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Opinion: The strength of long-term comprehensive observations to meet multiple grand challenges in different environments and in the atmosphere

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Abstract. To be able to meet global grand challenges (climate change; biodiversity loss; environmental pollution; scarcity of water, food and energy supplies; acidification; deforestation; chemicalization; pandemics), which all are closely interlinked with each other, we need comprehensive open data with proper metadata, along with open science. The large data sets from ground-based in situ observations, ground and satellite remote sensing, and multiscale modeling need to be utilized seamlessly. In this opinion paper, we demonstrate the power of the SMEAR (Station for Measuring Earth surface–Atmosphere Relations) concept via several examples, such as detection of new particle formation and the particles' subsequent growth, quantifying atmosphere–ecosystem feedback loops, and combining comprehensive observations with emergency science and services, as well as studying the effect of COVID-19 restrictions on different air quality and climate variables. The future needs and the potential of comprehensive observations of the environment are summarized.

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1 Background

The Earth is facing several environmental challenges on a global scale, often called “grand challenges” (https://www.wcrp-climate.org/grand-challenges/, last access: 20 November 2023). The growing population (https://pdp.unfpa.org, last access: 20 November 2023) needs fresh air, fresh water, food and energy while at the same time climate is changing; many cities have challenges with air quality; biodiversity is decreasing; and supplies of fresh water, food and energy are diminishing. Since these grand challenges are highly connected and interlinked, not only with each other but also with, e.g., pandemics and since potential solutions are tightly coupled with each other, they cannot be solved separately (e.g., Kulmala et al., 2015; Lappalainen et al., 2016; Nolan et al., 2018; Laughner et al., 2021; Wang et al., 2023). However, the solutions may also include unexpected trade-offs (e.g., Fastre et al., 2020). Therefore, integrated, comprehensive, big open data are required (Kulmala et al., 2021), together with a research and innovation framework in which multidisciplinary research with a critical mass of scientists utilizing proper resources is connected to fast-tracked policymaking and a wide stakeholder community. This allows aiming for practical solutions based on deep scientific understanding.

The global challenges are intimately linked to interactions and feedbacks between the different compartments of the planet Earth at different spatial and temporal scales. Fundamentally, the atmosphere is closely interconnected with various other parts of the Earth, including the biosphere, hydrosphere, cryosphere and lithosphere as well as urban surfaces over a range of temporal and spatial scales varying from seconds to millennia (Wanner et al., 2008). The sources, sinks and atmospheric concentrations of reactive trace gases, greenhouse gases and aerosol particles depend strongly on each other via physical, chemical and biological processes (e.g., Arneth et al., 2010; Stocker et al., 2013; Kulmala et al., 2014a; Unger, 2014; Green et al., 2017; Smith et al., 2023). Furthermore, both human actions and natural feedback mechanisms between the biosphere and atmosphere have substantial impacts on interactions between these atmospheric constituents and their influences on air quality and climate (Raes et al., 2010; Stocker et al., 2013; Kulmala et al., 2015; Kulmala, 2015; Nolan et al., 2018; Doherty et al., 2022; Wang et al., 2023). The importance of atmospheric aerosol particles for climate and human health on both regional and global scales has attracted plenty of research interest during recent years (Butt et al., 2017; Boy et al., 2019; Bellouin et al., 2020; Lappalainen et al., 2022; Lintunen et al., 2023). Despite these efforts, atmospheric aerosol particles remain perhaps the least known factor influencing radiative forcing, causing thereby large uncertainties in predicting the future behavior of the climate system (IPCC, 2013, 2021).

The global annual cost of climate change impacts are estimated to reach hundreds of billions of euros by 2030 (UNEP, 2016; Köberle et al., 2021), and, with increasing global warming, this cost is expected to increase strongly in the future. According to the World Economic Forum, climate change has cost the EU EUR 145 billion in a decade (https://www.weforum.org/agenda/2022/12/climate-europe-gdp-emissions/, last access: 20 November 2023). There is an urgent need to improve climate projections; reduce greenhouse gas emissions; and develop options to sequester terrestrial carbon by simultaneously taking into account the other climate forcers, such as atmospheric aerosol particles and trace gases. In addition, in order to have better understandings of natural and anthropogenic sources and sinks of carbon and of atmospheric processes influencing air quality, we need to develop the existing monitoring and forecasting systems of the terrestrial carbon cycle and to both enhance and improve measurements from process levels to a global scale. These practical needs provide emerging business opportunities for various industries. For example, European Green Deal Investment Plan will mobilize at least EUR 1 trillion of sustainable investments over the next decade (COM, 2020). The information produced using new verification systems is essential for society to design economically and socially optimal sustainability strategies and climate-neutrality pathways and to be able to meet Paris Agreement targets (Kriegler et al., 2018). The importance of comprehensive and standardized measurements is also underlined by rapid development of environmental data analysis based on artificial intelligence (AI). The quality of AI-based environmental analysis is as good as that of the measured source data. The novel Earth Virtualization Engines (EVE) concept (https://eve4climate.org/, last access: 20 November 2023) is under development, and the foreseen digital infrastructure of multi-tiered climate information for various types of users would build on optimal Earth system data integration and monitoring using AI methods like machine learning (Stevens et al., 2023).

Open science and open data are essential. Open science, the sharing of knowledge and data as early as possible in the research process (Vicente-Saez and Martinez-Fuentes, 2018), is essential as addressed by bodies like the European Commission (European Commission, 2021). Such in situ data can be obtained from global networks, such as GAW (Global Atmospheric Watch) and FLUXNET (Smith et al., 2012; Baldocci, 2019), and continental-scale infrastructures such as TERN (Terrestrial Ecosystem Research Network in Australia); NEON (National Ecological Observatory Network in the USA); ASCENT (Atmospheric Science and Chemistry mEasurement NeTwork in the USA); AmeriFlux (Boden et al., 2013); ChinaFLUX (Yu et al., 2006); AsiaFlux (Mizoguchi et al., 2008); AfriFlux (Ciais et al., 2011); and the European research infrastructures (RIs) ICOS (Integrated Carbon Observation System), ACTRIS (Aerosols, Clouds and Trace Gases Research Infrastructure) and eLTER (Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure) (Loescher et al., 2022). However, often the in situ data cover only some components of the Earth system and the proper integration of different data sets is lacking. This can be overcome by co-locating different measurements, which enables new knowledge of the interactions and feedbacks between the Earth components (biosphere, hydrosphere, atmosphere and geosphere) and allows for science-based solutions related to the interlinked grand challenges. An example of co-located measurements at a single station enabling new knowledge of the interactions and feedbacks between the Earth components, spearheading science-based solutions related to the interlinked grand challenges, is the Station for Measuring Earth surface–Atmosphere Relations (SMEAR) concept.

The primary objective of this paper is, using a few examples based mainly on data from the SMEAR II station located in Hyytiälä, Finland, to demonstrate the power of comprehensive, continuous and integrated long-term observations in providing a way towards addressing some of the grand challenges discussed above. This kind of an approach is closely tied with the SMEAR concept introduced earlier and summarized briefly in the next section. Besides research associated with the grand challenges, we demonstrate the strength of the SMEAR concept when rapid and unexpected changes occur in the environment and atmosphere.

2 SMEAR concept

The SMEAR concept is based on comprehensive, continuous and integrated long-term observations (Hari and Kulmala, 2005; Hari et al., 2016). It has been developed to meet environmental grand challenges and to collect big open data sets in order to test theories and develop models at the interfaces of different Earth components. Such unique environmental open data can contribute to solving burning questions of society – even questions that are currently unforeseen.

Current observations (see IPCC, 2013, 2021) are fragmented, which means that typically different infrastructures are measuring greenhouse gases, aerosols, air quality, ecosystems, climate and biodiversity. These measurements are conducted in different locations and environments and often during relatively short campaigns. However, to meet ongoing environmental challenges, an integrated approach with long-term measurements is needed. In practice this means co-location of various infrastructures, which enables simultaneous measurements of different Earth components (Guo, 2018; Kulmala et al., 2021; Lintunen et al., 2023). Changes in one of these components are directly or indirectly communicated to the others via intricately linked processes and feedbacks occurring at their interfaces (e.g., Stocker et al., 2013; Nolan et al., 2018; Smith et al., 2023).

The SMEAR stations, together with the SMEAR concept, were established before various international environmental research infrastructures were established (Hari and Kulmala, 2005). Today the four Finnish SMEAR stations and international SMEAR-like stations (Kulmala et al., 2021) contribute to the research infrastructures of the European Strategy Forum on Research Infrastructures (ESFRI) that are focused on standardized measurements of atmospheric composition and ecosystem processes. These research infrastructures include ICOS, ACTRIS, eLTER and the Analysis and Experimentation on Ecosystems (AnaEE) RI. SMEAR II participates in several global Earth observation systems and networks such as the World Meteorological Organization (WMO) GAW and/or European Monitoring and Evaluation Programme (EMEP), the Group on Earth Observations (GEO) Global Earth Observation System of Systems (GEOSS), FLUXNET, the Aerosol Robotic Network (AERONET), and the Solar Radiation Network (SolRad-Net). A key aspect is the colocation of these different thematic networks in a single site. This allows multi- and interdisciplinarity open science based on the collected data.

Crucial in the SMEAR concept is that it measures a set of variables needed for the atmosphere–Earth surface interactions and feedback analysis, providing fundamental knowledge for climate change mitigation and adaptation plans. The Earth surface can be, for example, forest, lake, ocean, peatland, urban area, glacier or agricultural land. The most established station, SMEAR II, is located in Hyytiälä, Finland, and it includes measurements of over 1200 different variables (Kulmala et al., 2021). The measurements are conducted at different scales from small chamber enclosures to a regional scale, which is made possible by the 128 m high measurement tower at the SMEAR II station. The measurements include meteorological variables, atmospheric compositions and fluxes (aerosols, clouds, atmospheric chemistry, greenhouse gases, etc.), as well as variables describing ecosystem functioning and soil dynamics. Long-term in situ measurements are accompanied by remote sensing, experiments (both lab and field) and multiscale modeling. Such an approach enables us to track regional and long-range transboundary pollution transport and to evaluate, e.g., trends in measured concentrations and fluxes; process dynamics; and feedbacks between processes and Earth components, such as soil–forest–atmosphere and forest–soil–stream–lake.

An important part of the SMEAR concept is open access to the research infrastructure and open data (https://smear.avaa.csc.fi/, last access: 20 November 2023). These data are massive and heterogeneous and thus challenging to manage, but the easy access to these data and both harmonized and standardized ways to analyze them are important (Junninen et al., 2009). As a summary, we can state that we need to work towards an open, integrated approach that can be accomplished with a global SMEAR network, i.e., a global Earth observatory (Hari et al., 2016; Kulmala, 2018).

In the following section, we give examples of the capabilities of the SMEAR concept, addressing different kinds of research questions: atmospheric new particle formation, the Continental Biosphere-Atmosphere-Cloud-Climate (COBACC) feedback loop that combines terrestrial carbon sinks with aerosol sources, COVID-19 impacts on air quality, and long-term trends in some of the quantities essential for air quality and climate research. We also discuss the future role of comprehensive measurements in detecting unexpected changes in the environment and atmosphere.

3 The utilization of comprehensive data sets

Here we provide examples of how we have used comprehensive data sets to meet several scientific and societal challenges and discuss briefly what has been learned from these investigations.

3.1 Atmospheric new particle formation (NPF)

A well-known example of the usefulness of comprehensive, long-term observations comprises investigations related to atmospheric NPF (e.g., Mäkelä et al., 1997; Kulmala et al., 2013). Before such observations, more emphasis was placed on binary nucleation in stratospheric conditions (e.g., Hamill et al., 1982). When looking at the scientific literature published prior to the mid-1990s, the common thought appears to have been that in the troposphere, NPF is a relatively rare and local phenomenon with minor contributions to regional or global aerosol particle budgets. However, the first long-term observations of particle number concentrations revealed a frequent occurrence of NPF and its regional character in a boreal forest environment (Mäkelä et al., 1997), and later observations confirmed the same to be the case in many other types of atmospheric environments (e.g., Kerminen et al., 2018; Nieminen et al., 2018; Chu et al., 2019; Brean et al., 2023). Motivated by long-term observations, explicit description of NPF was then included in several large-scale modeling frameworks. Simulations using such models demonstrated that NPF is the dominant source of the particle number concentration in the global atmosphere and an important contributor to concentrations of cloud condensation nuclei (e.g., Merikanto et al., 2009; Gordon et al., 2017).

In order to understand how atmospheric NPF is connected with climate and air pollution, or with emissions to the atmosphere, one needs to quantify the mechanistic pathways of atmospheric NPF and its basic characteristics, such as its frequency and associated particle formation and growth rates. Our mechanistic understanding of the initial steps of atmospheric NPF – clustering – relied for a long time on theories and laboratory experiments and was informed by a belief that the only important clustering mechanism in the atmosphere is the binary nucleation between sulfuric acid and water vapors (Malila, 2018). Atmospheric observations provided increasing evidence of the existence of multiple and possibly more complex clustering pathways (e.g., Kulmala et al., 2014b). Such findings inspired comprehensive and dedicated laboratory experiments in the Cosmics Leaving Outdoor Droplets (CLOUD) chamber at CERN (e.g., Kirkby et al., 2011; Almeida el al., 2013; Lehtipalo et al., 2018; He et al., 2021). Many of the clustering pathways quantified in these CLOUD experiments have recently been found in atmospheric observations (e.g., Sipilä et al., 2016; Jokinen et al., 2018; Lehtipalo et al., 2018; Beck et al., 2021; Yan et al., 2021), confirming the diversity of NPF in various atmospheric environments.

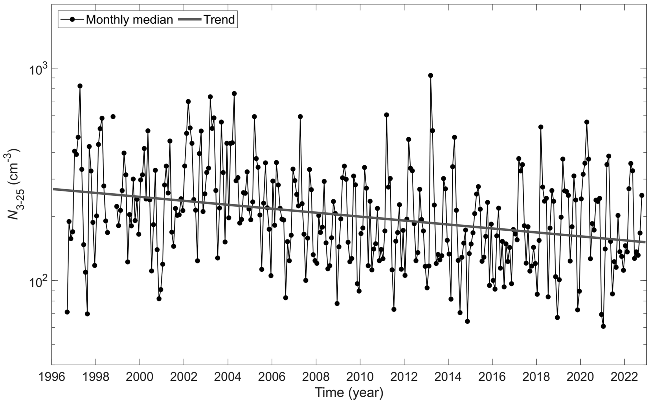

Figure 1. Monthly medians of the nucleation-mode particle (3–25 nm in mobility diameter) concentrations at the SMEAR II station in Hyytiälä, Finland. The line is a log-linear fit to the data and shows clearly the decreasing trend.

Atmospheric observations have revealed large differences in the NPF characteristics between different sites, as well as between different seasons at individual sites (e.g., Nieminen et al., 2018; Chu et al., 2019; Deng et al., 2020; Brean et al., 2023). At sites with multi-year observations, there appears to be a notable inter-annual variability in both frequency and intensity of NPF, and in some cases a long-term trend has also been reported (Asmi et al., 2011; Nieminen et al., 2014; Saha et al., 2018; Kalivitis et al., 2019; Neefjes et al., 2022). Figure 1 shows the monthly medians of nucleation-mode particle concentrations measured at the SMEAR II station. Over the 27-year observation period from 1996 until 2022, the monthly median concentrations decreased at a rate of $-0.9\,\%\,\text{yr}^{-1}$. The temporal variability in NPF characteristics has been ascribed to changes in meteorological conditions and aerosol precursor sources, including clear influences of reduced sulfur emissions and other air pollution control actions in Europe and North America (Hamed et al., 2010; Kyrö et al., 2014; Wang et al., 2017; Saha et al., 2018) and more recently also in China (Zhao et al., 2021; Zhu et al., 2021).

