phys. Chem. A* 103: 3535-3547.
- Rebmann C., Aubinet M., Schmid H., Arriga N., Aurela M., Burba G., Clement R., De Ligne A., Fratini G., Gielen B., Grace J., Graf A., Gross P., Haapanala S., Herbst M., Hörtnagl L., Ibrom A., Joly L., Kljun N., Kolle O., Kowalski A., Lindroth A., Loustau D., Mammarella I., Mauder M., Merbold L., Metzger S., Mölder M., Montagnani L., Papale D., Pavelka M., Peichl M., Roland M., Serrano-Ortiz P., Siebicke L., Steinbrecher R., Tuovinen J., Vesala T., Wohlfahrt G. & Franz D. 2018. ICOS eddy covariance flux-station site setup: a review. *Int. Agrophys.* 32: 471-494.
- Reich P.B., Sendall K.M., Rice K., Rich R.L., Stefanski A., Hobbie S.E. & Montgomery R.A. 2015. Geographic range predicts photosynthetic and growth response to warming in co-occurring tree species. *Nature Clim. Change* 5: 148-152.
- Riccobono F., Schobesberger S., Scott C., Dommen J., Ortega I., Rondo L., Almeida J., Amorim A., Bianchi F., Breitenlechner M., David A., Downard A., Dunne E., Duplissy J., Ehrhart S., Flagan R., Franchin A., Hansel A., Junninen H., Kajos M., Keskinen H., Kupc A., Kürten A., Kvashin A., Laaksonen A., Lehtipalo K., Makhmutov V., Mathot S., Nieminen T., Onnela A., Petäjä T., Praplan A., Santos F., Schallhart S., Seinfeld J., Sipilä M., Spracklen D., Stozhkov Y., Stratmann F., Tomé A., Tsagkogeorgas G., Vaattovaara P., Viisanen Y., Vrtala A., Wagner P., Weingartner E., Wex H., Wimmer D., Carslaw K., Curtius J., Donahue N., Kirkby J., Kulmala M., Worsnop D. & Baltensperger, U. 2014. Oxidation Products of Biogenic Emissions Contribute to Nucleation of Atmospheric Particles. *Science* 344: 717-721.
- Riipinen I., Yli-Juuti T., Pierce J., Petäjä T., Worsnop D. R., Kulmala M. & Donahue N. M. 2012. The contribution of organics to atmospheric nanoparticle growth. *Nature Geosci.* 5: 453-458.
- Rinne J., Hakola H. & Laurila T. 1999. Vertical fluxes of monoterpenes above a Scots pine stand in the boreal vegetation zone. *Physics and Chemistry of the Earth* 24: 711-715.
- Rinne J., Hakola H., Laurila T. & Rannik Ü. 2000. Canopy scale monoterpene emissions of Pinus sylvestris dominated forests. *Atmospheric Environment* 34: 1099-1107.
- Rinne H. J. I., Guenther A. B., Warneke C., de Gouw J. A. & Luxembourg S. L. 2001. Disjunct eddy covariance technique for trace gas flux measurements. *Geophysical Research Letters* 28:16: 3139-3142.
- Rinne J., Riutta T., Pihlatie M., Aurela M., Haapanala S., Tuovinen J.-P., Tuittila E.-S. & Vesala T. 2007a. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. *Tellus B: Chemical and Physical Meteorology*, 59:3: 449-457.
- Rinne J., Taipale R., Markkanen T., Ruuskanen T. M., Hellén H., Kajos M. K., Vesala T. & Kulmala M. 2007b. Hydrocarbon fluxes above a Scots pine forest canopy: measurements and modeling. *Atmos. Chem. Phys.* 7: 3361-3372.
- Rinne J., Bäck J. & Hakola H. 2009. Biogenic volatile organic compound emissions from Eurasian taiga: Current knowledge and future directions. *Boreal Env. Res.* 14: 807-826.
- Rinne J. & Ammann C. 2012. Disjunct Eddy Covariance Method. In: Aubinet M., Vesala T. & Papale D. (eds.) *Eddy Covariance - A Practical Guide to Measurement and Data Analysis*, Springer Netherlands, ISBN 978-94-007-2350-4, 289-305.
- Rinne J., Markkanen T., Ruuskanen T. M., Petäjä T., Keronen P., Tang M. J., Crowley J. N., Rannik Ü. & Vesala T. 2012. Effect of chemical degradation on fluxes of reactive compounds — a study with a stochastic Lagrangian transport model. *Atmos. Chem. Phys.* 12: 4843-4854.
- Rinne, J. & Tuittila E.-S. 2012. Methane flux measurements at Siikaneva wetland complex. *FluxLetter*, 4:3: 6-9. [https://fluxnet.org/wp-content/uploads/FluxLetter\\_Vol4\\_No3.pdf](https://fluxnet.org/wp-content/uploads/FluxLetter_Vol4_No3.pdf)
- Rinne J., Tuittila E.-S., Peltola O., Li X., Raivonen M., Alekseychik P., Haapanala S., Pihlatie M., Aurela M., Mammarella I. & Vesala T. 2018. Temporal Variation of Ecosystem Scale Methane Emission From a Boreal Fen in Relation to Temperature, Water Table Position, and Carbon Dioxide Fluxes. *Global Biogeochemical Cycles*

32:7: 1087-1106.

- Rinne J., Tuovinen J.-P., Klemmedtsson L., Aurela M., Holst J., Lohila A., Weslien P., Vestin P., Łakomiec P., Peichl M., Tuittila E.-S., Heiskanen L., Laurila T., Li X., Alekseychik P., Mammarella I., Ström L., Crill P. and Nilsson M. B. 2020. Effect of the 2018 European drought on methane and carbon dioxide exchange of northern mire ecosystems. *Phil. Trans. R. Soc. B* 375: 20190517. <http://doi.org/10.1098/rstb.2019.0517>
- Rinne J., Ammann C., Pattey E., Paw U K.T. & Desjardins R.L. 2021. Alternative Turbulent Trace Gas Flux Measurement Methods. In: Foken T. (eds) *Springer Handbook of Atmospheric Measurements*. Springer Handbooks. Springer, Cham. [https://doi.org/10.1007/978-3-030-52171-4\\_56](https://doi.org/10.1007/978-3-030-52171-4_56)
- Rissanen K., Hölttä T., Vanhatalo A., Aalto J., Nikinmaa E., Rita H. & Bäck J. 2016. Diurnal patterns in Scots pine stem oleoresin pressure in a boreal forest. *Plant, cell & environment* 39: 527-538.
- Rissanen K., Vanhatalo A., Salmon Y., Bäck J. & Hölttä T. 2020. Stem emissions of monoterpenes, acetaldehyde and methanol from Scots pine (*Pinus sylvestris* L.) affected by tree-water relations and cambial growth. *Plant, cell & environment* 43: 1751-1765.
- Rissanen M. P., Mikkilä J., Iyer S. & Hakala J. 2019. Multi-scheme chemical ionization inlet (MION) for fast switching of reagent ion chemistry in atmospheric pressure chemical ionization mass spectrometry (CIMS) applications. *Atmos. Meas. Tech.* 12: 6635-6646.
- Riutta T., Laine J., Aurela M., Rinne J., Vesala T., Laurila T., Haapanala S., Pihlatie M. & Tuittila E.-S. 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. *Tellus B: Chemical and Physical Meteorology*. 59:5: 838-852.
- Riuttanen L., Bister M., Kerminen V.-M., John V. O., Sundström A.-M., Dal Maso M., Räisänen J., Sinclair V. A., Makkonen R., Xausa F., de Leeuw G. & Kulmala M. 2016. Observational evidence for aerosols increasing upper tropospheric humidity. *Atmos. Chem. Phys.* 16: 14331-14342.
- Romakkaniemi S., Kokkola H. & Laaksonen A. 2005. Parameterization of the nitric acid effect on CCN activation. *Atmos. Chem. Phys.* 5: 879-885.
- Ruiz-Jimenez J., Zanca N., Lan H., Jussila M., Hartonen K. & Riekkola M.-L. 2019. Aerial drone as a carrier for miniaturized air sampling systems. *J. Chromatogr. A* 1597: 202-208.
- Ruiz-Jimenez J., Lan H., Leleev Y., Hartonen K. & Riekkola M.-L. 2020. Comparison of multiple calibration approaches for the determination of volatile organic compounds in air samples by solid phase microextraction Arrow and in-tube extraction. *J. Chromatogr. A* 1616: 460825. <https://doi.org/10.1016/j.chroma.2019.460825>
- Ruiz-Jimenez J., Okuljar M., Sietiö O.-M., Demaria G., Liangsupree T., Zagatti E., Aalto J., Hartonen K., Heinsonsalo J., Bäck J., Petäjä T. & Riekkola M.-L. 2021. Determination of free amino acids, saccharides, and selected microbes in biogenic atmospheric aerosols—seasonal variations, particle size distribution, chemical and microbial relations. *Atmos. Chem. Phys.* 21: 8775-8790.
- Ruosteenoja K. & Räisänen J. 2021. Evolution of observed and modelled temperatures in Finland in 1901–2018 and potential dynamical reasons for the differences. *International Journal of Climatology* 41:5: 3374-3390.
- Ruuskanen A., Romakkaniemi S., Kokkola H., Arola A., Mikkonen S., Portin H., Virtanen A., Lehtinen K. E. J., Komppula M. & Leskinen A. 2021. Observations on aerosol optical properties and scavenging during cloud events. *Atmos. Chem. Phys.* 21: 1683–1695.
- Ryhti K., Kulmala L., Pumpanen J., Isotalo J., Pihlatie M., Helmisaari H.-S., Leppälampi-Kujansuu J., Kieloaho A.-J., Bäck J. & Heinonsalo J. 2021. Partitioning of forest floor CO<sub>2</sub> emissions reveals the belowground interactions between different plant groups in a Scots pine stand in southern Finland. *Agricultural and Forest Meteorology* 297: 108266.
- Ryhti K., Schiestl-Aalto P., Tang Y., Rinne-Garmston K., Ding Y., Pumpanen J., Biasi C., Saurer M., Bäck J. & Kulmala L. (2022) Effects of variable temperature and moisture conditions on respiration and nonstructural carbohydrate dynamics of tree roots. *Agricultural and Forest Meteorology* 323: 109040.
- Sabbatini S., Mammarella I., Arriga N., Fratini G., Graf A., Hörtnagl L., Ibrom A., Longdoz B., Mauder M., Merbold L., Metzger S., Montagnani L., Pitacco A., Rebmann C., Sedlak P., Sigut L., Vitale D. & Papale D. 2018. Eddy covariance raw data processing for CO<sub>2</sub> and energy flux calculation at ICOS ecosystem stations. *Int. Agrophys.* 32: 495-515.
- Salma I., Then W., Aalto P., Kerminen V.-M., Kern A., Barcza Z., Petäjä T. & Kulmala M. 2021. Influence of vegetation on occurrence and time distributions of regional new aerosol particle formation and growth. *Atmos. Chem. Phys.* 21: 2861-2880.
- Salmon Y., Lintunen A., Dayet A., Chan T., Dewar R., Vesala T. & Hölttä T. 2020. Leaf carbon and water status control stomatal and non-stomatal limitations of photosynthesis in trees. *New Phytologist* 226: 690-703.
- Samset B. H. 2018 How cleaner air changes the climate. *Science* 360: 148-150.
- Santalahti M., Sun H., Jumpponen A., Pennanen T. & Heinonsalo J. 2016. Seasonal and vertical dynamics of fungal communities in boreal Scots pine forest soil. *FEMS Microbiology Ecology* 92: 11: fiw170. DOI: <http://dx.doi.org/10.1093/femsec/fiw170>
- Šantl-Temkiv T., Sikoparija B., Maki T., Carotenuto F., Amato P., Yao M., Morris C. E., Schnell R., Jaenicke R., Pöhlker C., DeMott P. J., Hill T. C. J. & Huffman J. A. 2020. Bioaerosol field measurements: Challenges and perspectives in outdoor studies. *Aerosol Science and Technology* 54: 520-546.