Long-term atmospheric observations have played a central role in atmospheric model development. The first semi-empirical parameterizations of new particle formation rates for modeling purposes were based on simultaneous and continuous measurements of gas-phase sulfuric acid concentrations and particle number size distributions (Sihto et al., 2006; Paasonen et al., 2010; Semeniuk and Dastoor, 2018).

Later, long-term observations have been essential in testing the performance of large-scale models in simulating NPF and subsequent growth of newly formed particles to cloud condensation nuclei (CCN; e.g., Spracklen et al., 2010; Fountoukis et al., 2012; Yu et al., 2015; Qi et al., 2018).

While models are likely to be the main tool for estimating the future impacts of atmospheric NPF on climate and air quality, they regularly need observations to verify their performance. In addition, many related scientific issues remain that cannot be solved without comprehensive and continuous observations. One of them is the relative importance of different clustering pathways in different environments, considering continually changing atmospheric composition in these environments. The second issue is the quantification of factors dictating the frequency and intensity of NPF, including the role of "quiet NPF", i.e., relatively weak NPF not captured by traditional NPF event analysis methods (Kulmala et al., 2022a). The third issue is to understand the growth of newly formed particles into sizes where they may act as CCN or contribute to haze formation (e.g., Ren et al., 2021; Kulmala et al., 2022b; Stolzenburg et al., 2023). Related to this issue, we need long-term observations to better understand how small clusters survive while growing to larger sizes, especially in polluted environments (Kulmala et al., 2017; Tuovinen et al., 2022), in order to find out the relative importance of condensation and heterogeneous reactions in growth and to quantify the most important precursor vapors causing this growth.

3.2 COBACC feedback loop

To understand better the complex feedbacks between the atmosphere and ecosystems, we have developed a concept called the Continental Biosphere-Atmosphere-Cloud-Climate (COBACC) feedback loop (Kulmala et al., 2013). It utilizes a multidisciplinary and integrated approach to quantify the feedbacks. The loop consists of several interrelated processes (for a detailed description, see Kulmala et al., 2014a; Artaxo et al., 2022; Kulmala et al., 2023): (1) the atmospheric temperature and CO_2 influences on biogenic volatile organic compound (BVOC) emissions; (2) the influence of BVOCs on the formation and growth of aerosol particles; (3) the effect of aerosol particles on clouds; (4) the effect of aerosol particles and clouds on solar radiation, in particular, on its diffuse fraction; and (5) the link between diffuse radiation and photosynthesis and the carbon sink in general.

The various processes involved in the interactions within the COBACC feedback loop occur over different timescales. Increases in atmospheric temperatures and carbon dioxide concentrations occur at inter-annual timescales, carbon cycling including photosynthesis and emission of BVOCs varies on scales from sub-hourly to seasonal, and the cloud variability and its effect on radiation that drive photosynthesis operate at sub-hourly timescales. Therefore, continuous and comprehensive observations, together with modeling, are key to solving such complex questions. In what follows, we summarize our current understanding of the feedback loop in the boreal zone (for a more comprehensive review, see Artaxo et al., 2022) and indicate future directions. Continuous observations serve as a base for most of the studies cited below, and the SMEAR II data set, used in most of them, remains the most comprehensive one to date.

Paasonen et al. (2013) considered the effect of a warming climate on BVOC emissions and associated increases in >100 nm aerosol particle number concentrations (a proxy for CCN), quantifying the potential cooling effect due to this feedback. The pilot study of Kulmala et al. (2014a) made the first estimate of the COBACC feedback loop using SMEAR II data, focusing on the direct aerosol effect and excluding clouds from the consideration. After that, Ezhova et al. (2018) refined and extended the analysis of the aerosol-diffuse radiation–photosynthesis part of the feedback loop using data from five sites in the boreal zone, also excluding clouds. Clouds were included in the Earth system model (ESM) studies on the feedback loop (Rap et al., 2018; Sporre et al., 2019). However, the link between BVOC, aerosol particles and clouds in various ESMs is a source of substantial discrepancies, even of different sign, in the radiation – the main driver of photosynthesis (Sporre et al., 2020). Therefore, observations remain an extremely relevant source of data for this complex question.

Based on the COBACC feedback loop, Kulmala et al. (2020) developed the CarbonSink+ concept, which, beside aerosols, takes into account the effect of forest on clouds and surface albedo. The next step is to include all radiative forcers. Current COBACC feedback loop studies are directed towards quantifying the role of clouds (Fig. 2), including their interaction with surface-based parameters and their effects on radiation and photosynthesis, based on observations. A combination of on-site and satellite observations was employed to show that clouds become optically thicker in a warmer climate with larger quantities of organic aerosol particles (Yli-Juuti et al., 2021). Furthermore, Petäjä et al. (2022) showed that continuous interaction of an air mass with emissions from the boreal forest changes the properties of this air mass over a time period of several days, including both aerosol physical and chemical characteristics and humidity. Both factors are important for the formation and evolution of clouds. Räty et al. (2023) extended this approach to a data set covering more than a decade and confirmed the main conclusions that showed an increase in, e.g., cloud condensation nuclei and specific humidity as well as cloud optical thickness and precipitation frequency (Fig. 2).

However, the outcome from this study regarding the effect of forest on cloud properties remains somewhat obscure: cloud properties were taken from the satellite data sets, which drastically decreases the number of data available for analysis. To overcome this problem, the cloud classification algorithm by Ylivinkka et al. (2020), for example, can be

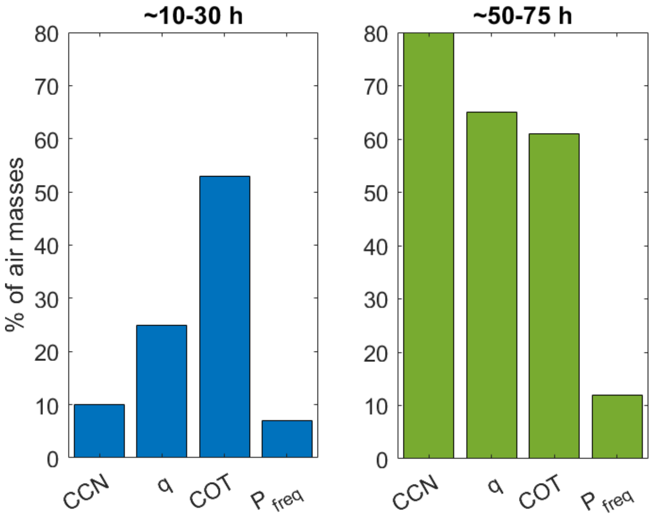

Figure 2. Illustration of forest–boundary layer cloud link (Räty et al., 2023): the fraction of air masses with the parameter value above median after 10–30 h and 50–75 h of interaction with boreal forest. Parameters are cloud condensation nuclei at 0.2 % supersaturation (CCN, median value 180 $\mathrm{cm^{-3}}$), specific humidity (q, median value 5 $\mathrm{g\,kg^{-1}}$) and cloud optical thickness (COT, median value 11). Note also an increase in precipitation frequency from 7 % to 12 % (P_{freq}). Results are obtained from an 11-year data set featuring growing seasons, SMEAR II–MODIS.

used. The algorithm allows quantifying some cloud properties, e.g., optical thickness for some types of clouds, whereas the cloud fraction is linked to patchiness. The radiation measurements, an input parameter for this algorithm, have been measured at SMEAR II for more than 2 decades, and therefore the cloud-related data set can potentially be extended significantly. Overall, continuous, comprehensive observations play a key role in tackling multidisciplinary problems with multiple timescales.

While the COBACC feedback has, until now, been studied primarily in the boreal ecosystem, more data to constrain similar feedbacks within other ecosystems – particularly tropical and (semi)arid as well as urban – are urgently needed.

BVOC and semivolatile organic compounds (SVOCs) are closely linked to secondary organic aerosol (SOA) formation as a function of ecosystems. Therefore, quantification and research of the fluxes of these volatile organic compounds (VOCs) are crucial. Field measurements of fluxes of BVOC and their oxidation products exhibiting reduced volatility, such as SVOCs, are challenging, and they can only be measured with rather short inlets to avoid wall losses during sampling. Recently a PTR3 instrument was used on top of the SMEAR II tower in Hyytiälä (Fischer et al., 2021) at 36 m above ground level and 15 m above the canopy of a forested ecosystem dominated by terpenoid emitters. The PTR3 instrument was installed approximately 4 m away from the tower structure, and the virtually wall-less inlet was successfully tested, allowing undisturbed gas sampling from this distance. For the first time emission fluxes of sesquiterpene ozonolysis products and diterpenes were recorded. With the low flux signal-to-noise ratio achieved with the new instrumentation, we can now track and study clear diurnal patterns, even for the smallest emissions rates virtually in real time. Such intensive campaigns demonstrate the feasibility of new technology to be integrated in flagship stations, providing an extended parameter set in the future.

3.3 COVID-19 restrictions

By the end of 2021, the global spread of COVID-19 caused by the SARS-CoV-2 virus had resulted in the loss of over 10 million lives (Adam, 2022; Msemburi et al., 2023). In China, national interventions were implemented starting from January 2020 to prevent the spread of the virus (China NHC, 2020). The strict lockdown measures associated with the COVID-19 pandemic provide a unique opportunity to investigate, in a real-world atmospheric laboratory, the direct and indirect effects of reduced emissions, as well as atmospheric chemistry and interacting processes associated with these emission changes, on air quality (e.g., Kroll et al., 2020; Jiang et al., 2021; Wang et al., 2021; Sokhi et al., 2021; Amouei Torkmahalleh et al., 2021).

This unique opportunity is a good demonstration of the strength of the SMEAR concept applied to atmospheric observations. First, in such an unplanned situation where new research activities have also been restricted, it is impossible to organize and carry out targeted intensive observations. Second, although there are several functioning observing stations, the relatively poor measurement capacity in most of them is unable to support the in-depth analyses needed for new scientific insights. To date, there are hundreds of atmospheric science studies relevant to the COVID-19 lockdown (https://docs.google.com/document/d/1UTQvW_OytC37IatMNR5qJK7qKfSylNpI2fT3pdteVZA/edit, last access: 20 November 2023). However, a large proportion of these studies only report variations in a few atmospheric parameters and are far from providing a mechanistic understanding of changes in atmospheric processes. There are also studies that use regional models to understand the atmospheric processes during the lockdown, but these modeling results have limited verification due to the lack of comprehensive observations.

The Aerosol and Haze Laboratory of Beijing University of Chemical Technology (AHL/BUCT; Liu et al., 2020) is one of the stations fully implementing the SMEAR concept. This station was established in January 2018, and since then it has been operating uninterruptedly with a full measurement capacity. Our comprehensive observations showed that the lockdown caused changes of different magnitudes in various atmospheric parameters (Fig. 3). In general, most of the primary pollutants, such as NO_x, $\mathrm{SO_2}$, black carbon (BC) and VOCs, showed a reduction in their abundance but at different levels. For example, NO_x was reduced by more than 50 %, SO_2 by ∼ 25 % and VOCs only by ∼ 15 %. This suggests that emissions from different source sectors were affected differently by the lockdown. In contrast to the primary pollutants, most of the secondary pollutants showed increased concentrations. Particulate nitrate, sulfate, ammonia, organics and gas-phase highly oxygenated organic molecules (HOMs) increased by ∼ 50 %–150 %. This indicates that secondary pollution, i.e., the conversion of primary pollutants into secondary ones, became more efficient. This phenomenon is closely related to the increased oxidation capacity of the atmosphere, as indicated by the increased concentrations of OH, NO_3 and O_3.

Our comprehensive data sets allow us to obtain cutting-edge knowledge in several research directions. Here, we provide two examples that provide direct observational evidence, showing the substantial influence of anthropogenic emissions on the atmospheric oxidative capacity in both the daytime and the nighttime.

3.3.1 How did the atmospheric new particle formation respond to COVID-19 lockdown

Yan et al. (2022) explored how NPF responded to emission reductions in Beijing during the COVID-19 lockdown. Clustering between sulfuric acid and base molecules drove the initial NPF in both the pre-lockdown and the lockdown periods. Our results show that this clustering was insensitive to emission reductions. Through direct observation, this study provided evidence that traffic emissions do not appear to be a significant source of NPF in Beijing, in contrast to conclusions drawn from some recent urban studies (Rönkkö et al., 2017; Guo et al., 2020).

During the lockdown period, we hypothesized that the reduction in nitrogen oxide (NO_x) concentrations would promote particle growth. This is because NO can suppress particle growth by changing the composition of oxidized organic molecules (OOMs) and make them more volatile on average (Yan et al., 2020). However, our study found otherwise. Although we noted changes in the composition of OOMs, especially in molecules arising from the oxidation of aromatic volatile organic compounds, there were only negligible changes in the volatility of OOMs. These results indicate that the reaction between RO_2 and NO still plays a vital role in OOM formation even after a dramatic reduction in NO_x levels. It has been suggested that the autoxidation of RO_2 will become more important in atmospheric chemistry as NO_x concentrations continue to decrease in North America (Praske et al., 2018), leading to increased toxicity of peroxide-driven particles and the formation of secondary organic aerosols (Zhao et al., 2017). However, our findings suggest that these harmful effects on human health and air quality in Beijing are less likely to arise in the immediate future.

3.3.2 Enhanced formation of secondary organic carbon associated with NO_3 radicals

Carbonaceous aerosols are acknowledged to have significant impacts on climate change, the Earth's radiation balance, visibility and human health (Donahue et al., 2009; Bond et al., 2013; IPCC, 2021). We examined carbonaceous aerosols measured with an organic carbon and elemental carbon ratio analyzer between 1 December 2019 and 15 March 2020 in Beijing, encompassing the COVID-19 pandemic period (Feng et al., 2022). Our findings showed that anthropogenic gas-phase pollutants and primary organic compounds were greatly reduced during the lockdown period. However, we also observed the emergence of enhanced nighttime secondary organic carbon, which we attributed to nocturnal chemistry associated with the oxidation by NO_3 radicals. Our results indicate that this nocturnal chemistry phenomenon warrants greater attention in efforts to reduce particulate matter (PM) concentration in China.

3.4 Long-term trends in comprehensive observations of atmospheric variables

The long-term observations at the SMEAR II station in Hyytiälä, Finland, cover measurements of trace gas concentrations (SO_2, O_3, NO_x, CO, CO_2) as well as volatile organic compounds (VOCs, such as monoterpenes), which are measured at multiple heights above the ground at the 128 m high mast. The continuous time series of measurements starting from 1996 allow us to quantify long-term trends in these variables (Fig. 4). In addition, mass spectrometer measurements of sulfuric acid (H_2SO_4, the main oxidation product of SO_2) started in 2016, and proxy calculations based on the measured H_2SO_4 concentrations enable the extension of this time series (Petäjä et al., 2009; Dada et al., 2020).

The monthly median concentration of the H_2SO_4 proxy has a decreasing trend of $-2.6\,\%\,\mathrm{yr}^{-1}$ (Fig. 4a). The H_2SO_4 proxy is calculated based on the production of H_2SO_4 due to the oxidation of SO_2 by OH radicals and via stabilized Criegee intermediates which are produced in the ozonolysis of monoterpenes (Dada et al., 2020) and on the loss of H_2SO_4 due to its condensation into pre-existing particles. Both the source and the sink terms of H_2SO_4 have decreasing trends in Hyytiälä during 1996–2022, being $-2.7\,\%\,\mathrm{yr}^{-1}$ for the SO_2 concentration and $-1.0\,\%\,\mathrm{yr}^{-1}$ for the condensation sink (Fig. 4c–d). The stronger decrease in the H_2SO_4 precursor vapor concentration compared with the H_2SO_4 sink seems to determine the long-term trend observed in the sulfuric acid proxy concentrations.

The monoterpene concentrations are characterized by a large year-to-year variability and do not show a statistically significant trend (Fig. 4b) (see also, e.g., Tarvainen et al., 2005; Taipale et al., 2011; Rantala et al.; 2015; Hellén et al., 2018). In the summertime, the monoterpene concentrations are highest during the year and have stayed relatively

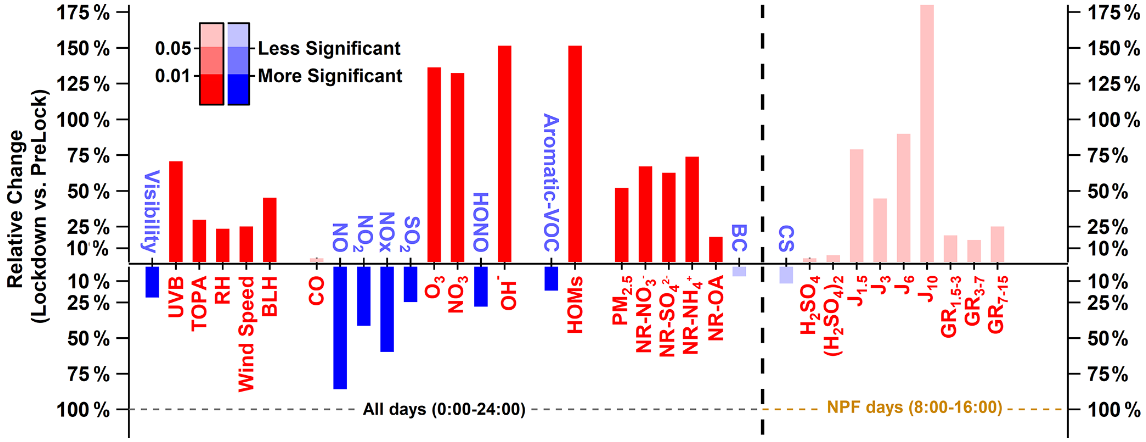

Figure 3. Variations in primary and secondary pollutants caused by the lockdown. Relative changes in atmospheric variables between the COVID-19 lockdown period (24 January–5 March 2020) and pre-lockdown period (1–23 January 2020). The relative changes are defined as $([X]_{\mathrm{lock}} - [X]_{\mathrm{pre}})/[X]_{\mathrm{pre}} \times 100\,\%$, where $[X]$ is the average of each variable. Variables associated with new particle formation (NPF) are shown only for NPF days during the daytime. TOPA is time over polluted area, BLH is boundary layer height, HOMs is highly oxygenated organic molecules, CS is condensation sink, J is formation rate and GR is growth rate.

constant, whereas the annually lowest concentrations during winter and spring also show the largest variability between years. The long-term data show strong seasonal and diurnal patterns in emission rates, which mostly relate to changes in temperature and partly also light availability. Furthermore, vegetation phenological events and biotic and abiotic stresses produce high-emission peaks (e.g., Aalto et al., 2014). The amplitude of the daily and seasonal variations in monoterpene emission rates is high and masks the potential climate change effect over the years. This emphasizes the importance of versatile, comprehensive measurements for quantifying atmospheric processes.

4 Integration of the data from satellites, models and in situ observations

4.1 Satellite and airborne observation

Satellites provide data on a global scale about atmospheric composition, radiation, surface properties and meteorology. Passive satellite measurements of atmospheric gases and aerosols are representative over an entire atmospheric column, and hence they are not directly comparable to in situ measurements. Although satellites cannot provide as detailed and wide a range of different atmospheric parameters as comprehensively equipped in situ measurement stations, such as SMEAR II, with their spatial coverage they can provide very valuable and complementary information. After understanding and analyzing in situ and satellite measurements together on a station-by-station basis, satellite data can enable the transition from point-like measurements to the interpretation of regional variability in atmospheric processes (e.g., Viatte et al., 2021; Pseftogkas et al., 2022; Hakala et al., 2019).

One example of utilizing satellite data, when moving from pointwise to global (or regional) analysis, has been to better understand the new particle formation (NPF) phenomena on a larger spatial scale (Kulmala et al., 2011; Sundström et al., 2015). As satellites cannot essentially detect aerosol particles smaller than 100 nm in diameter, these observations as such are not directly applicable for NPF studies. However, satellites provide information on many atmospheric parameters tightly linked to NPF, such as UV radiation, trace gas concentrations and estimations of ambient aerosol loads. By analyzing these data with detailed in situ measurements, it is possible to develop merged satellite variables that can be used to study the regional variation in NPF. Other examples are various climate-related feedback loops, e.g., between the atmosphere and the biosphere, where satellite observations could have the potential to increase understanding of the spatial-scale variation. Such development work would not be possible without SMEAR-type observations that have the capability of providing process-level understanding of the phenomena. It is also essential that such extensive in situ observations exist in various environments so that the sensitivity of satellite observations in these kinds of applications can be properly tested.

Passive satellite instruments provide typically so-called columnar measures, and for instance aerosol optical depth (AOD) is the vertically integrated aerosol extinction. Similarly, gas concentrations measured by satellite represent column or partial column concentrations, typically over a tropospheric column. Therefore, comparison with surface in situ measurements cannot offer a direct validation of the measurements made by satellite instruments. However, all possible columnar measurements (e.g., AOD by ground-based sun-photometers) at the same ground station would facilitate

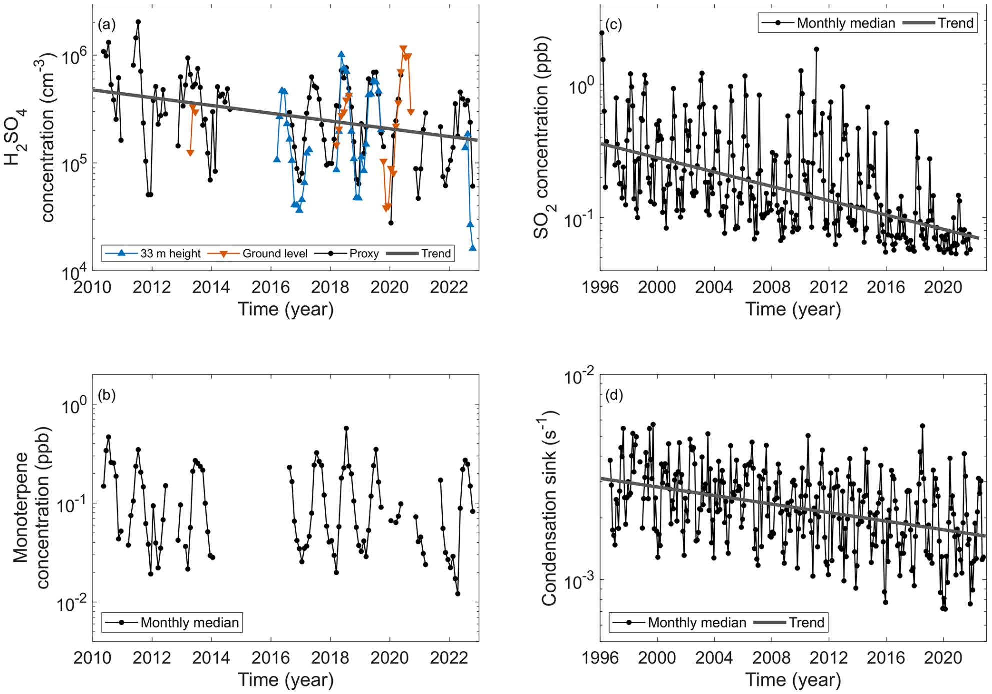

Figure 4. Trends in **(a)** sulfuric acid concentration, **(b)** monoterpene concentration, **(c)** sulfur dioxide concentration and **(d)** the condensation sink. Note the different time periods: in panels **(a)** and **(b)** 2010–2022 and in panels **(c)** and **(d)** 1996–2022. The dotted black lines show monthly medians of observations, and the solid grey lines are trends fitted to the logarithmic values of the monthly data. Monoterpene concentrations do not have a statistically significant trend, and therefore the trend line is not shown in panel **(b)**.

satellite data validation and provide information on the accuracy of the satellite observations. Currently, the SMEAR II station in Hyytiälä is accompanied by an Aerosol Robotic Network (AERONET) station (Holben et al., 1998), which allows a direct validation of satellite-based aerosol observations. Moreover, satellite validation would strongly benefit from reliable gas and aerosol vertical profile observations from the surface level up to the stratosphere.

One possible future pathway in better bridging the spatial-scale gap between pointwise in situ measurements and large-scale satellite measurements would be to utilize unoccupied aerial vehicle (UAV) measurements (Motlagh et al., 2023). Satellite data have spatial resolutions limited to a few hundred meters at best and in atmospheric observations more typically to kilometers. Drone measurements (e.g., Kezoudi et al., 2021) could bring more insight into the sub-kilometer-scale variations if carried out in the vicinity of SMEAR-type stations at the time of the satellite overpass.

4.2 Model frameworks

Model frameworks for the global climate and Earth systems have been constructed to replicate real-world processes and interactions as closely as is necessary to understand the current state of these systems and reasons for past changes and ultimately to simulate future climate pathways in order to support adaptation and mitigation efforts (Bauer et al., 2021). Modern Earth system models (ESMs) combine an increasing number of individual components, including not only the physical ocean and atmosphere models but also detailed descriptions of chemistry, aerosols and the biosphere (e.g., Döscher et al., 2022). This increase in model complexity has established groundbreaking research of Earth system feedbacks and quantification of their strength in current and future climates (Sporre et al., 2019; Thornhill et al., 2021).

Despite rigorous validation of its individual process components, evaluation and constraining of highly coupled ESMs remain difficult due to the large number of interactions and feedbacks within the Earth system (e.g., Sporre et al., 2020). At the temporal and spatial scales of ESMs, even the observational record as a whole remains brief and irregular, and therefore the observations must be extended by proxies for changes in the historical period (Wandji Nyamsi et al., 2020) towards the Earth's deep past over millions of years (Wong et al., 2021). Only integrated long-term observations can provide multidisciplinary data to support the evaluation of simulated Earth system feedbacks and their components.

With increasing complexity and process details, ESMs can arrive at correct results via the wrong reasons and counteracting biases. The advancement of spatial resolution and process descriptions within ESMs already allows evaluation at the process scale. For example, NPF events can be co-analyzed from ESMs and long-term data sets (Bergman et al., 2022).

Such process-oriented analysis is essential for validating the reasons for biases or systematic errors in simulated properties (e.g., CCN), but this requires dedicated long-term observations to constrain the models throughout distinct climate states and changing environments (Fanourgakis et al., 2019). Recent advances in trajectory-based analysis of ESMs provide a novel way to investigate simulated air masses and station footprints co-located with observations. To complete a global 4D evaluation of ESM performance, the long-term stationary data sets should be complemented with surface or airborne transects, vertical profiles, and satellite retrievals (e.g., van Noije et al., 2021).

With the competition between increasing spatial resolution and more detailed process descriptions in ESMs, data-driven approaches have been suggested to replace computationally intensive modules (Ahola et al., 2022). Whether through emulation, neural networks or other machine learning techniques, the teaching and learning process requires comprehensive understanding of the model realm complemented with an integrated observational suite (e.g., Schreck et al., 2022).

4.3 Integration of different approaches

The combination of emerging long-term in situ measurements, satellite data and process understanding bears great potential for finding new ways to evaluate and constrain ESMs and to reduce uncertainties in their projections (see Fig. 5, adopted from the FORCeS project). The inevitable spatial limitation related to in situ observations can, to some degree, be overcome by ensuring long enough temporal coverages and enhancing the number of representative data points (to be compared with satellites and models) this way (e.g., Isokääntä et al., 2022; Khadir et al., 2023).

Long-term, global, in situ observations are specifically useful in pinpointing the model weaknesses and strengths, as well as in providing detailed observations with various techniques at well-defined altitudes, as opposed to sampling the entire atmospheric column. Long-term in situ observations offer great opportunities to compare detailed process-level observations with satellite observations and large-scale models. Detailed measurements enable, e.g., investigations of size-segregated trends in aerosol loadings in a regional context using both ESM and observational data (e.g., Leinonen et al., 2022). While the number of relevant data is steadily increasing, more long-term observations from under-sampled parts of the atmosphere (the Global South, highly remote areas) are needed. In addition, combining long-term in situ measurements, satellite data, ESM model outputs and process understanding offers great potential for finding new ways to evaluate and constrain the biosphere–climate feedbacks in ESMs, the magnitudes of which are still highly variable between models (Thornhill et al., 2021). By separating the different processes (e.g., those that relate biogenic emissions and resulting aerosol concentrations to air temperatures and cloud properties) and by combining long-term observations with satellite data and multiscale modeling, one can facilitate the evaluation of the predictive abilities of the models (Blichner et al., 2023). This approach can help to isolate the impact of individual factors and improve our understanding of the underlying processes.

For example, the uncertainty in the effective radiative forcing due to aerosol–cloud interactions is governed by the cloud susceptibility to aerosol perturbations (Bellouin et al., 2020). This is split into two components which are (i) the response of the cloud droplet number concentration to aerosol perturbations – relevant for the radiative forcing due to aerosol–cloud interactions, also known as the Twomey effect – and (ii) the rapid adjustments in particular of the cloud liquid water path and cloud fraction (Bellouin et al., 2020). In situ long-term aerosol and cloud observations enable investigations of cloud susceptibility to aerosol perturbations. In situ observations (both long-term and campaign-wise) and process understanding combined with ESM model outputs (or with satellites) facilitate pinpointing specific processes or factors that should be improved in order to be able to describe the cloud activation and aerosol indirect forcing correctly in the models.

5 Future perspectives and possibilities

Currently, the speed of climate change along with its unpredictable consequences is challenging the capacities of existing observation systems. In addition, the ability to analyze the still unknown questions and challenges, the “black swans” (Taleb, 2010), calls for comprehensive, continuous observations. For example, COVID-19 gave an unexpected opportunity to demonstrate the effect of exceptional reductions in anthropogenic emissions on air quality and climate (e.g., Gettelman et al., 2020; Wijnands et al., 2022). In this case, the already-running SMEAR-type, comprehensive measurements at the AHL/BUCT station in Beijing enabled us to investigate the atmospheric processes in detail. Other examples of this type of unusual and extraordinary event could be volcanic eruptions, gas pipe attacks, extreme weather events, forest fires, exceptionally dry periods, economic collapses or chemical weapons. All these events have both short- and long-term dynamic effects on air quality and the climate system as well as effects on the functioning of societies. Also, the possibility of global tipping points that have been realized, such as permafrost loss or boreal forest shift towards tundra, may lead to unexpected environmental episodes, events and feedbacks (Rockström et al., 2009; Kulmala et al., 2015; Lenton et al., 2019). The key questions are whether the majority of current observation systems contain sufficiently comprehensive sets of variables to capture these events and whether we have the preparedness to detect, analyze and quantify these events.