- Saros M. T., Weber R. J., Marti J. J. & McMurry P. H. 1996. Ultrafine aerosol measurement using a condensation nucleus counter with pulse height analysis. *Aerosol Sci. Tech.* 25: 200-213.
- Schallhart S., Rantala P., Kajos M. K., Aalto J., Mammarella I., Ruuskanen T. M. & Kulmala M. 2018. Temporal variation of VOC fluxes measured with PTR-TOF above a boreal forest. *Atmos. Chem. Phys.* 18: 815–832.
- Scharlemann J.P.W., Tanner E.V.J., Hiederer R., Kapos V.

2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management* 5:1: 81-91.
- Schiestl-Aalto P., Nikinmaa E. & Mäkelä A. 2013. Duration of shoot elongation in Scots pine varies within crown and between years. *Ann. Bot.* 112:1181-1191.
- Schiestl-Aalto P., Kulmala L., Mäkinen H., Nikinmaa E. & Mäkelä A. 2015. CASSIA - a dynamic model for predicting intra-annual sink demand and interannual growth variation in Scots pine. *New Phytologist* 206: 647-659.
- Schiestl-Aalto P., Ryhti K., Mäkelä A., Peltoniemi M., Bäck J. & Kulmala L. 2019. Analysis of the NSC storage dynamics in tree organs reveals the allocation to belowground symbionts in the framework of whole tree carbon balance. *Front. For. Glob. Change* 2: 17.
- Schobesberger S., Junninen H., Bianchi F., Lönn G., Ehn M., Lehtipalo K., Dommen J., Ehrhart S., Ortega Colomer I. K., Franchin A., Nieminen T., Riccobono F., Hutterli M., Duplissy J., Almeida J., Amorim A., Breitenlechner M., Downard A. J., Dunne E. M., Flagan R. C., Kajos M., Keskinen H., Kirkby J., Kupc A., Kuerten A., Kurten T., Laaksonen A., Mathot S., Onnela A., Praplan A. P., Rondo L., Santos F. D., Schallhart S., Schnitzhofer R., Sipilä M., Tome A., Tsigogeorgas G., Vehkamäki H., Wimmer D., Baltensperger U., Carslaw K. S., Curtius J., Hansel A., Petäjä T., Kulmala M., Donahue N. M. & Worsnop D. R. 2013. Molecular understanding of atmospheric particle formation from sulfuric acid and large oxidized organic molecules. *Proc. Natl. Acad. Sci.* 110: 17223-17228.
- Scott C. E., Arnold S.R., Monks S. A., Asmi A., Paasonen P. & Spracklen D. V. 2014. Substantial large-scale feedbacks between natural aerosols and climate. *Nature Geosci.* 11: 44-48.
- Sgro L. A. & Fernández de la Mora J. 2004. A simple turbulent mixing CNC for charged particle detection down to 1.2 nm. *Aerosol Sci. Tech.* 38: 1-11.
- Shi X., Zhao X., Zhang R., Xu F., Cheng J., Zhang Q. & Wang W. 2019. Theoretical study of the cis-pinonic acid and its atmospheric hydrolysate participation in the atmospheric nucleation. *Sci. Total Environ.* 674: 234-241.
- Shindell D., Kuylensstierna J.C.I., Vignati E., van Dingenen R., Amann M., Klimont Z., Anenberg S.C., Müller N., Janssens-Maenhout G., Raes F., Schwartz J., Faluvegi G., Pozzoli L., Kupiainen K., Höglund-Isaksson L., Emberson L., Streets L., Ramanathan V., Hicks K., Oanh N.T.K., Milly G., Williams M., Demkine W., & Fowler D. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335: 183-189.
- Sietiö O.-M., Tuomivirta T., Santalahti M., Kiheri H., Timonen S., Sun H., Fritze H. & Heinonsalo J. 2018. Ericoid plant species and *Pinus sylvestris* shape fungal communities in their roots and surrounding soil. *New Phytologist* 218: 738-751.
- Sietiö O.-M., Santalahti M., Putkinen A., Adamczyk S., Sun H. & Heinonsalo J. 2019. Restriction of plant roots in boreal forest organic soils affects the microbial community but does not change the dominance from ectomycorrhizal to saprotrophic fungi. *FEMS Microbiology Ecology* 95:9: fiz133. <https://doi.org/10.1093/femsec/fiz133>
- Sihto S.-L., Kulmala M., Kerminen V.-M., Dal Maso M., Petäjä T., Riipinen I., Korhonen H., Arnold F., Janson R., Boy M., Laaksonen A. & Lehtinen K. E. J. 2006. Atmospheric sulphuric acid and aerosol formation: implications from atmospheric measurements for nucleation and early growth mechanisms. *Atmos. Chem. Phys.* 6: 4079-4091.
- Sihto S.-L., Mikkilä J., Vanhanen J., Ehn M., Liao L., Lehtipalo K., Aalto P. P., Duplissy J., Petäjä T., Kerminen V.-M., Boy M. & Kulmala M. 2011. Seasonal variation of CCN concentrations and aerosol activation properties in boreal forest. *Atmos. Chem. Phys.* 11: 13269-13285.
- Sipilä M., Lehtipalo K., Kulmala M., Petäjä T., Junninen H., Aalto P. P., Manninen H. E., Kyrö E.-M., Asmi E., Riipinen I., Curtius J., Kurten A., Borrmann S. & O'Dowd C. D. 2008. Applicability of condensation particle counters to measure atmospheric clusters. *Atmos. Chem. Phys.* 8: 4049-4060.
- Sipilä M., Lehtipalo K., Attoui M., Neitola K., Petäjä T., Aalto P. P., O'Dowd C. D. & Kulmala M. 2009. Laboratory Verification of PH-CPC's Ability to Monitor Atmospheric Sub-3 nm Clusters. *Aerosol Sci. Tech.* 43: 126-135.
- Sipilä M., Berndt T., Petäjä T., Brus D., Vanhanen J., Stratmann F., Patokoski J., Mauldin III R. L., Hyvärinen A.-P., Lihavainen H. & Kulmala M. 2010. The role of sulfuric acid in atmospheric nucleation. *Science* 5: 1243-1246.