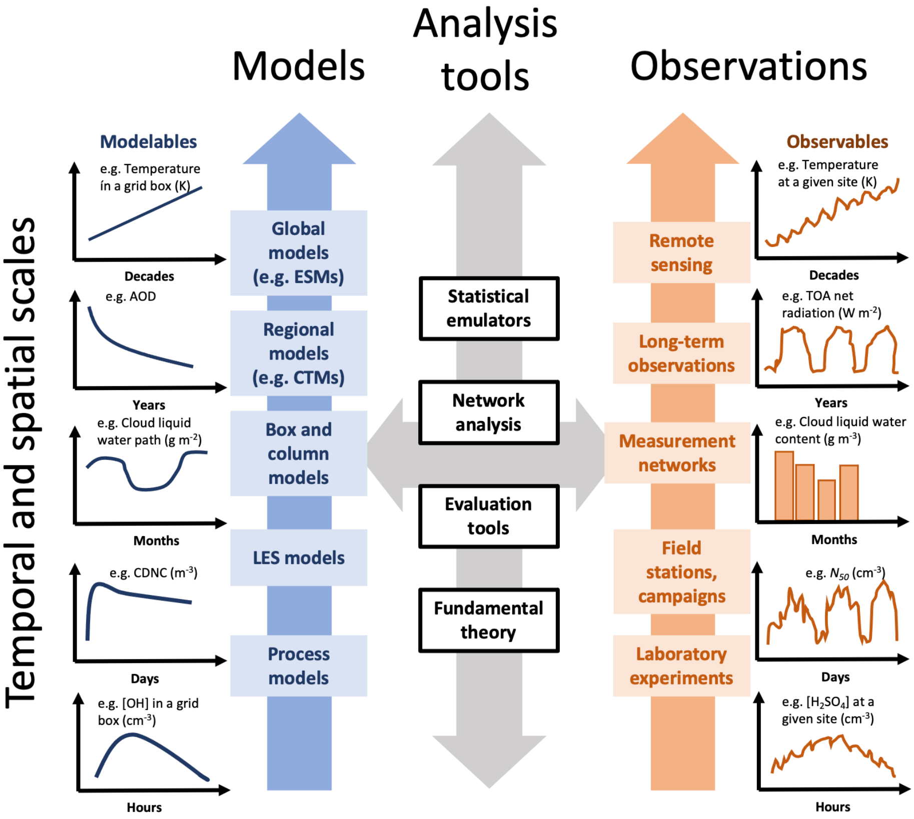

Figure 5. Combination of methods to integrate "bottom-up" and "top-down" insights into atmospheric aerosol and its interactions with clouds, as outlined within the FORCeS project (see https://forces-project.eu/). Figure courtesy of Tinja Olenius. CDNC: cloud droplet number concentration; LES: large eddy simulation; TOA: top of the atmosphere.

Recently proposed geoengineering approaches for mitigating global warming include a clear potential for large-magnitude feedbacks which can have significant, yet unpredictable, consequences on other processes. Risks related to uncontrolled geoengineering without international laws and the manipulation of the atmosphere highlight the value of continuous, comprehensive measurements detecting the changes. For example, operational solar radiation modification (SRM) deployment would introduce new environmental and socio-economic threats like damaging the ozone layer and overcompensating for climate change at regional scales (UNEP, 2023).

We need big open data to meet the present grand challenges, and we need to collect comprehensive data to be able to answer questions which do not exist today. The questions can be societal, economic or scientific or any combination of these. To effectively collect, distribute and utilize big data, there are several key actions that need to be considered.

Firstly, it is important to promote open data flows and storage globally via open-access data platforms and structures. This can be achieved through optimizing data flows by also considering how to access and analyze the data at the storage site instead of transferring huge numbers of data. Advanced AI and data-mining techniques should be employed to explore and utilize the data effectively. As importantly the in situ community should actively take part in the ongoing development of AI-based Earth Virtualization Engines (EVE), which aim to animate the Earth observations and in situ and satellite data together, at a 1 km scale for different users (Stevens et al., 2023). It is also important to transfer knowledge to make the data more accessible and to develop and provide examples and roadmaps for local data owners that highlight how to obtain merits via open data. The more local the data and data needs are, the more challenging it is to have them fully open. Therefore, it is crucial to demonstrate the benefits of offering open access to the data.

Secondly, global collaboration is needed to develop measurement protocols and data standards to reliably observe concentrations, fluxes and changes in the atmosphere and the environment. When using low-cost sensors, it is crucial to establish a proper calibration system that ensures data quality and traceability. Also, existing observation station types require calibrated sensors and enhanced harmonization. It is important to connect to existing harmonization actions by international organizations, such as the European Committee for Standardization (CEN), European environmental research infrastructures and Network of Air Quality Reference Laboratories (AQUILA). Several World Meteorological Organization working groups are already active in working towards these goals. However, we need to go to the next level to make in-house processes more effective.

Finally, it is necessary to establish a hierarchy of stations ranging from cost-effective sensors (low cost) to comprehensive flagship stations, such as SMEAR – Stations to Measure Earth surface Atmosphere Relationships, by utilizing the knowledge and experience from ESFRI as well as from operational observation networks pertinent to different domains in the atmosphere–environment continuum. Within the next 20 years, we should have a station network utilizing the hierarchy of stations with three steps, namely flagship stations, median stations and low-cost sensors, with enough flagship stations scattered globally spatially and at the ecosystem level to have enough representativeness of varying conditions. The comprehensive flagship stations should be preferably part of the GAW network with 500–1000 stations like the Station for Observing Regional Processes of the Earth System (SORPES), the Svalbard Integrated Arctic Earth Observing System (SIOS) and SMEAR (Kulmala, 2018). The median stations are high-end stations but typically focus on a specific topic (e.g., flux stations, air quality networks). Low-cost sensors need calibration from flagship and median stations and the utilization of AI and 5G, 6G and 7G networks (Rebeiro-Hargrave et al., 2021).

Taking these actions will improve our understanding of the environment and our ability to respond to environmental challenges. An important question is, who is willing to take the lead? Large international organizations like WMO are probably needed. In practice, we need to develop steps towards a GAW+ and maybe even to establish an international climate–atmosphere institute. The institute should be a multinational and multi-institutional research center following, e.g., the model of CERN but focusing on atmospheric and Earth system research.

This would be based on combining the experiences from WMO Global Atmospheric Watch (GAW) program (WMO, 2017); Copernicus; and international in situ research infrastructures like ICOS, ACTRIS and eLTER of ESFRI (see Sect. 1). The observation systems and research infrastructures, present standards, protocols, and recommendations are consensus-based. For example, essential atmospheric variables and data product management have been developed by several different actors, such as the Global Climate Observing System (GCOS) (WMO, 2022) and GAW program (WMO, 2017). These standardized systems have taken years to develop and are still in progress but need to be continued.

Under WMO leadership, we should aim for the establishment of a global observatory for comprehensive data set(s) on *weather*, *climate*, *water* and *environment*. This framework would provide a wide range of benefits, such as creating a real-world component and comparison for a digital twin or digital twins. It will also allow a proper WMO contribution to sharing integrated big data sets. The global observatory will provide a seamless connection between in situ observations, remote sensing and multiscale model data. This will enable easy access to and the utilization of remote sensing products, such as inland water altimetry for rivers, lakes and reservoirs as well as arctic snow and ice cover. Furthermore, it would provide observational support for global food forecasting through real-time dissemination of river level and discharge data, air quality forecasting, and food and water supply forecasting. It would also enable us to predict future climate and uncover feedbacks and interactions between various environmental factors.

Once we have collected all these data, it is crucial that they are utilized effectively. To be able to use the big data, open access is typically needed. However, there are several barriers to be overcome before the data can be used. The barriers include lack of documentation, unknown data, misunderstood user needs, discipline-specific jargon, bad and unusable interfaces, authorization problems, wrong terminology, training problems, unknown formats, difficulties in licensing and documentation, etc. To overcome the barriers of information, we need to have mutual trust and understanding of needs, in addition to which we need to have access to the data to make new discoveries. This can be achieved by implementing the FAIR principles (findable, accessible, interoperable, reusable) (Wilkinson et al., 2016), open-data policies and proper knowledge transfer and by conducting impact investigations, e.g., via the International Institute for Applied Systems Analysis (IIASA).

It is worth noting that the most important reason to investigate multiple variables with continuous measurements is that we never know beforehand when we will meet a “black swan”. When we have comprehensive, continuous, open data, we can analyze the data to study unexpected phenomena and find answers to upcoming challenges.

6 Conclusions

The need for comprehensive open data sets is obvious. The climate emergency and fast development of AI-based climate analysis force us to develop a new-generation observation system. Within the next 20 years, we should have a well-established station network, a “global earth observatory”, providing standardized data from different environments and scales.

Traditionally, and even in many cases today, there exist distinct infrastructures and their designated users with experiences rather far from each other. Different research groups typically have their own instruments, raw data, data analysis methods and publications. This is not an efficient way to meet grand challenges that can only be tackled with an interdisciplinary approach. In the future, we need to utilize more joint efforts, including the co-location of research infrastructures. Storing raw data jointly and analyzing it together in systematic ways already provide a big advantage. To have common data repositories for storing analyzed and published data is a big step forward.

One example of how comprehensive observations can be utilized is to solve air quality issues. In order to be able to understand the chemistry of air pollution, we need to observe multiple pollutants in existing air pollution cocktails (Kulmala, 2015). We should also remember that we spend 90 % of our time indoors, and therefore indoor air quality also needs to be understood. Air quality is important, e.g., for health effects, for visibility and from the acidification point of view. The multiple pollutants include $PM_{2.5}$, the size-resolved particle number, black carbon, O_3, NO_x, SO_2, CO, acids, various organic compounds, etc., as well as their interactions and feedbacks. Our typical framework is a seamless chain from deep understanding to solutions, starting from observations and then continuing to understanding processes, feedbacks and interactions. These steps are needed to control air pollution and to improve air quality.

In basic and applied research, we make new discoveries and new knowledge from the resources we have with the money we have at our disposal. New discoveries and knowledge often lead to innovations, and with innovations people make money from that knowledge. Innovations and new knowledge are a key for society to maintain and enhance well-being, and in this way the circle closes.

It is crucial to utilize a multidimensional, multidisciplinary, multiscale approach to be able to answer questions related to grand challenges. It is also important to have a clear and ambitious vision from deep understanding to practical solutions. Also, we need a seamless chain to connect measurements, modeling and theory as well as connecting research to innovations, economic growth and human well-being.

The main benefits that the research community can gain from using an integrated research infrastructure approach include higher-quality science, higher visibility, recognition from society and its various stakeholders, and a higher number of scientific users both nationally and internationally. Moreover, collaboration possibilities will be enhanced, including feedbacks between domains, landscape analysis, and up- and downscaling. Detailed experiments and observations can support each other so that new observational and numerical methods can be developed. The improved utilization of data flows and synergies in data use are foreseen.

In order to meet grand challenges and answer open scientific, societal and economic questions, we need to build upon a network of domain-specific research infrastructures, such as ACTRIS, eLTER and ICOS. We need to acknowledge that, for example, ACTRIS is already integrating several subfields, namely aerosol in situ, trace gas and cloud in situ observations and ground-based remote sensing of aerosols, clouds and trace gases. The human–environment relationship, i.e., socio-ecology research, is part of the transdisciplinary approach in eLTER, enabling policy-relevant research and interaction with society at different scales. The SMEAR concept in essence includes co-location and integration of the observations performed in the domain-specific environmental RIs. Further connection to and integration with, e.g., health and societal data are needed. Furthermore, we need excellent science, with high quality, a critical mass and interdisciplinary research as well as education and training, i.e., knowledge exchange. We need to contribute to innovation ecosystems and have continuous, long-term dialogue with policy-makers. Internationally, this enables clear contributions to science diplomacy based on integrated scientific viewpoints.

Data availability. The SMEAR II data are available at the SmartSMEAR data repository (https://smear.avaa.csc.fi/, SmartSMEAR, 2023). The AHL/BUCT data are available from the authors upon reasonable request.

Author contributions. MK conceptualized the paper. TN, CY and EE performed the data analysis. Management of SMEAR II and AHL/BUCT stations was by TP and CY. All the authors participated in the writing and editing of the original manuscript and its revision.

Competing interests. At least one of the (co-)authors is a member of the editorial board of *Atmospheric Chemistry and Physics*. The peer-review process was guided by an independent editor, and the authors also have no other competing interests to declare.

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References

Aalto, J., Kolari, P., Hari, P., Kerminen, V.-M., Schiestl-Aalto, P., Aaltonen, H., Levula, J., Siivola, E., Kulmala, M., and Bäck, J.: New foliage growth is a significant, unaccounted source for volatiles in boreal evergreen forests, Biogeosciences, 11, 1331–1344, https://doi.org/10.5194/bg-11-1331-2014, 2014.

Adam, D.: True COVID death toll could be more than double official count, Nature, 605, 206–206, https://doi.org/10.1038/d41586-022-01245-6, 2022.

Ahola, J., Raatikainen, T., Alper, M. E., Keskinen, J.-P., Kokkola, H., Kukkurainen, A., Lipponen, A., Liu, J., Nordling, K., Partanen, A.-I., Romakkaniemi, S., Räisänen, P., Tonttila, J., and Korhonen, H.: Technical note: Parameterising cloud base updraft velocity of marine stratocumuli, Atmos. Chem. Phys., 22, 4523–4537, https://doi.org/10.5194/acp-22-4523-2022, 2022.

Almeida, J., Schobesberger, S., Kurten, A., Ortega, I. K., Kupiainen-Maatta, 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., Leppa, J., Loukonen, V., Makhmutov, V., Mathot, S., McGrath, M. J., Nieminen, T., Olenius, T., Onnela, A., Petaja, 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., Sipila, M., Stozhkov, Y., Stratmann, F., Tome, A., Trostl, J., Tsagkogeorgas, G., Vaattovaara, P., Viisanen, Y., Virtanen, A., Vrtala, A., Wagner, P. E., Weingartner, E., Wex, H., Williamson, C., Wimmer, D., Ye, P. L., Yli-Juuti, T., Carslaw, K. S., Kulmala, M., Curtius, J., Baltensperger, U., Worsnop, D. R., Vehkamaki, H., and Kirkby, J.: Molecular understanding of sulphuric acid-amine particle nucleation in the atmosphere, Nature, 502, 359–363, https://doi.org/10.1038/nature12663, 2013.

Amouei Torkmahalleh, M., Akhmetvaliyeva, Z., Omran, A. D., Faezeh Darvish Omran, F., Kazemitabar, M., Naseri, M., Naseri, M., Sharifi, H., Malekipirbazari, M., Kwasi Adotey, E., Gorjinezhad, S., Eghtesadi, N., Sabanov, S., Alastuey, A., de Fátima Andrade, M., Buonanno, G., Carbone, S., Cárdenas-Fuentes, D. E., Cassee, F. R., Dai, Q., Henríquez, A., Hopke, P. K., Keronen, P., Khwaja, H. A., Kim, J., Kulmala, M., Kumar, P., Kushta, J., Kuula, J., Massagué, J., Mitchell, T., Mooibroek, D., Morawska, L., Niemi, J. V., Ngagine, S. H., Norman, M., Oyama, B., Oyola, P., Öztürk, F., Petäjä, T., Querol, X., Rashidi, Y., Reyes, F., Ross-Jones, M., Salthammer, T., Savvides, C., Stabile, L., Sjöberg, K., Söderlund, K., Sunder Raman, R., Timonen, H., Umezawa, M., Viana, M., and Xie, S.: Global Air Quality and COVID-19 Pandemic: Do We Breathe Cleaner Air?, Aerosol Air Qual. Res., 21, 200567, https://doi.org/10.4209/aaqr.200567, 2021.

Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P., J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., and Vesala, T.: Terrestrial biogeochemical feedbacks in the climate system, Nat. Geosci., 3, 525–532, 2010.

Artaxo, P., Hansson, H.-C., Andreae, M. O., Bäck, J., Gomes Alves, E., Barbosa, H. M. J., Bender, F., Bourtsoukidis, E., Carbone, S., Chi, J., Decesari, S., Despres, B. V. R., Ditas, F., Ezhova, E., Fuzzi, S., Hasselquist, N. J., Heitzenberg, 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., Yanez-Serrano, A. M., Zieger, P., Mikhailov, E., Smith, J. N., and Kesselmeier, J.: Tropical and boreal forest – atmosphere interactions, A review, Tellus B, 74, 24–163, 2022.

Asmi, E., Kivekäs, N., Kerminen, V.-M., Komppula, M., Hyvärinen, A.-P., Hatakka, J., Viisanen, Y., and Lihavainen, H.: Secondary new particle formation in Northern Finland Pallas site between the years 2000 and 2010, Atmos. Chem. Phys., 11, 12959–12972, https://doi.org/10.5194/acp-11-12959-2011, 2011.

Baldocci, D. D.: How eddy covariance flux measurements have contributed to our understanding of global change biology, Global Change Biol., 26, 242–260, https://doi.org/10.1111/gcb.14807, 2019.

Bauer, P., Stevens, B., and Hazeleger, W.: A digital twin of Earth for the green transition, Nat. Clim. Change, 11, 80–83, 2021.

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., Cappelletti, 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., and Sipilä, M.: Differing mechanisms of new particle formation at two arctic sites, Geophys. Res. Lett., 48, e2020GL091334, https://doi.org/10.1029/2020GL091334, 2021.

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K. S., Christensen, M., Daniau, A.-L., Dufresne, J.-L., Feingold, G., Fiedler, S., Forster, P., Gettelman, A., Haywood, J. M., Lohmann, U., Malavelle, F., Mauritsen, T., McCoy, D. T., Myhre, G., Mülmenstädt, J., Neubauer, D., Possner, A., Rugenstein, M., Sato, Y., Schulz, M., Schwartz, S. E., Sourdeval, O., Storelvmo, T., Toll, V., Winker, D., and Stevens, B.: Bounding Global Aerosol Radiative Forcing of Climate Change, Rev. Geophys., 58, e2019RG000660, https://doi.org/10.1029/2019RG000660, 2020.

Bergman, T., Makkonen, R., Schrödner, R., Swietlicki, E., Phillips, V. T. J., Le Sager, P., and van Noije, T.: Description and evaluation of a secondary organic aerosol and new particle formation scheme within TM5-MP v1.2, Geosci. Model Dev., 15, 683–713, https://doi.org/10.5194/gmd-15-683-2022, 2022.

Blichner, S. M., Yli-Juuti, T., Kokkola, H., Mielonen, T., Holopainen, E., Heikkinen, L., Petäjä, T., Pöhlker, C., Artaxo, P., Meller, B., Scott, C., Sporre, M., Svenhag, C., Partridge, D., Tovazzi, E., Virtanen, A., and Riipinen, I.: Constraining the BVOC feedback in models with process based evaluation along the scale chain, in preparation, 2023.

Boden, T. A., Krassovski, M., and Yang, B.: The AmeriFlux data activity and data system: an evolving collection of data management techniques, tools, products and services, Geosci. Instrum. Method. Data Syst., 2, 165–176, https://doi.org/10.5194/gi-2-165-2013, 2013.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Gttikundia, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender C. S.: Bounding the role of black carbon in the climate system, J. Geophys. Res.-Atmos., 118, 5380–5552, 2013.

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, A., Korhola, A., Krejci, R., Kristjansson, J. E., Lappalainen, H. K., 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., and Kulmala, M.: Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes, Atmos. Chem. Phys., 19, 2015–2061, https://doi.org/10.5194/acp-19-2015-2019, 2019.

Brean, J., Beddows, D. C. S., Harrison, R. M., Song, C., Tunved, P., Ström, J., Krejci, R., Freud, E., Massling, A., Skov, H., Asmi, E., Lupi, A., and Dall'Osto, M.: Collective geographical ecoregions and precursor sources driving Arctic new particle formation, Atmos. Chem. Phys., 23, 2183–2198, https://doi.org/10.5194/acp-23-2183-2023, 2023.

Butt, E. W., Turnock, S. T., Rigby, R., Reddington, C. L., Yoshioka, M., Johnson, J. S., Regayre, L. A., Pringle, K. J., Mann, G. W., and Spracklen, D. W.: Global and regional trends in particulate air pollution and attributable health burden over the past 50 years, Environ. Res. Lett., 12, 104017, https://doi.org/10.1088/1748-9326/aa87be, 2017.

China NHC.: COVID-19 prevention and control plan (6th edition), http://www.nhc.gov.cn/jkj/s3577/202003/4856d5b0458141fa9f376853224d41d7.shtml (last access: 20 November 2023), 2020.

Chu, B., Kerminen, V.-M., Bianchi, F., Yan, C., Petäjä, T., and Kulmala, M.: Atmospheric new particle formation in China, Atmos. Chem. Phys., 19, 115–138, https://doi.org/10.5194/acp-19-115-2019, 2019.

Ciais, P., Bombelli, A., Williams, M., Piao, S. L., Chave, J., Ryan, C. M., Henry, M., Prender, P., and Valentini, R.: The carbon balance of Africa: synthesis of recent research studies, Phil. Trans. Royal Soc. A., 369, 2038–2057, https://doi.org/10.1098/rsta.2010.0328, 2011.

COM(2020)21: European Green Deal Investment Plan, Brussels, 14.1.2020, https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vl5bgbajymzx (last access: 20 November 2023), 2020.

Dada, L., Ylivinkka, I., Baalbaki, R., Li, C., Guo, Y., Yan, C., Yao, L., Sarnela, N., Jokinen, T., Daellenbach, K. R., Yin, R., Deng, C., Chu, B., Nieminen, T., Wang, Y., Lin, Z., Thakur, R. C., Kontkanen, J., Stolzenburg, D., Sipilä, M., Hussein, T., Paasonen, P., Bianchi, F., Salma, I., Weidinger, T., Pikridas, M., Sciare, J., Jiang, J., Liu, Y., Petäjä, T., Kerminen, V.-M., and Kulmala, M.: Sources and sinks driving sulfuric acid concentrations in contrasting environments: implications on proxy calculations, Atmos. Chem. Phys., 20, 11747–11766, https://doi.org/10.5194/acp-20-11747-2020, 2020.

Deng, C., Fu, Y., Dada, L., Yan, C., Cai, R., Yang, D., Zhou, Y., Yin, R., Lu, Y., Li, X., Qiao, X., Fan, X., Nie, W., Kontkanen, J., Kangasluoma, J., Chu, B., Ding, A., Kerminen, V.-M., Paasonen, P., Worsnop, D. R., Bianchi, F., Liu, Y., Zheng, J., Wang, L., Kulmala, M., and Jiang, J.: Seasonal characteristics of new particle formation and growth in Urban Beijing. Environ. Sci. Technol., 54, 8547–8557, 2020.

Doherty, R. M., O'Connor, F. M., and Turnock, S. T.: Projections of future air quality are uncertain. But which source of uncertainty is most important? J. Geophys. Res.-Atmos., 127, e2022JD037948, https://doi.org/10.1029/2021JD035985, 2022.

Donahue, N. M., Robinson, A. L., and Pandis, S. N.: Atmospheric organic particulate matter: From smoke to secondary particulate matter, Atmos. Environ., 43, 94–106, 2009.

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégoz, M., Miller, P. A., Moreno-Chamarro, E., Nieradzik, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., and Zhang, Q.: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.

European Commission: Directorate-General for Research and Innovation, Monitoring the open access policy of Horizon 2020: final report, Publications Office, https://data.europa.eu/doi/10.2777/268348 (last access: 20 November 2023), 2021.

Ezhova, E., Ylivinkka, I., Kuusk, J., Komsaare, K., Vana, M., Krasnova, A., Noe, S., Arshinov, M., Belan, B., Park, S.-B., Lavrič, J. V., Heimann, M., Petäjä, T., Vesala, T., Mammarella, I., Kolari, P., Bäck, J., Rannik, Ü., Kerminen, V.-M., and Kulmala, M.: Direct effect of aerosols on solar radiation and gross primary production in boreal and hemiboreal forests, Atmos. Chem. Phys., 18, 17863–17881, https://doi.org/10.5194/acp-18-17863-2018, 2018.

Fanourgakis, G. S., Kanakidou, M., Nenes, A., Bauer, S. E., Bergman, T., Carslaw, K. S., Grini, A., Hamilton, D. S., Johnson, J. S., Karydis, V. A., Kirkevåg, A., Kodros, J. K., Lohmann, U., Luo, G., Makkonen, R., Matsui, H., Neubauer, D., Pierce, J. R., Schmale, J., Stier, P., Tsigaridis, K., van Noije, T., Wang, H., Watson-Parris, D., Westervelt, D. M., Yang, Y., Yoshioka, M., Daskalakis, N., Decesari, S., Gysel-Beer, M., Kalivitis, N., Liu, X., Mahowald, N. M., Myriokefalitakis, S., Schrödner, R., Sfakianaki, M., Tsimpidi, A. P., Wu, M., and Yu, F.: Evaluation of global simulations of aerosol particle and cloud condensation nuclei number, with implications for cloud droplet formation, Atmos. Chem. Phys., 19, 8591–8617, https://doi.org/10.5194/acp-19-8591-2019, 2019.

Fastre, C., Possingham, H. P., Strubbe, D., and Matthysen, E.: Identifying trade-offs between biodiversity conservation and ecosystem services delivery for land-use decisions, Sci. Rep.-Uk, 10, 7971, https://doi.org/10.1038/s41598-020-64668-z, 2020.

Feng, Z., Zheng, F., Liu, Y., Fan, X., Yan, C., Zhang, Y., Daellenbach, K. R., Bianchi, F., Petäjä, T., Kulmala, M., and Bao, X.: Evolution of organic carbon during COVID-19 lockdown period: possible contribution of nocturnal chemistry, Sci. Total Environ., 808, 152191, https://doi.org/10.1016/j.scitotenv.2021.152191, 2022.

Fischer, L., Breitenlechner, M., Canaval, E., Scholz, W., Striednig, M., Graus, M., Karl, T. G., Petäjä, T., Kulmala, M., and Hansel, A.: First eddy covariance flux measurements of semi-volatile organic compounds with the PTR3-TOF-MS, Atmos. Meas. Tech., 14, 8019–8039, https://doi.org/10.5194/amt-14-8019-2021, 2021.

Fountoukis, C., Riipinen, I., Denier van der Gon, H. A. C., Charalampidis, P. E., Pilinis, C., Wiedensohler, A., O'Dowd, C., Putaud, J. P., Moerman, M., and Pandis, S. N.: Simulating ultrafine particle formation in Europe using a regional CTM: contribution of primary emissions versus secondary formation to aerosol number concentrations, Atmos. Chem. Phys., 12, 8663–8677, https://doi.org/10.5194/acp-12-8663-2012, 2012.

Gettelman, A., Lamboll, R., Bardeen C. G., Forster, P. M., and Watson-Paris, D.: Climate impacts of COVID-19 induced emission changes, Geophys. Res. Lett., 48, e2020GL091805, https://doi.org/10.1029/2020GL091805, 2020.

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., Kurten, A., Lehtipalo, K., Makhtutov, V., Molteni, U., Rissanen, M. P., Stozkhov, Y., Tröstl, J., Tsagkogeorgs, G., Wagner, R., Williamsson, C., Wimmer, D., Winkler, P. M. Yan, C., and Carslaw, K. S.: Causes and importance of new particle formation in the present-day and preindustrial atmospheres. J. Geophys. Res.-Atmos, 122, 8739–8760, 2017.

Green, J. K., Konings, A. G., Alemohammad, S. H., Berry, J., Entekhapi, D., Kolassa, J., Lee, J.-E., and Gentine, P.: Regionally strong feedbacks between the atmosphere and terrestrial biosphere, Nat. Geosci., 10, 410–413, 2017.

Guo, H.: Steps to the digital Silk Road, Nature, 554, 25–27, 2018.

Guo, S., Hu, M., Peng, J., Wu, Z., Zamora, M. L., Shang, D., Du, Z., Zheng, J., Fang, X., Tang, R., Wu, Y., Zeng, L., Shuai, S., Zhang, W., Wang, Y., Ji, Y., Li, Y., Zhang, A. L., Wang, W., Zhang, F., Zhao, J., Gong, X., Wang, C., Molina, M. J., and Zhang, R.: Remarkable Nucleation and Growth of Ultrafine Particles from Vehicular Exhaust, P. Natl. Acad. Sci. USA, 117, 3427–3432, https://doi.org/10.1073/pnas.1916366117, 2020.

Hakala, S., Alghamdi, M. A., Paasonen, P., Vakkari, V., Khoder, M. I., Neitola, K., Dada, L., Abdelmaksoud, A. S., Al-Jeelani, H., Shabbaj, I. I., Almehmadi, F. M., Sundström, A.-M., Lihavainen, H., Kerminen, V.-M., Kontkanen, J., Kulmala, M., Hussein, T., and Hyvärinen, A.-P.: New particle formation, growth and apparent shrinkage at a rural background site in western Saudi Arabia, Atmos. Chem. Phys., 19, 10537–10555, https://doi.org/10.5194/acp-19-10537-2019, 2019.

Hamed, A., Birmili, W., Joutsensaari, J., Mikkonen, S., Asmi, A., Wehner, B., Spindler, G., Jaatinen, A., Wiedensohler, A., Korhonen, H., Lehtinen, K. E. J., and Laaksonen, A.: Changes in the production rate of secondary aerosol particles in Central Europe in view of decreasing SO_2 emissions between 1996 and 2006, Atmos. Chem. Phys., 10, 1071–1091, https://doi.org/10.5194/acp-10-1071-2010, 2010.

Hamill, P., Turco, R. P., Kiang, C. S., Toon, O. B., and Whitten, R. C.: An analysis of various nucleation mechanisms for sulfate particles in the stratosphere, J. Aerosol. Sci, 13, 561–585, 1982.

Hari, P. and Kulmala, M.: Station for Measuring Ecosystem–Atmosphere Relations (SMEAR II), Boreal Env. Res., 10, 315–322, 2005.

Hari, P., Petäjä, T., Bäck, J., Kerminen, V.-M., Lappalainen, H. K., Vihma, T., Laurila, T., Viisanen, Y., Vesala, T., and Kulmala, M.: Conceptual design of a measurement network of the global change, Atmos. Chem. Phys., 16, 1017–1028, https://doi.org/10.5194/acp-16-1017-2016, 2016.

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., Amorim1, A., Ataei, F., Baccarini, 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., Kemppainen, D., Kim, C., Kong, W., Krechmer, J. E., Kvashin, A., Laitinen, T., Lamkaddam, H., Lee, C. P., Lehtipalo, K., Leiminger, M., Li, Z., Makhmutov, 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., and Sipilä, M.: Role of iodine oxoacids in atmospheric aerosol nucleation. Science, 371, 589–595, 2021.