- Sipilä M., Sarnela N., Jokinen T., Junninen H., Hakala J., Rissanen M. P., Praplan A., Simon M., Kürten A., Bianchi F., Dommen J., Curtius J., Petäjä T. & Worsnop D. R. 2015. Bisulfate — cluster based atmospheric pressure chemical ionization mass spectrometer for high-sensitivity (< 100 ppqV) detection of atmospheric dimethyl amine: proof-of-concept and first ambient data from boreal forest. *Atmos. Meas. Tech.* 8: 4001-4011.
- Sipilä M., Sarnela N., Jokinen T., Henschel H., Junninen H., Kontkanen J., Richters S., Kangasluoma J., Franchin A., Peräkylä O., Rissanen M. P., Ehn M., Vehkamäki H., Kurten T., Berndt T., Petäjä T., Worsnop D., Ceburnis D., Kerminen V.-M., Kulmala M. & O'Dowd C. 2016. Molecular-scale evidence of aerosol particle formation via sequential addition of HIO<sub>3</sub>. *Nature* 537: 532-534.
- Sizov O., Ezhova E., Tsybarovich P., Soromotin A., Pridhod'ko N., Petäjä T., Zilitinkevich S., Kulmala M., Bäck J. & Köster K. 2021. Fire and vegetation dynamics in northwest Siberia during the last 60 years based on high-resolution remote sensing. *Biogeosciences* 18: 207-228.
- Skiba U., Drewer J., Tang Y. S., van Dijk N., Helfter C., Nemitz E., Famulari D., Cape J. N., Jones S. K., Twigg M., Pihlatie M., Vesala T., Larsen K. S., Carter M. S., Ambus P., Ibrom A., Beier C., Hensen A., Frumau A., Erisman J. W., Brüggemann N., Gasche R., Butterbach-Bahl K., Neftel A., Spirig C., Horvath L., Freibauer A., Cellier P., Laville P., Loubet B., Magliulo E., Bertolini T., Seufert G., Andersson M., Manca G.,

- Laurila T., Aurela M., Lohila A., Zechmeister-Boltenstern S., Kitzler B., Schauffler G., Siemens J., Kindler R., Flechard C. & Sutton M. A. 2009. Biosphere-atmosphere exchange of reactive nitrogen and greenhouse gases at the NitroEurope core flux measurement sites: measurement strategy and first data sets. *Agriculture, Ecosystems and Environment* 133:3-4: 139-149.
- Sorjamaa R., Svenningsson B., Raatikainen T., Henning S., Bilde M. & Laaksonen A. 2004. The role of surfactants in Köhler theory reconsidered. *Atmos. Chem. Phys.* 4: 2107–2117.
- Sporre M. K., Blichner S. M., Karsset I. H. H., Makkonen R. & Bernsten T. K. 2019. BVOC-aerosol-climate feedbacks investigated using NorESM. *Atmos. Chem. Phys.* 19: 4763-4782.
- Sporre M. K., Blichner S. M., Schrödner R., Karsset I. H. H., Bernsten T. K., van Noije T., Bergman T., O'Donnel D. & Makkonen R. 2020. Large differences in aerosol radiative effects from BVOC-SOA treatment in three Earth system models. *Atmos. Chem. Phys.* 20: 8953-8973.
- Spracklen D. V., Carslaw K. S., Kulmala M., Kerminen V.-M., Sihto S.-L., Riipinen I., Merikanto J., Mann G. W., Chipperfield M. P., Wiedensohler A., Birmili W. & Lihavainen H. 2008. Contribution of particle formation to global cloud condensation nuclei concentrations. *Geophys. Res. Lett.* 35: 06808. doi:10.1029/2007GL033038
- Stolzenburg D., Simon M., Ranjithkumar A., Kürten A., Lehtipalo K., Gordon H., Ehrhart S., Finkenzeller H., Pichelstorfer L., Nieminen T., He X.-C., Brilke S., Xiao M., Amorim A., Baalbaki R., Baccarini A., Beck L., Bräkling S., Caudillo Murillo L., Chen D., Chu B., Dada L., Dias A., Dommen J., Duplissy J., El Haddad I., Fischer L., Gonzalez Carracedo L., Heinritzi M., Kim C., Koenig T. K., Kong W., Lamkaddam H., Lee C. P., Leiminger M., Li Z., Makhmutov V., Manninen H. E., Marie G., Marten R., Müller T., Nie W., Partoll E., Petäjä T., Pfeifer J., Philippov M., Rissanen M. P., Rörup B., Schobesberger S., Schuchmann S., Shen J., Sipilä M., Steiner G., Stozhkov Y., Tauber C., Tham Y. J., Tomé A., Vazquez-Pufleau M., Wagner A. C., Wang M., Wang Y., Weber S. K., Wimmer D., Wlasits P. J., Wu Y., Ye Q., Zauner-Wieczorek M., Baltensperger U., Carslaw K. S., Curtius J., Donahue N. M., Flagan R. C., Hansel A., Kulmala M., Lelieveld J., Volkamer R., Kirkby J. & Winkler P. M. 2020. Enhanced growth rate of atmospheric particles from sulfuric acid. *Atmos. Chem. Phys.* 20: 7359–7372.
- Sulo J., Samela N., Kontkanen J., Ahonen L., Paasonen P., Laurila T., Jokinen T., Kangasluoma J., Junninen H., Sipilä M., Petäjä T., Kulmala M. & Lehtipalo K. 2021. Long-term measurement of sub-3 nm particles and their precursor gases in the boreal forest. *Atmos. Chem. Phys.* 21: 695-715.
- Sun H., Santalahti M., Pumpanen J., Köster K., Berninger F., Raffaello T., Asiegbu F.O. and Heinonsalo J. 2016. Bacterial community structure and function shift across a northern boreal forest fire chronosequence. *Scientific Reports* 6: 32411
- Sun Y., Frankenberg C., Wood J. D., Schimel D. S., Jung M., Guanter L., Drewry D. T., Verma M., Porcar-Castell A., Griffis T. J., Gu L., Magney T. S., Köhler P., Evans B. & Yuen K. 2017. OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. *Science* 358: eaam5747. 10.1126/science.aam5747
- Tagesson T., Schurgers G., Horion S., Ciais P., Tian F., Brandt M., Ahlström A., Wigneron J.-P., Ardö J., Olin S., Fan L., Wu Z. & Fensholt R. 2020. Recent divergence in the contributions of tropical and boreal forests to the terrestrial carbon sink. *Nat. Ecol. Evol.* 4: 202–209.