Hellén, H., Praplan, A. P., Tykkä, T., Ylivinkka, I., Vakkari, V., Bäck, J., Petäjä, T., Kulmala, M., and Hakola, H.: Long-term measurements of volatile organic compounds highlight the importance of sesquiterpenes for the atmospheric chemistry of a boreal forest, Atmos. Chem. Phys., 18, 13839–13863, https://doi.org/10.5194/acp-18-13839-2018, 2018.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET – A Federated Instrument Network and Data Archive for Aerosol Characterization, Remote Sens. Environ., 66, 1–16, https://doi.org/10.1016/S0034-4257(98)00031-5, 1998.

IPCC: Climate Change 2013: The Physical Science Basis, fifth assessment report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, ISBN 978-1-107-66182-0, 2013.

IPCC: Climate Change 2021: The Physical Science Basis, sixth assessment of the Inter-governmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896, 2021.

Isokääntä, S., Kim, P., Mikkonen, S., Kühn, T., Kokkola, H., Yli-Juuti, T., Heikkinen, L., Luoma, K., Petäjä, T., Kipling, Z., Partridge, D., and Virtanen, A.: The effect of clouds and precipitation on the aerosol concentrations and composition in a boreal forest environment, Atmos. Chem. Phys., 22, 11823–11843, https://doi.org/10.5194/acp-22-11823-2022, 2022.

Jiang, Z., Shi, H., Zhao, B., Gu, Y., Zhu, Y., Miyazaki, K., Lu, X., Zhang, Y., Bowman, K. W., Sekiya, T., and Liou, K.-N.: Modeling the impact of COVID-19 on air quality in southern California: implications for future control policies, Atmos. Chem. Phys., 21, 8693–8708, https://doi.org/10.5194/acp-21-8693-2021, 2021.

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., and Kerminen, V.-M.: Ion induced sulfurivc acid-ammonia nucleation drives particle formation in coastal Antractica. Sci. Adv., 4, eaat9744, https://doi.org/10.1126/sciadv.aat9744, 2018.

Junninen, H., Lauri, A., Keronen, P., Aalto, P., Hiltunen, V., Hari, P., and Kulmala, M.: Smart-SMEAR: on-line data exploration and visualization tool for SMEAR stations, Boreal Environ. Res., 14, 447–457, 2009.

Kalivitis, N., Kerminen, V.-M., Kouvarakis, 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., and Mihalopoulos, N.: Formation and growth of atmospheric nanoparticles in the eastern Mediterranean: results from long-term measurements and process simulations, Atmos. Chem. Phys., 19, 2671–2686, https://doi.org/10.5194/acp-19-2671-2019, 2019.

Kerminen, V.-M., Chen, X., Vakkari, V., Petäjä, T., Kulmala, M., and Bianchi F.: Atmospheric new particle formation and growth: review of field observations, Environ. Res. Lett., 13, 103003, https://doi.org/10.1088/1748-9326/aadf3c, 2018.

Kezoudi, M., Keleshin, C., Antoniou, P., Biskos, G., Bronz, M., Constantinides, C., Desservettaz, M., Gao, R.-S., Girdwood, J., Harnetiaux, J., Kandler, K., Leonidou, A., Liu, Y., Lelieveld, J., Marenco, F., Mihalopoulos, N., Mocnik, G., Neitola, K., Paris, J.-D., Pikridas, M., Sarda-Esteve, R., Stopford, C., Unga, F., Vrekoussis, M., and Sciare, J.: The Unmanned Systems Research Laboratory (USRL): A new facility for UAV-based atmospheric observations, Atmosphere 12, 1042, https://doi.org/10.3390/atmos12081042, 2021.

Khadir, T., Riipinen, I., Talvinen, S., Heslin-Rees, D., Pöhlker, C., Rizzo, L., Machado, L. A. T., Franco, M. A., Kremper, L. A., Artaxo, P., Petäjä, T., Kulmala, M., Tunved, P., Ekman, A. M. L., Krejci, R., and Virtanen, A.: Sink, Source or Something In-Between? Net Effects of Precipitation on Aerosol Particle Populations, Geophys. Res. Lett., 50, e2023GL104325, https://doi.org/10.1029/2023GL104325, 2023.

Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., Franchin, A., Gagne, S., Ickes, L., Kurten, 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., Haider, S., Hansel, A., Hauser, D., Jud, W., Junninen, H., Kreissl, F., Kvashin, A., Laaksonen, A., Lehtipalo, K., Lima, J., Lovejoy, E. R., Makhmutov, V., Mathot, S., Mikkila, J., Minginette, P., Mogo, S., Nieminen, T., Onnela, A., Pereira, P., Petaja, T., Schnitzhofer, R., Seinfeld, J. H., Sipila, 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., and Kulmala, M.: Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation, Nature, 476, 429–477, https://doi.org/10.1038/nature10343, 2011.

Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., Tavoni, M., and Rogelj, J.: The cost of mitigation revisited, Nat. Clim. Change, 11, 1035–1045, https://doi.org/10.1038/s41558-021-01203-6, 2021.

Kriegler, E., Luderer, G., Bauer, N., Baumstark, L., Fujimori, S., Popp, A., Rogelj, J., Strefler, J., and van Vuuren, D. P.: Pathways limiting warming to 1.5 degrees C: a tale of turning around in no time?, Philos. T. R. Soc. A, 376, 20160457, https://doi.org/10.1098/rsta.2016.0457, 2018.

Kroll, J. H., Heald, C. L., Cappa, C. D., Farmer, D. K., Fry, J. L., Murphy, J. G., and Steiner, A. L.: The complex chemical effects of COVID-19 shutdowns on air quality, Nat. Chem., 12, 777–779, https://doi.org/10.1038/s41557-020-0535-z, 2020.

Kulmala, M.: China's chocking air cocktail, Nature, 526, 497–499, https://doi.org/10.1038/526497a, 2015.

Kulmala, M.: Build a global Earth observatory, Nature, 553, 21–23, https://doi.org/10.1038/d41586-017-08967-y, 2018.

Kulmala, M., Arola, A., Nieminen, T., Riuttanen, L., Sogacheva, L., de Leeuw, G., Kerminen, V.-M., and Lehtinen, K. E. J.: The first estimates of global nucleation mode aerosol concentrations based on satellite measurements, Atmos. Chem. Phys., 11, 10791–10801, https://doi.org/10.5194/acp-11-10791-2011, 2011.

Kulmala, M., Nieminen, T., Chellapermal, R., Makkonen, R., Bäck, J., and Kerminen, V.-M.: Climate feedbacks linking the increasing atmospheric CO_2 concentration, BVOC emissions, aerosols and clouds in forest ecosystems, in: Biology, Controls and Models of Tree Volatile Organic Compound Emissions, edited by: Niinemets, Ü. and Monson, R. K., Springer, 489–508, https://doi.org/10.1007/978-94-007-6606-8_17, 2013.

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., and Kerminen, V.-M.: CO_2-induced terrestrial climate feedback mechanism: From carbon sink to aerosol source and back, Boreal Env. Res., 19, Suppl. B, 122–131, 2014a.

Kulmala, M., Petäjä, T., Ehn, M., Thornton, J., Sipilä, M., Worsnop, D. R., and Kerminen, V.-M.: Chemistry of atmospheric nucleation: On the recent advances on precursor characterization and atmospheric cluster composition in connection with atmospheric new particle formation, Annu. Rev. Phys. Chem., 65, 21–37, 2014b.

Kulmala, M., Lappalainen, H. K., Petäjä, T., Kurten, T., Kerminen, V.-M., Viisanen, Y., Hari, P., Sorvari, S., Bäck, J., Bondur, V., Kasimov, N., Kotlyakov, V., Matvienko, G., Baklanov, A., Guo, H. D., Ding, A., Hansson, H.-C., and Zilitinkevich, S.: Introduction: The Pan-Eurasian Experiment (PEEX) – multidisciplinary, multiscale and multicomponent research and capacity-building initiative, Atmos. Chem. Phys., 15, 13085–13096, https://doi.org/10.5194/acp-15-13085-2015, 2015.

Kulmala, M., Kerminen, V.-M., Petäjä, T., Ding, A. J., and Wang, L.: Atmospheric gas-to-particle conversion: why NPF events are observed in megacities?, Faraday Discuss., 200, 271–288, https://doi.org/10.1039/c6fd00257a, 2017.

Kulmala, M., Ezhova, E., Kalliokoski, T., Noe, S., Vesala, T., Lohila, A., Liski, J., Makkonen, R., Bäck, J., Petäjä, T., and Kerminen, V.M.: CarbonSink plus – Accounting for multiple climate feedbacks from forests, Boreal Environ. Res., 25, 145–159, 2020.

Kulmala, M., Lintunen, A., Ylivinkka, I., Mukkala, J., Rantanen, R., Kujansuu, J., Petäjä, T., and Lappalainen, H.K.: Atmospheric and ecosystem big data providing key contributions in reaching United Nations' sustainable development goals, Big Earth Data, 5, 277–305, doi:v10.1080/20964471.2021.1936943, 2021.

Kulmala, M., Junninen, H., Dada, L., Salma, I., Weidinger, T., Thén, W., Vörösmarty, M., Komsaare, K., Stolzenburg, D., Cai, R., Yan, C., Li, X., Deng, C., Jiang, J., Petäjä, T., Nieminen, T., and Kerminen, V.-M.: Quiet New Particle Formation in the Atmosphere, Front. Environ. Sci., 10, 912385, https://doi.org/10.3389/fenvs.2022.912385, 2022a.

Kulmala, M., Cai, R., Stolzenburg, D., Zhou, Y., Dada, L., Guo, Y., Yan, C., Petäjä, T., Jiang, J., and Kerminen, V.-M.: The contribution of new particle formation and subsequent growth to haze formation, Environ. Sci.-Atmos., 2, 352–361, 2022b.

Kulmala, M., Kokkonen, T., Ezhova, E., Baklanov, A., Mahura, A., Mammarella, I., Bäck J., Lappalainen, H., Tyuryakov, S., Kerminen, V.-M., Zilitinkevich, S., and Petäjä, T.: Aerosols, Clusters, Greenhouse Gases, Trace Gases and Boundary-Layer Dynamics: on Feedbacks and Interactions, Bound.-Lay. Meteorol., 186, 475–503, 2023.

Kyrö, E.-M., Väänänen, R., Kerminen, V.-M., Virkkula, A., Petäjä, T., Asmi, A., Dal Maso, M., Nieminen, T., Juhola, S., Shcherbinin, A., Riipinen, I., Lehtipalo, K., Keronen, P., Aalto, P. P., Hari, P., and Kulmala, M.: Trends in new particle formation in eastern Lapland, Finland: effect of decreasing sulfur emissions from Kola Peninsula, Atmos. Chem. Phys., 14, 4383–4396, https://doi.org/10.5194/acp-14-4383-2014, 2014.

Lappalainen, H. K., Kerminen, V.-M., Petäjä, T., Kurten, T., Baklanov, A., Shvidenko, A., Bäck, J., Vihma, T., Alekseychik, P., Andreae, M. O., Arnold, S. R., Arshinov, M., Asmi, E., Belan, B., Bobylev, L., Chalov, S., Cheng, Y., Chubarova, N., de Leeuw, G., Ding, A., Dobrolyubov, S., Dubtsov, S., Dyukarev, E., Elansky, N., Eleftheriadis, K., Esau, I., Filatov, N., Flint, M., Fu, C., Glezer, O., Gliko, A., Heimann, M., Holtslag, A. A. M., Hõrrak, U., Janhunen, J., Juhola, S., Järvi, L., Järvinen, H., Kanukhina, A., Konstantinov, P., Kotlyakov, V., Kieloaho, A.-J., Komarov, A. S., Kujansuu, J., Kukkonen, I., Duplissy, E.-M., Laaksonen, A., Laurila, T., Lihavainen, H., Lisitzin, A., Mahura, A., Makshtas, A., Mareev, E., Mazon, S., Matishov, D., Melnikov, V., Mikhailov, E., Moisseev, D., Nigmatulin, R., Noe, S. M., Ojala, A., Pihlatie, M., Popovicheva, O., Pumpanen, J., Regerand, T., Repina, I., Shcherbinin, A., Shevchenko, V., Sipilä, M., Skorokhod, A., Spracklen, D. V., Su, H., Subetto, D. A., Sun, J., Terzhevik, 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., and Kulmala, M.: 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, https://doi.org/10.5194/acp-16-14421-2016, 2016.

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., Konovalov, V., Konovalov, 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., Pulliainen, J., Rautiainen, 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., and Kulmala, M.: 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, https://doi.org/10.5194/acp-22-4413-2022, 2022.

Laughner, J. L., Neu, J. L., Schimel, D., Wennberg, P. O., Barsanti, K., Bowman, K. W., Chatterjee, A., Croes, B. E., Fitzmaurice, H. L., Henze, D. K., Kim, J., Kort, E. A., Liu, Z., Miyazaki, K., Turner, A. J., Anenberg, S., Avise, J., Cao, H., Crisp, D., de Gouw, J., Eldering, A., Fyfe, J. C., Goldberg, D. L., Gurney, K. R., Hasheminassab, S., Hopkins, F., Ivey, C. E., Jones, D. B. A., Liu, J., Lovenduski, N. S., Martin, R. V., McKinley, G. A., Ott, L., Poulter, B., Ru, M., Sander, S. P., Swart, N., Yung, Y. L., and Zeng, Z.-C.: Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change, P. Natl. Acad. Sci. USA, 118, e2109481118, https://doi.org/10.1073/pnas.2109481118, 2021.

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., Bernhamme,r A.-K., Breitenlechner, M., Brilke, S., Buckholz, 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. C., 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, K., Tomé, A., Tröstl, J., Väisänen, O., Vogel, A. L., Volkamer, A., 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., and Worsnop, D. R.: Multicomponent new particle formation from sulfuric acid, ammonia, and biogenic vapors, Sci. Adv., 4, eaau5363, https://doi.org/10.1126/sciadv.aau5363, 2018.

Leinonen, V., Kokkola, H., Yli-Juuti, T., Mielonen, T., Kühn, T., Nieminen, T., Heikkinen, S., Miinalainen, T., Bergman, T., Carslaw, K., Decesari, S., Fiebig, M., Hussein, T., Kivekäs, N., Krejci, R., Kulmala, M., Leskinen, A., Massling, A., Mihalopoulos, N., Mulcahy, J. P., Noe, S. M., van Noije, T., O'Connor, F. M., O'Dowd, C., Olivie, D., Pernov, J. B., Petäjä, T., Seland, Ø., Schulz, M., Scott, C. E., Skov, H., Swietlicki, E., Tuch, T., Wiedensohler, A., Virtanen, A., and Mikkonen, S.: Comparison of particle number size distribution trends in ground measurements and climate models, Atmos. Chem. Phys., 22, 12873–12905, https://doi.org/10.5194/acp-22-12873-2022, 2022.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., and Schellnhuber, H. J.: Climate tipping points – too risky to bet against, Nature, 575, 592–595, https://doi.org/10.1038/d41586-019-03595-0, 2019.

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., Köster, K., Köster, E., Kulmala, L., Kurten, T., Laaksonen, A., Lappalainen, H.K., Laurila, T., Lehtipalo, K., Lihavainen, H., Lohila, A., Mäkelä, A., Mäki, M., Makkonen, R., 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., Viisanen, Y., Virtanen, A., Ylivinkka, I., Hari, P., and Kulmala, M.: The Center of Excellence in Atmospheric Science (2002–2019) – from molecular and biological processes to the global climate, Boreal Env. Res., 28, 15–80, 2023.

Liu, Y., 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., and Kulmala, M.: Continuous and comprehensive atmospheric observations in Beijing: a station to understand the complex urban atmospheric environment, Big Earth Data, 4, 295–321, https://doi.org/10.1080/20964471.2020.1798707, 2020.

Loescher, H. W., Vargas, R., Mirtl, M., Morris, B., Pauw, J., Yu, X., Kutsch, W., Mabee, P., Tang, J., Ruddell, B.L., Pulsifer, P., Bäck, J., Zacharias, S., Grant, M., Feig, G., Zheng L., Waldmann C., and Genazzio, M. A.: Building a Global Ecosystem Research Infrastructure to address global grand challenges for macrosystem ecology, Earth's Future, 10, e2020EF001696, https://doi.org/10.1029/2020EF001696, 2022.

Mäkelä, J. M., Aalto, P., Jokinen, V., Pohja, T., Nissinen, A., Palmroth, S., Markkanen, T., Seitsonen, K., Lihavainen, H., and Kulmala, M.: Observations of ultrafine aerosol particle formation and growth in boreal forest. Geophys. Res. Lett., 24, 1219–1222, 1997.

Malila, J.: On the early studies recognizing the role of sulfuric acid in atmospheric haze and new particle formation, Tellus, 70, 1471913, https://doi.org/10.1080/16000889.2018.1471913, 2018.

Merikanto, J., Spracklen, D. V., Mann, G. W., Pickering, S. J., and Carslaw, K. S.: Impact of nucleation on global CCN, Atmos. Chem. Phys., 9, 8601–8616, https://doi.org/10.5194/acp-9-8601-2009, 2009.

Mizoguchi, Y., Miyata, A., Ohtani, Y., Hirata, R., and Yuta, S.: A review of tower flux observation sites in Asia, J. Forest. Res., 14, 1–9, https://doi.org/10.1007/s10310-008-0101-9, 2008.

Motlagh, N.H., Irjala, M., Zuniga, A., Lagerspetz, E., Rantala, V., Flores, H., Nurmi, P., and Tarkoma, S.: Toward Blue Skies: City-Scale Air Pollution Monitoring Using UAVs, IEEE Consum. Electron. Mag, 12, 21–31, doi:v10.1109/MCE.2022.3167800, 2023.

Msemburi, W., Karlinsky, A., Knutson, V., Aleshin-Guendel, S., Chatterji, S., and Wakefield, J.: The WHO estimates of excess mortality associated with COVID-19 pandemic, Nature, 613, 130–137, 2023.

Neefjes, I., Laapas, M., Liu, Y., Medus, E., Miettunen, E., Ahonen, L., Quelever, L., Aalto, J., Bäck, J., Kerminen, V.-M., Lampilahti, J., Luoma, K., Mäki, M., Mammarella, I., Petäjä, T, Räty, M., Sarnela, N., Ylivinkka, I., Hakala, S., Kulmala, M., Nieminen, T., and Lintunen, A.: 25 years of atmospheric and ecosystem measurements in a boreal forest – Seasonal variation and responses to warm and dry years, Boreal Environ. Res., 27, 1–31, 2022.

Nieminen, T., Asmi, A., Dal Maso, M., Aalto, P. P., Keronen, P., Petäjä, T., Kulmala, M., and Kerminen, V.-M.: Trends in atmospheric new-particle formation: 16 years of observations in a boreal-forest environment, Boreal Env. Res., 19, Suppl. B, 191–214, 2014.

Nieminen, T., Kerminen, V.-M., Petäjä, T., Aalto, P. P., Arshinov, M., Asmi, E., Baltensperger, U., Beddows, D. C. S., Beukes, J. P., Collins, D., Ding, A., Harrison, R. M., Henzing, B., Hooda, R., Hu, M., Hõrrak, U., Kivekäs, N., Komsaare, K., Krejci, R., Kristensson, A., Laakso, L., Laaksonen, A., Leaitch, W. R., Lihavainen, H., Mihalopoulos, N., Németh, Z., Nie, W., O'Dowd, C., Salma, I., Sellegri, K., Svenningsson, B., Swietlicki, E., Tunved, P., Ulevicius, V., Vakkari, V., Vana, M., Wiedensohler, A., Wu, Z., Virtanen, A., and Kulmala, M.: Global analysis of continental boundary layer new particle formation based on long-term measurements, Atmos. Chem. Phys., 18, 14737–14756, https://doi.org/10.5194/acp-18-14737-2018, 2018.

Nolan, C., Overpeck, J. T., Allen, J. R. M., Anderson, P. M., Betancourt, J. L., Binney, H. A., Brewer, S., Bush, M. B., Chase, B. M., Cheddadi, R., Djamali, M., Dodson, J., Edwards, M. E., Gosling, W. D., Haberle, S., Hotchkiss, S. C., Huntley, B., Ivory, S. J., Kershaw, A. P., Kim, S. H., Latorre, C., Leydet, M., Lezine, A. M., Liu, K. B., Liu, Y., Lozhkin, A. V., McGlone, M. S., Marchant, R. A., Momohara, A., Moreno, P. I., Muller, S., Otto-Bliesner, B. L., Shen, C. M., Stevenson, J., Takahara, H., Tarasov, P. E., Tipton, J., Vincens, A., Weng, C. Y., Xu, Q. H., Zheng, Z., and Jackson, S. T.: Past and future global transformation of terrestrial ecosystems under climate change, Science, 361, 920–923, https://doi.org/10.1126/science.aan5360, 2018.

Paasonen, P., Nieminen, T., Asmi, E., Manninen, H. E., Petäjä, T., Plass-Dülmer, C., Flentje, H., Birmili, W., Wiedensohler, A., Hõrrak, U., Metzger, A., Hamed, A., Laaksonen, A., Facchini, M. C., Kerminen, V.-M., and Kulmala, M.: 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, https://doi.org/10.5194/acp-10-11223-2010, 2010.

Paasonen, P., Asmi, A., Petäjä, T., Kajos, M. K., Äijälä, M, Junninen, H., Holst, T., Abbatt J. P. D., Arneth, A., Birmili, W., Denier van der Gon, H., Hamed, A., Hoffer, A., Laakso L., Laaksonen, A., Leaitch, W. R., Plass-Dulmer, C., Pryor, S. C., Räisänen, P., Swietlicki, E., Wiedensohler, A., Worsnop, D. R., Kerminen, V.-M., and Kulmala, M.: Warming-induced increase in aerosol number concentration likely to moderate climate change, Nat. Geosci., 6, 438–442, https://doi.org/10.1038/ngeo1800, 2013.

Petäjä, T., Mauldin, III, R. L., Kosciuch, E., McGrath, J., Nieminen, T., Paasonen, P., Boy, M., Adamov, A., Kotiaho, T., and Kulmala, M.: Sulfuric acid and OH concentrations in a boreal forest site, Atmos. Chem. Phys., 9, 7435–7448, https://doi.org/10.5194/acp-9-7435-2009, 2009.

Petäjä, T., Tabakova, K., Manninen, A., Ezhova, E., O'Connor, E., Moisseev, D., Sinclai,r V. A., Backman, J., Levula, J., Luoma, K., Virkkula, A., Paramonov, M., Räty, 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., and Kerminen, V.-M.: Influence of biogenic emissions from boreal forests on aerosol–cloud interactions, Nat. Geosci., 15, 42–47, 2022.

Praske, E., Otkjaer, R. V., Crounse, J. D., Hethcox, J. C., Stoltz, B. M., Kjaergaard, H. G., and Wennberg, P. O.: Atmospheric Autoxidation Is Increasingly Important in Urban and Suburban North America, P. Natl. Acad. Sci. USA, 115, 64–69, https://doi.org/10.1073/pnas.1715540115, 2018.

Pseftogkas, A., Koukouli, M.-E., Segers, A., Manders, A., Geffen, Jv., Balis, D., Meleti, C., Stavrakou, T., and Eskes, H.: Comparison of S5P/TROPOMI Inferred NO_2 Surface Concentrations with In Situ Measurements over Central Europe, Remote Sens., 14, 4886, https://doi.org/10.3390/rs14194886, 2022.

Qi, X., Ding, A., Roldin, P., Xu, Z., Zhou, P., Sarnela, N., Nie, W., Huang, X., Rusanen, A., Ehn, M., Rissanen, M. P., Petäjä, T., Kulmala, M., and Boy, M.: Modelling studies of HOMs and their contributions to new particle formation and growth: comparison of boreal forest in Finland and a polluted environment in China, Atmos. Chem. Phys., 18, 11779–11791, https://doi.org/10.5194/acp-18-11779-2018, 2018.

Raes, F., Liao, H., Chen, W.-T., and Seinfeld, J. H. J.: Atmospheric chemistry-climate feedbacks, J. Geophys. Res., 115, D12121, https://doi.org/10.1029/2009Jd013300, 2010.

Rantala, P., Aalto, J., Taipale, R., Ruuskanen, T. M., and Rinne, J.: Annual cycle of volatile organic compound exchange between a boreal pine forest and the atmosphere, Biogeosciences, 12, 5753–5770, https://doi.org/10.5194/bg-12-5753-2015, 2015.

Räty, M., Sogacheva, L., Keskinen, H.-M., Kerminen, V.-M., Nieminen, T., Petäjä, T., Ezhova, E., and Kulmala, M.: Dynamics of aerosol, humidity, and clouds in air masses travelling over Fennoscandian boreal forests, Atmos. Chem. Phys., 23, 3779–3798, https://doi.org/10.5194/acp-23-3779-2023, 2023.

Rap, A., Scott, C. E., Reddington, C. L., Mercado, L., Ellis, R. J., Garraway, S., Evans, M. J., Beerling, D. J., MacKenzie, A. R., Hewitt, C. N., and Spracklen, D. V.: Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization, Nat. Geosci., 11, 640–644, https://doi.org/10.1038/s41561-018-0208-3, 2018.

Rebeiro-Hargrave, A., Fung, P. L., Varjonen, S., Huertas, A., Sillanpää, S., Luoma, K., Hussein, T., Petäjä, T., Timonen, H., Limo, J., Nousiainen, V., and Tarkoma, S.: City Wide Participatory Sensing of Air Quality, Front. Environ. Sci., 9, 773778, https://doi.org/10.3389/fenvs.2021.773778, 2021.

Ren, J. Chen, L., Fan, T., Liu, J., Jiang, S., and Zhang, F.: The NPF effect on CCN number concentration: a review and re-evaluation of observations from 35 sites worldwide, Geophys. Res. Lett., 48, e2021GL095190, https://doi.org/10.1029/2021GL095190, 2021.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472–475, https://doi.org/10.1038/461472a, 2009.

Rönkkö, T., Kuuluvainen, H., Karjalainen, P., Keskinen, J., Hillamo, R., Niemi, J. V., Pirjola, L., Timonen, H. J., Saarikoski, S., Saukko, E., Järvinen, A., Silvennoinen, H., Rostedt, A., Olin, M., Yli-Ojanpera, J., Nousiainen, P., Kousa, A., and Dal Maso, M.: Traffic is a major source of átmospheric nanocluster aerosol, P. Natl. Acad. Sci. USA, 114, 7549–7554, https://doi.org/10.1073/pnas.1700830114, 2017.

Saha, P. K., Robinson, E., S., Shah, R., U., Zimmerman, N., Apte J. S., Robinson, A. L., and Presto, A. A.: Reduced ultrafine particle concentrations in urban air: Changes in nucleation and anthropogenic emissions, Environ. Sci. Technol., 52, 6798–6806, 2018.

Schreck, J. S., Becker, C., Gagne, D. J., Lawrence, K., Wang, S., Mouchel-Vallon, C., Choi, J., and Hodzic, A.: Neural Network Emulation of the Formation of Organic Aerosols Based on the Explicit GECKO-A Chemistry Model, J. Adv. Model Earth Sy., 14, e2021MS002974, https://doi.org/10.1029/2021MS002974, 2022.

Semeniuk, K. and Dastoor, A.: Current state of aerosol nucleation parameterizations for air-quality and climate modeling, Atmos. Environ., 179, 77–106, 2018.

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., and Lehtinen, K. E. J.: Atmospheric sulphuric acid and aerosol formation: implications from atmospheric measurements for nucleation and early growth mechanisms, Atmos. Chem. Phys., 6, 4079–4091, https://doi.org/10.5194/acp-6-4079-2006, 2006.

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., and O'Dowd, C. D.: Molecular-scale evidence of aerosol particle formation via sequential addition of HIO3, Nature, 537, 532–534, https://doi.org/10.1038/nature19314, 2016.

SmartSMEAR: About SmartSMEAR, AVAA [data set], https://smear.avaa.csc.fi/ (last access: 20 November 2023), 2023.

Smith, C., Baker, J. C. A., and Spracklen, D. V.: Tropical deforestation causes large reductions in observed precipitation, Nature, 615, 270–275, https://doi.org/10.1038/s41586-022-05690-1, 2023.

Smith, P., Davies, C. A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., Boddey, R. M., McNamara, N. P., Powlson, D., Cowie, A., van Nordwijk, M., Davis, S. C., Richter, D. D. B., Kryzanowski, L., van Wijk, M. T., Stuart, J., Kirton, A., Eggar, D., Newton-Cross, G., Adhya, T. K., and Braimoh, A. K.: Towards an integrated global framework to assess theimpacts of land use and management change on soilcarbon: current capability and future vision, Global Change Biol., 18, 2089–2101, https://doi.org/10.1111/j.1365-2486.2012.02689.x, 2012.

Sokhi, R. S., Singh, V., Querol, X., Finardi, S., Targino, A. C., Andrade, M. d. F., Pavlovic, R., Garland, R. M., Massagué, J., Kong, S., Baklanov, A., Ren, L., Tarasova, O., Carmichael, G., Peuch, V.-H., Anand, V., Arbilla, G., Badali, K., Beig, G., Belalcazar, L. C., Bolignano, A., Brimblecombe, P., Camacho, P., Casallas, A., Charland, J.-P., Choi, J., Chourdakis, E., Coll, I., Collins, M., Cyrys, J., da Silva, C. M., Di Giosa, A. D., Di Leo, A., Ferro, C., Gavidia-Calderon, M., Gayen, A., Ginzburg, A., Godefroy, F., Gonzalez, Y. A., Guevara-Luna, M., Haque, S. M., Havenga, H., Herod, D., Hõrrak, U., Hussein, T., Ibarra, S., Jaimes, M., Kaasik, M., Khaiwal, R., Kim, J., Kousa, A., Kukkonen, J., Kulmala, M., Kuula, J., La Violette, N., Lanzani, G., Liu, X., MacDougall, S., Manseau, P. M., Marchegiani, G., McDonald, B., Mishra, S. V., Molina, L. T., Mooibroek, D., Mor, S., Moussiopoulos, N., Murena, F., Niemi, J. V., Noe, S., Nogueira, T., Norman, M., Pérez-Camaño, J. L., Petäjä, T., Piketh, S., Rathod, A., Reid, K., Retama, A., Rivera, O., Rojas, N. Y., Rojas-Quincho, J. P., San José, R., Sánchez, O., Seguel, R. J., Sillanpää, S., Su, Y., Tapper, N., Terrazas, A., Timonen, H., Toscano, D., Tsegas, G., Velders, G. J. M., Vlachokostas, C., von Schneidemesser, E., Vpm, R., Yadav, R., Zalakeviciute, R., and Zavala, M.: A global observational analysis to understand changes in air quality during exceptionally low anthropogenic emission conditions, Environ. Int., 157, 106818, https://doi.org/10.1016/j.envint.2021.106818, 2021.