- Taipale R., Ruuskanen T. M. & Rinne J. Lag time determination in DEC measurements with PTR-MS. *Atmos. Meas. Tech.* 3: 853–862.
- Taipale R., Kajos M. K., Patokoski J., Rantala P., Ruuskanen T. M. & Rinne J. 2011. Role of de novo biosynthesis in ecosystem scale monoterpene emissions from a boreal Scots pine forest. *Biogeosciences* 8: 2247–2255.
- Tammeth H. 2006. Continuous scanning of the mobility and size distribution of charged clusters and nanometer particles in atmospheric air and the Balanced Scanning Mobility Analyzer BSMA. *Atmos. Res.* 82: 523-535.
- Terreri C., Phillips R. P., Hungate B. A., Rosende J., Pett-Ridge J., Craig, M. E., van Groenigen K. J., Keenan T. F., Sulman B. N., Stocker B. D., Reich P. B., Pellegrini A. F. A., Pendall E., Zhang H., Evans R. D., Carrillo Y., Fisher J. B., Van Sundert K., Vicca S. & Jackson, R. B. 2021. A trade-off between plant and soil carbon storage under elevated CO<sub>2</sub>. *Nature* 591: 599–603.
- Thomsen D., Elm J., Rosati B., Skonager J. T., Bilde M. & Glasius M. 2021. Large Discrepancy in the Formation of Secondary Organic Aerosols from Structurally Similar Monoterpenes. *ACS Earth Space Chem.* 5:3: 632–644.
- Tian X., Minunno F., Cao T.J., Peltoniemi M., Kalliokoski T., Mäkelä A. 2020. Extending the range of applicability of the semi-empirical ecosystem flux model PRELES for varying forest types and climate. *Global Change Biology* 26: 2923– 2943.
- Timofeev V., Bahtjeva I., Mironova R., Titareva G., Lev I., Christiany D., Borzilov A., Bogun A. & Vergnaud G. 2019. Insights from Bacillus anthracis strains isolated from permafrost in the tundra zone of Russia. *PLoS One.* 14:5:e0209140. doi: 10.1371/journal.pone.0209140
- Tonttila J., Maalick Z., Raatikainen T., Kokkola H., Kühn T. & Romakkaniemi S. 2017. UCLALES-SALSA v1.0: a large-eddy model with interactive sectional microphysics for aerosol, clouds and precipitation. *Geosci. Model Dev.* 10: 169-188.
- Tonttila J., Afzalifar A., Kokkola H., Raatikainen T., Korhonen H. & Romakkaniemi S. 2021. Precipitation enhancement in stratocumulus clouds through airborne seeding: sensitivity analysis by UCLALES-SALSA. *Atmos. Chem. Phys.* 21: 1035–1048.
- Tröstl J., Chuang W.K., Gordon H., Heinritzi M., Yan C., Molteni U., Ahlm L., Frege C., Bianchi F, Wagner R., Simon M., Lehtipalo K., Williamson C., Craven J.S., Duplissy J., Adamov A., Almeida J., Bernhammer A., Breitenlechner M., Brilke S., Dias A., Ehrhart S., Flagan R.C., Franchin A., Fuchs C., Guida R., Gysel M., Hansel A., Hoyle C.R, Jokinen T., Junninen H., Kangasluoma J., Keskinen H., Kim J., Krapf M., Kürten A., Laaksonen

- A., Lawler M., Leiminger M., Mathot S., Möhler O., Nieminen T., Onnela A., Petäjä T., Piel F.M., Miettinen P., Rissanen M.P., Rondo L., Sarnela N., Schobesberger S., Sengupta K., Sipilä M., Smith J.N., Steiner G., Tome A., Virtanen A., Wagner A.C., Weingartner E., Wimmer D., Winkler P.M., Ye P., Carslaw K.S., Curtius J., Donahue N.M. & Baltensperger U. 2016. Low-volatility organic compounds are key to initial particle growth in the atmosphere. *Nature* 533: 527-531.
- Tunved P., Hansson H.-C., Kerminen V.-M., Ström J., Dal Maso M., Lihavainen H., Viisanen Y., Aalto P. P., Komppula M. & Kulmala M. 2006. High natural aerosol loading over boreal forests. *Science* 312: 261-263.
- Tuomivaara T., Hari P., Rita H. & Häkkinen R. 1994. The guide-dog approach: a methodology for ecology. University of Helsinki, Department of forest ecology publications 11. 92 p.
- Tuovinen J.-P., Aurela M., Hatakka J., Räsänen A., Virtanen T., Mikola J., Ivakhov V., Kondratyev V. & Laurila T. 2019. Interpreting eddy covariance data from heterogeneous Siberian tundra: land-cover-specific methane fluxes and spatial representativeness. *Biogeosciences* 16: 255-274.
- 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., Persson P.O.G., 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. & Intrieri J.M. 2016. International Arctic Systems for Observing the Atmosphere (IASOA): An International Polar Year Legacy Consortium. *Bulletin of the American Meteorological Society* 97: 1034-1056.
- Vainio E., Peltola O., Kasurinen V., Kieloaho A.-J., Tuittila E.-S. & Pihlatie M. 2021. Topography-based statistical modelling reveals high spatial variability and seasonal emission patches in forest floor methane flux. *Biogeosciences* 18: 2003–2025.
- Väisänen O., Ruuskanen A., Ylirirmö A., Miettinen P., Portin H., Hao L., Leskinen A., Komppula M., Romakkaniemi S., Lehtinen K. E. J. & Virtanen A. 2016. In-cloud measurements highlight the role of aerosol hygroscopicity in cloud droplet formation. *Atmos. Chem. Phys.* 16: 10385-10398.
- Vakkari V., Tiitta P., Jaars K., Croteau P., Beukes J. P., Josipovic M., Kerminen V.-M., Kulmala M., Venter A. D., van Zyl P. G., Worsnop D. R. & Laakso L. 2015. Reevaluating the contribution of sulfuric acid and the origin of organic compounds in atmospheric nanoparticle growth. *Geophys. Res. Lett.* 42: 10486-10493.
- Vanhanen J., Mikkilä J., Lehtipalo K., Sipilä M., Manninen H. E., Siivola E., Petäjä T. & Kulmala M. 2011. Particle Size Magnifier for Nano-CN Detection. *Aerosol Sci. Tech.* 45: 533-542.
- Vanhatalo A., Chan T., Aalto J., Korhonen J. F., Kolari P., Hölttä T., Nikinmaa E. & Bäck J. 2015. Tree water relations trigger monoterpene emissions from Scots pine stem during spring recovery. *Biogeosciences* 12: 5353-5363.
- Venter A.D., van Zyl P.G., Beukes J.P., Swartz J.-S., Josipovic M. & Laakso L. 2018. Size-resolved characteristics of inorganic ionic species in atmospheric aerosols at a regional background site on the South African Highveld. *J. Atmos. Chem.* 75: 285–304.
- Vesala T., Markkanen T., Palva L., Siivola E., Palmroth S. & Hari P. 2000. Effects of variations of PAR on CO<sub>2</sub> estimation for Scots pine. *Agricultural and Forest Meteorology* 100: 337–347.
- Vesala T., Järvi L., Launiainen S., Sogachev A., Rannik Ü., Mammarella I., Siivola E., Keronen P., Rinne J., Riikonen A. & Nikinmaa E. 2008. Surface-atmosphere interactions over complex urban terrain in Helsinki, Finland. *Tellus B: Chemical and Physical Meteorology*. 60:2: 188-199. DOI: 10.1111/j.1600-0889.2007.00312.x
- Vesala T., Launiainen S., Kolari P., Pumpanen J., Sevanto S., Hari P., Nikinmaa E., Kaski P., Mannila H., Ukkonen E., Piao S.L. & Ciais P. 2010. Autumn temperature and carbon balance of a boreal Scots pine forest in Southern Finland. *Biogeosciences* 7: 163-176.
- Vesala T., Kohonen K.-M., Praplan A. P., Kooijmans L. M. J., Foltýnová L., Kolari P., Kulmala M., Bäck J., Nelson D., Yakir D., Zahniser M. & Mammarella I. 2022. Long-term fluxes of carbonyl sulfide and their seasonality and interannual variability in a boreal forest. *Atmos. Chem. Phys. Discuss.* doi: 10.5194/acp-2021-721.
- Vihma T., Uotila P., Sandven S., Pozdnyakov D., Makshtas A., Pelyasov A., Pirazzini R., Danielsen F., Chalov S., Lappalainen H. K., Ivanov V., Frolov I., Albin A., Cheng B., Dobrolyubov S., Arkhipkin V., Myslenkov S., Petäjä T. & Kulmala M. 2019. Towards an advanced observation system for the marine Arctic in the framework of the Pan-Eurasian Experiment (PEEX). *Atmos. Chem. Phys.* 19: 1941–1970.
- Virkkula A., Levula J., Pohja T., Aalto P. P., Keronen P., Schobesberger S., Clements C. B., Pirjola L., Kieloaho A.-J., Kulmala L., Aaltonen H., Patokoski J., Pumpanen J., Rinne J., Ruuskanen T., Pihlatie M., Manninen H. E., Aaltonen V., Junninen H., Petäjä T., Backman J., Dal Maso M., Nieminen T., Olsson T., Grönholm T., Aalto J., Virtanen T. H., Kajos M., Kerminen V.-M., Schultz D. M., Kukkonen J., Sofiev M., De Leeuw G., Bäck J., Hari P. & Kulmala M. 2014. Prescribed burning of logging slash in the boreal forest of Finland: emissions and effects on meteorological quantities and soil properties. *Atmos. Chem. Phys.* 14: 4473–4502.
- Viskari T., Asmi E., Kolmonen P., Vuollekoski H., Petäjä T. & Järvinen H. 2012a. Estimation of aerosol particle distributions with Kalman Filtering. Part I: Theory, general aspects and statistical validity. *Atmos. Chem. Phys.* 12: 11767-11779.
- Viskari T., Asmi E., Virkkula A., Kolmonen P., Petäjä T. & Järvinen H. 2012b. Estimation of aerosol particle number distribution with Kalman Filtering. Part II:



- Simultaneous use of DMPS, APS and Nephelometer measurements. *Atmos. Chem. Phys.* 12: 11781-11793.
- Wagner R., Yan C., Lehtipalo K., Duplissy J., Nieminen T., Kangasluoma J., Ahonen L. R., Dada L., Kontkanen J., Manninen H. E., Dias A., Amorim A., Bauer P. S., Bergen A., Bernhammer A.-K., Bianchi F., Brilke S., Buenrostro Mazon S., Chen X., Draper D. C., Fischer L., Frege C., Fuchs C., Garmash O., Gordon H., Hakala J., Heikkinen L., Heinritzi M., Hofbauer V., Hoyle C. R., Kirkby J., Kürten A., Kvashnin A. N., Laurila T., Lawler M. J., Mai H., Makhmutov V., Mauldin III R. L., Molteni U., Nichman L., Nie W., Ojdanic A., Onnela A., Piel F., Quéléver L. L. J., Rissanen M. P., Sarnela N., Schallhart S., Sengupta K., Simon M., Stolzenburg D., Stozhkov Y., Tröstl J., Viisanen Y., Vogel A. L., Wagner A. C., Xiao M., Ye P., Baltensperger U., Curtius J., Donahue N. M., Flagan R. C., Gallagher M., Hansel A., Smith J. N., Tomé A., Winkler P. M., Worsnop D., Ehn M., Sipilä M., Kerminen V.-M., Petäjä T. & Kulmala M. 2017. The role of ions in new particle formation in the CLOUD chamber. *Atmos. Chem. Phys.* 17: 15181-15197.
- Wang M. Kong W., Marten R., He X.-C., Chen D., Pfeifer J., Heitto A., Kontkanen J., Dada L., Kürten A., Yli-Juuti T., Manninen H., Amanatidis S., Amorim A., Baalbaki R., Baccarini A., Bell D., Bertozzi B., Bräkling S., Brilke S., Murillo L., Chiu R., Chu B., De Menezes, L.-P., Duplissy J., Finkenzeller H., Carracedo L., Granzin M., Guida R., Hansel A., Hofbauer V., Krechmer J., Lehtipalo K., Lamkaddam H., Lampimäki M., Lee C., Makhmutov V., Marie G., Mathot S., Mauldin R., Mentler B., Müller T., Onnela A., Partoll E., Petäjä T., Philippov M., Pospisilova V., Ranjithkumar A., Rissanen M., Rörup B., Scholz W., Shen J., Simon M., Sipilä M., Steiner G., Stolzenburg D., Tham Y., Tomé A., Wagner A., Wang D., Wang Y., Weber S., Winkler P., Wlasits P., Wu Y., Xiao M., Ye Q., Zauner-Wieczorek M., Zhou X., Volkamer R., Riipinen I., Dommen J., Curtius J., Baltensperger U., Kulmala M., Worsnop D., Kirkby J., Seinfeld J., El-Haddad I., Flagan R. & Donahue N. 2020. Rapid growth of new atmospheric particles by nitric acid and ammonia condensation. *Nature* 581: 184-189.
- Wang S., Wu R., Berndt T., Ehn M. & Wang L. 2017. Formation of highly oxidized radicals and multifunctional products from the atmospheric oxidation of alkylbenzenes. *Environ. Sci. Technol.* 51, 15: 8442-8449.
- Wang Z., Ehn M., Rissanen M.P., Garmash O., Quéléver L., Xing L., Monge-Palacios M., Rantala P., Donahue N.M., Berndt T & Sarathy S.M. 2021. Efficient alkane oxidation under combustion engine and atmospheric conditions. *Commun. Chem.* 4: 18, <https://doi.org/10.1038/s42004-020-00445-3>.
- Wanner H., Beer J., Bütikofer J., Crowley T.J., Cubasch U., Flückiger J., Goosse H., Grosjean M., Joos F., Kaplan J.O., Küttel M., Müller S.A., Prentice I.C., Solomina O., Stocker T.F., Tarasov P., Wagner M. & Widmann M. 2008. Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* 27: 1791-1828.
- Webb M.J., Lambert F.H. & Gregory J.M. 2013. Origins of differences in climate sensitivity, forcing and feedback in climate models. *Clim. Dyn.* 40: 677-707.
- Whelan M. E., Lennartz S. T., Gimeno T. E., Wehr R., Wohlfahrt G., Wang Y., Kooijmans L. M. J., Hilton T. W., Belviso S., Peylin P., Commane R., Sun W., Chen H., Kuai L., Mammarella I., Maseyk K., Berkelhammer M., Li K.-F., Yakir D., Zunker A., Katayama Y., Ogée J., Spielmann F. M., Kitz F., Rastogi B., Kesselmeier J., Marshall J., Erkkilä K.-M., Wingate L., Meredith L. K., He W., Bunk R., Launois T., Vesala T., Schmidt J. A., Fichot C. G., Seibt U., Saleska S., Saltzman E. S., Montzka S. A., Berry J. A. & Campbell J. E. 2018. Reviews and syntheses: Carbonyl sulfide as a multi-scale tracer for carbon and water cycles. *Biogeosciences* 15(12): 3625-3657.
- Williams R. G., Katavouta A. & Goodwin P. 2019. Carbon-cycle feedbacks operating in the climate system. *Curr. Clim. Change Rep.* 5: 282-290.
- Wilson D., Blain D., Couwenberg J., Evans C.D., Murdiyarso D., Page S.E., Renou-Wilson F., Rieley J.O., Sirin A., Strack M. & Tuittila, E.-S. 2016. Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat* 17:04: 1- 28.
- Van Wittenberghe S., Laparra V., García-Plazaola J. I., Fernández-Marín B., Porcar-Castell A. & Moreno J. 2021. Combined dynamics of the 500–600 nm leaf absorption and chlorophyll fluorescence changes in vivo: Evidence for the multifunctional energy quenching role of xanthophylls. *Biochimica et Biophysica Acta (BBA) - Bioenergetics* 1862:2: 148351.
- Woodley W. L., Gordon G., Henderson T. J., Vonnegut B., Rosenfeld D. & Detwiler A. 2003. Aircraft-produced ice particles (APIPs): Additional results and further insights. *Journal of Applied Meteorology* 42:5: 640-651.
- Xu S., Atherton J., Riikonen A., Zhang C., Oivukkamäki J., MacArthur A., Honkavaara E., Hakala T., Koivumäki N., Liu Z. & Porcar-Castell A. 2021. Structural and photosynthetic dynamics mediate the response of SIF to water stress in a potato crop. *Remote Sensing of Environment* 263: 112555.
- Yan C., Nie W., Äijälä M., Rissanen M. P., Canagaratna M. R., Massoli P., Junninen H., Jokinen T., Sarnela N., Häme S. A. K., Schobesberger S., Canonaco F., Yao L., Prévôt A. S. H., Petäjä T., Kulmala M., Sipilä M., Worsnop D. R. & Ehn M. 2016. Source characterization of highly oxidized multifunctional compounds in a boreal forest environment using positive matrix factorization. *Atmos. Chem. Phys.* 16: 12715-12731.
- Yan C., Nie W., Vogel A. L., Dada L., Lehtipalo K., Stolzenburg D., Wagner R., Rissanen M. P., Xiao M., Ahonen L., Fischer L., Rose C., Bianchi F., Gordon H., Simon M., Heinritzi M., Garmash O., Roldin P., Dias A., Ye P., Hofbauer V., Amorim A., Bauer P. S., Bergen A., Bernhammer A.-K., Breitenlechner M., Brilke S., Buchholz A., Buenrostro Mazon S., Canagaratna M. R., Chen X., Ding A., Dommen J., Draper D. C., Duplissy J., Frege C., Heyn C., Guida R., Hakala J., Heikkinen L., Hoyle C. R., Jokinen T., Kangasluoma J., Kirkby J., Kontkanen J., Kürten A., Lawler M. J., Mai H., Mathot S., Mauldin R. L., Molteni U., Nichman L., Nieminen T., Nowak J., Ojdanic A., Onnela A., Pajunoja A., Petäjä T., Piel F., Quéléver L. L. J., Sarnela N., Schallhart S., Sengupta

- K., Sipilä M., Tomé A., Tröstl J., Väisänen O., Wagner A. C., Ylisirniö A., Zha Q., Baltensperger U., Carslaw K. S., Curtius J., Flagan R. C., Hansel A., Riipinen I., Smith J. N., Virtanen A., Winkler P. M., Donahue N. M., Kerminen V.-M., Kulmala M., Ehn M. & Worsnop D. R. 2020. Size-dependent influence of NO<sub>x</sub> on the growth rates of organic aerosol particles. *Sci. Adv.* 6: eaay4945.
- Yan C., Yin R., Lu Y., Dada L., Yang D., Fu Y., Kontkanen J., Deng C., Garmash O., Ruan J., Baalbaki R., Schervish M., Cai R., Bloss M., Chan T., Chen T., Chen Q., Chen X., Chen Y., Chu B., Dällenbach K., Foreback B., He X., Heikkinen L., Jokinen T., Junninen H., Kangasluoma J., Kokkonen T., Kurppa M., Lehtipalo K., Li H., Li H., Li X., Liu Y. Ma Q., Paasonen P., Rantala P., Pileci R. E., Rusanen A., Sarnela N., Simonen P., Wang S., Wang W., Wang Y. Xue M., Yang G., Yao L., Zhou Y., Kujansuu J., Petäjä T., Nie W., Ma N., Ge M., He H., Donahue N. M., Worsnop D. R., Kerminen V.-M., Wang L., Liu Y., Zheng J., Kulmala M., Jiang J. & Bianchi F. 2021. The synergistic role of sulfuric acid, bases, and oxidized organics governing new-particle formation in Beijing. *Geophysical Research Letters* 48: e2020GL091944. <https://doi.org/10.1029/2020GL091944>
- Yang Y., Shao M., Wang X., Nölscher A. C., Kessel S., Guenther A. & Williams J. 2016. Towards a quantitative understanding of total OH reactivity: A review. *Atmos. Environ.* 134: 147–161.
- Yang B.Y., Qian Z.M., Li S., Chen G., Bloom M.S., Elliott M., Syberg K.W., Heinrich J., Markevych I., Wang S.Q., Chen D., Ma H., Chen D.H., Liu Y., Komppula M., Leskinen A., Liu K.K., Zeng X.W., Hu L.W., Guo Y. & Dong G.H. 2018. Ambient air pollution in relation to diabetes and glucose-homoeostasis markers in China: a cross-sectional study with findings from the 33 Communities Chinese Health Study. *Lancet Planet Health* 2: e64-e73. [https://doi.org/10.1016/s2542-5196\(18\)30001-9](https://doi.org/10.1016/s2542-5196(18)30001-9)
- Yao L., Garmash O., Bianchi F., Zhen J., Yan C., Kontkanen J., Junninen H., Buenrostro Mazon S., Ehn M., Paasonen P., Sipilä M., Wang M., Wang X., Xiao S., Chen H., Lu Y., Zhang B., Wang D., Fu Q., Geng F., Li L., Wang H., Qiao L., Yang X., Chen J., Kerminen V.-M., Petäjä T., Worsnop D. R., Kulmala M. & Wang L. 2018. Atmospheric new particle formation from sulfuric acid and amines in a Chinese megacity. *Science* 361: 278-281.
- Yli-Juuti T., Mielonen T., Heikkinen L., Arola A., Ehn M., Isokääntä S., Keskinen H., Kulmala M., Laakso A., Lipponen A., Luoma K., Mikkonen S., Nieminen T., Paasonen P., Petäjä T., Romakkaniemi S., Tonttila J., Kokkola H. & Virtanen A. 2021. Significance of the organic aerosol driven climate feedback in the boreal area. *Nature Communications* 12: 5637. <https://doi.org/10.1038/s41467-021-25850-7>
- Zanca T., Kubečka J., Zapadinsky E., Passananti M., Kurtén T. & Vehkamäki H. 2020. HOM cluster decomposition in API-TOF mass spectrometers. *Atmos. Meas. Tech.* 13: 3581–3593.
- Zapadinsky E., Passananti M., Mylly N., Kurtén T. & Vehkamäki H. 2019. Modelling on Fragmentation of Clusters Inside a Mass Spectrometer. *J. Phys. Chem. A* 123: 611–624.
- Zelinka M.D., Myers T.A., McCoy D.T., Po-Chedley S., Caldwell P.M., Ceppi P., Klein S.A & Taylor K.E. 2020. Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters* 47: e2019GL085782. <https://doi.org/10.1029/2019GL085782>
- Zha Q., Yan C., Junninen H., Riva M., Sarnela N., Aalto J., Quéléver L., Schallhart S., Dada L., Heikkinen L., Peräkylä O., Zou J., Rose C., Wang Y., Mammarella I., Katul G., Vesala T., Worsnop D. R., Kulmala M., Petäjä T., Bianchi F. & Ehn M. 2018. Vertical characterization of highly oxygenated molecules (HOMs) below and above a boreal forest canopy. *Atmos. Chem. Phys.* 18: 17437-17450.
- Zhang C., Atherton J., Peñuelas J., Filella I., Kolari P., Aalto J., Ruhanen H., Bäck J., Porcar-Castell A. 2019. Do all chlorophyll fluorescence emission wavelengths capture the spring recovery of photosynthesis in boreal evergreen foliage? *Plant, Cell and Environment* 12: 3264-3279.
- Zhang H., Tuittila E.-S., Korrensalo A., Räsänen A., Virtanen T., Aurela M., Penttilä T., Laurila T., Gerin S., Lindholm V. & Lohila A. 2020. Water flow controls the spatial variability of methane emissions in a northern valley fen ecosystem. *Biogeosciences* 17: 6247-6270.
- Zhou X., Sun H., Sietiö O.-M., Pumpanen J., Heinonsalo J., Köster K. & Berninger F. 2020. Wildfire effects on soil bacterial community and its potential functions in a permafrost region of Canada. *Applied Soil Ecology* 156: 103713.