Spracklen, D. V., Carslaw, K. S., Merikanto, J., Mann, G. W., Reddington, C. L., Pickering, S., Ogren, J. A., Andrews, E., Baltensperger, U., Weingartner, E., Boy, M., Kulmala, M., Laakso, L., Lihavainen, H., Kivekäs, N., Komppula, M., Mihalopoulos, N., Kouvarakis, G., Jennings, S. G., O'Dowd, C., Birmili, W., Wiedensohler, A., Weller, R., Gras, J., Laj, P., Sellegri, K., Bonn, B., Krejci, R., Laaksonen, A., Hamed, A., Minikin, A., Harrison, R. M., Talbot, R., and Sun, J.: Explaining global surface aerosol number concentrations in terms of primary emissions and particle formation, Atmos. Chem. Phys., 10, 4775–4793, https://doi.org/10.5194/acp-10-4775-2010, 2010.

Sporre, M. K., Blichner, S. M., Karset, I. H. H., Makkonen, R., and Berntsen, T. K.: BVOC–aerosol–climate feedbacks investigated using NorESM, Atmos. Chem. Phys., 19, 4763–4782, https://doi.org/10.5194/acp-19-4763-2019, 2019.

Sporre, M. K., Blichner, S. M., Schrödner, R., Karset, I. H. H., Berntsen, T. K., van Noije, T., Bergman, T., O'Donnell, D., and Makkonen, R.: Large difference in aerosol radiative effects from BVOC-SOA treatment in three Earth system models, Atmos. Chem. Phys., 20, 8953–8973, https://doi.org/10.5194/acp-20-8953-2020, 2020.

Stevens, B., Adami, S., Ali, T., Anzt, H., Aslan, Z., Attinger, S., Bäck, J., Baehr, J., Bauer, P., Bernier, N., Bishop, B., Bockelmann, H., Bony, S., Bouchet, V., Brasseur, G., Bresch, D. N., Breyer, S., Brunet, G., Buttigieg, P. L., Cao, J., Castet, C., Cheng, Y., Dey Choudhury, A., Coen, D., Crewell, S., Dabholkar, A., Dai, Q., Doblas-Reyes, F., Durran, D., El Gaidi, A., Ewen, C., Exarchou, E., Eyring, V., Falkinhoff, F., Farrell, D., Forster, P. M., Frassoni, A., Frauen, C., Fuhrer, O., Gani, S., Gerber, E., Goldfarb, D., Grieger, J., Gruber, N., Hazeleger, W., Herken, R., Hewitt, C., Hoefler, T., Hsu, H.-H., Jacob, D., Jahn, A., Jakob, C., Jung, T., Kadow, C., Kang, I.-S., Kang, S., Kashinath, K., Kleinen-von Königslöw, K., Klocke, D., Kloenne, U., Klöwer, M., Kodama, C., Kollet, S., Kölling, T., Kontkanen, J., Kopp, S., Koran, M., Kulmala, M., Lappalainen, H., Latifi, F., Lawrence, B., Lee, J. Y., Lejeun, Q., Lessig, C., Li, C., Lippert, T., Luterbacher, J., Manninen, P., Marotzke, J., Matsouoka, S., Merchant, C., Messmer, P., Michel, G., Michielsen, K., Miyakawa, T., Müller, J., Munir, R., Narayanasetti, S., Ndiaye, O., Nobre, C., Oberg, A., Oki, R., Özkan-Haller, T., Palmer, T., Posey, S., Prein, A., Primus, O., Pritchard, M., Pullen, J., Putrasahan, D., Quaas, J., Raghavan, K., Ramaswamy, V., Rapp, M., Rauser, F., Reichstein, M., Revi, A., Saluja, S., Satoh, M., Schemann, V., Schemm, S., Schnadt Poberaj, C., Schulthess, T., Senior, C., Shukla, J., Singh, M., Slingo, J., Sobel, A., Solman, S., Spitzer, J., Stammer, D., Stier, P., Stocker, T., Strock, S., Su, H., Taalas, P., Taylor, J., Tegtmeier, S., Teutsch, G., Tompkins, A., Ulbrich, U., Vidale, P.-L., Wu, C.-M., Xu, H., Zaki, N., Zanna, L., Zhou, T., and Ziemen, F.: Earth Virtualization Engines (EVE), Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2023-376, in review, 2023.

Stocker, B. D., Roth, R., Joos, F., Spahni, R., Steinacher, M., Zaehle, S., Bouwman, L., Ri, X., and Prentice, I. C.: Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios, Nat. Clim. Change, 3, 666–671, 2013.

Stolzenburg, D., Cai, R., Blichner, S. M., Kontkanen, J., Zhou, P., Makkonen, R., Kerminen, V.-M., Kulmala, M., Riipinen, I., and Kangasluoma, J.: Atmospheric nanoparticle growth, Rev. Modern Phys., 95, 045002, https://doi.org/10.1103/RevModPhys.95.045002, 2023.

Sundström, A.-M., Nikandrova, A., Atlaskina, K., Nieminen, T., Vakkari, V., Laakso, L., Beukes, J. P., Arola, A., van Zyl, P. G., Josipovic, M., Venter, A. D., Jaars, K., Pienaar, J. J., Piketh, S., Wiedensohler, A., Chiloane, E. K., de Leeuw, G., and Kulmala, M.: Characterization of satellite-based proxies for estimating nucleation mode particles over South Africa, Atmos. Chem. Phys., 15, 4983–4996, https://doi.org/10.5194/acp-15-4983-2015, 2015.

Taipale, R., Kajos, M. K., Patokoski, J., Rantala, P., Ruuskanen, T. M., and Rinne, J.: Role of de novo biosynthesis in ecosystem scale monoterpene emissions from a boreal Scots pine forest, Biogeosciences, 8, 2247–2255, https://doi.org/10.5194/bg-8-2247-2011, 2011.

Taleb, N. N.: The black swan: the impact of the highly improbable, 2nd, Random House Trade Paperbacks, New York, 444 p., ISBN 9780679604181, 2010.

Tarvainen, V., Hakola, H., Hellén, H., Bäck, J., Hari, P., and Kulmala, M.: Temperature and light dependence of the VOC emissions of Scots pine, Atmos. Chem. Phys., 5, 989–998, https://doi.org/10.5194/acp-5-989-2005, 2005.

Thornhill, G., Collins, W., Olivié, D., Skeie, R. B., Archibald, A., Bauer, S., Checa-Garcia, R., Fiedler, S., Folberth, G., Gjermundsen, A., Horowitz, L., Lamarque, J.-F., Michou, M., Mulcahy, J., Nabat, P., Naik, V., O'Connor, F. M., Paulot, F., Schulz, M., Scott, C. E., Séférian, R., Smith, C., Takemura, T., Tilmes, S., Tsigaridis, K., and Weber, J.: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models, Atmos. Chem. Phys., 21, 1105–1126, https://doi.org/10.5194/acp-21-1105-2021, 2021.

Tuovinen, S., Cai, R., Kerminen, V.-M., Jiang, J., Yan, C., Kulmala, M., and Kontkanen, J.: Survival probabilities of atmospheric particles: comparison based on theory, cluster population simulations, and observations in Beijing, Atmos. Chem. Phys., 22, 15071–15091, https://doi.org/10.5194/acp-22-15071-2022, 2022.

UNEP: The Adaptation Finance Gap Report 2016. United Nations Environment Programme (UNEP), Nairobi, Kenya, ISBN 978-92-807-3498-0, 72 pp., 2016.

UNEP: An independent expert review on Solar Radiation Modification research and deployment, https://doi.org/10.59117/20.500.11822/41903, 44 pp., 2023.

Unger, N.: Human land-use-driven reduction of forest volatiles cools global climate, Nat. Clim. Change, 4, 907–910, 2014.

van Noije, T., Bergman, T., Le Sager, P., O'Donnell, D., Makkonen, R., Gonçalves-Ageitos, M., Döscher, R., Fladrich, U., von Hardenberg, J., Keskinen, J.-P., Korhonen, H., Laakso, A., Myriokefalitakis, S., Ollinaho, P., Pérez García-Pando, C., Reerink, T., Schrödner, R., Wyser, K., and Yang, S.: EC-Earth3-AerChem: a global climate model with interactive aerosols and atmospheric chemistry participating in CMIP6 , Geosci. Model Dev., 14, 5637–5668, https://doi.org/10.5194/gmd-14-5637-2021, 2021.

Viatte, C., Petit, J.-E., Yamanouchi, S., Van Damme, M., Doucerain, C., Germain-Piaulenne, E., Gros, V., Favez, O., Clarisse, L., Coheur, P.-F., Strong, K., and Clerbaux, C.: Ammonia and $PM_{2.5}$ Air Pollution in Paris during the 2020 COVID Lockdown, Atmosphere, 12, 160, https://doi.org/10.3390/atmos12020160, 2021.

Vicente-Saez, R. and Martinez-Fuentes, C.: Open Science now: A systematic literature review for an integrated definition, J. Business. Res., 88, 428–436, https://doi.org/10.1016/j.jbusres.2017.12.043, 2018.

Wandji Nyamsi, W., Lipponen, A., Sanchez-Lorenzo, A., Wild, M., and Arola, A.: A hybrid method for reconstructing the historical evolution of aerosol optical depth from sunshine duration measurements, Atmos. Meas. Tech., 13, 3061–3079, https://doi.org/10.5194/amt-13-3061-2020, 2020.

Wang, N., Xu, J., Pei, C., Tang, R., Zhou, D., Chen, Y., Li, M., Deng, X., Deng, T., Huang, X., and Ding A.: Air quality during COVID-19 lockdown in the Yangtze River Delta and the Pearl River Delta: two different responsive mechanisms to emission reduction in China, Environ. Sci. Technol., 55, 5721–5730, 2021.

Wang, S. Foster, A., Lenz, E. A., Kessler, J. D., Stroeve, J. C., Anderson L. O., Turetsky, M., Betts, R., Zou, S., Liu, W., Boos, W. R., and Hausfather, Z.: Mechanisms and impacts of Earth system tipping elements, Rev. Geophys., 61, e2021RG000757, https://doi.org/10.1029/2021RG000757, 2023.

Wang, Z., Birmila, W., Hamed, A., Wehner, B., Spindler, G., Pei X., Wu, Z., Chaen, Y., Su, H., and Wiedensohler, A.: Contributions of volatile and nonvolatile compounds (at 300 °C) to condensational growth of atmospheric nanoparticles: An assessment based on 8.5 years of observations at the Central Europe background site Melpitz, J. Geophys. Res.-Atmos., 122, 485–497, 2017.

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., and Widmann, M.: Mid- to Late Holocene climate change: an overview, Quaternary Sci. Rev., 27, 1791–1828, https://doi.org/10.1016/j.quascirev.2008.06.013, 2008.

Wijnands, J. S., Nice, K. A., Seneviratne, S., Thompson, J., and Stevenson, M.: The impact of the COVID-19 pandemic on air pollution: A global assessment using machine learning techniques, Atmos. Poll. Res., 13, 101438, https://doi.org/10.1016/j.apr.2022.101438, 2022.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR Guiding Principles for scientific data management and stewardship, Sci. Data, 3, 160018, https://doi.org/10.1038/sdata.2016.18, 2016.

WMO: Global Atmosphere Watch (GAW), Implementation Plan: 2016–2023, GAW Report No. 228, ISBN 978-92-63-11156-2, 84 pp., 2017.

WMO: 2022 GCOS Implementation Plan (GCOS-244), GCOS- No. 244, 98 pp., https://library.wmo.int/idurl/4/58104 (last access: 20 November 2023), 2022.

Wong, T. E., Cui, Y., Royer, D. L., and Keller, K.: A tighter constraint on Earth-system sensitivity from long-term temperature and carbon-cycle observations, Nat. Commun., 12, 3173, https://doi.org/10.1038/s41467-021-23543-9, 2021.

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., Mazon, S. B., 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., and Worsnop, D. R.: Size-dependent influence of NO_x on the growth rates of organic aerosol particles, Sci. Adv., 6, eaay4945, https://doi.org/10.1126/sciadv.aay4945, 2020.

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., and Bianchi, F.: The synergistic role of sulfuric acid, bases, and oxidized organics governing new-particle formation in Beijing, Geophys. Res. Lett., 48, e2020GL091944, https://doi.org/10.1029/2020GL091944, 2021.

Yan, C., Shen, Y., Stolzenburg, D., Dada, L., Qi, X., Hakala, S., Sundström, A.-M., Guo, Y., Lipponen, A., Kokkonen, T. V., Kontkanen, J., Cai, R., Cai, J., Chan, T., Chen, L., Chu, B., Deng, C., Du, W., Fan, X., He, X.-C., Kangasluoma, J., Kujansuu, J., Kurppa, M., Li, C., Li, Y., Lin, Z., Liu, Y., Liu, Y., Lu, Y., Nie, W., Pulliainen, J., Qiao, X., Wang, Y., Wen, Y., Wu, Y., Yang, G., Yao, L., Yin, R., Zhang, G., Zhang, S., Zheng, F., Zhou, Y., Arola, A., Tamminen, J., Paasonen, P., Sun, Y., Wang, L., Donahue, N. M., Liu, Y., Bianchi, F., Daellenbach, K. R., Worsnop, D. R., Kerminen, V.-M., Petäjä, T., Ding, A., Jiang, J., and Kulmala, M.: The effect of COVID-19 restrictions on atmospheric new particle formation in Beijing, Atmos. Chem. Phys., 22, 12207–12220, https://doi.org/10.5194/acp-22-12207-2022, 2022.

Yli-Juuti, T., Mielonen, T., Heikkinen, L., Arola, A., Ehn, M., Isokäänta, S., Keskinen, H. M., Kulmala, M., Laakso, A., Lipponen, A., Luoma, K., Mikkonen, S., Nieminen, T., Paasonen, P., Petäjä, T., Romakkaniemi, S., Tonttila, J., Kokkola, H., and Virtanen, A.: Significance of the organic aerosol driven climate feedback in the boreal area, Nat. Commun., 12, 5637, https://doi.org/10.1038/s41467-021-25850-7, 2021.

Ylivinkka, I., Kaupinmäki, S., Virman, M., Peltola, M., Taipale, D., Petäjä, T., Kerminen, V.-M., Kulmala, M., and Ezhova, E.: Clouds over Hyytiälä, Finland: an algorithm to classify clouds based on solar radiation and cloud base height measurements, Atmos. Meas. Tech., 13, 5595–5619, https://doi.org/10.5194/amt-13-5595-2020, 2020.

Yu, G.-R., Wen, X.-F., Sun, X.-M., Tanner, B. D., Lee, X., and Chen, J.-Y.: Overview of ChinaFLUX and evaluation of its eddy covariance measurement, Agric. Forest Met., 137, 125–137, https://doi.org/10.1016/j.agrformet.2006.02.011, 2006.

Yu, F., Luo, G., Pryor, S. C., Pillai, P. R., Lee, S. H., Ortega, J., Schwab, J. J., Hallar, A. G., Leaitch, W. R., Aneja, V. P., Smith, J. N., Walker, J. T., Hogrefe, O., and Demerjian, K. L.: Spring and summer contrast in new particle formation over nine forest areas in North America, Atmos. Chem. Phys., 15, 13993–14003, https://doi.org/10.5194/acp-15-13993-2015, 2015.

Zhao, S. P., Yu, Y., Yin, D. Y., and Qin, H.: Contrasting response of ultrafine particle number and $PM_{2.5}$ mass concentrations to clean air actions in China, Geophys. Res. Lett., 48, e2921GL093886, https://doi.org/10.1029/2021GL093886, 2021.

Zhao, Y., Saleh, R., Saliba, G., Presto, A. A., Gordon, T. D., Drozd, G. T., Goldstein, A. H., Donahue, N. M., and Robinson, A. L.: Reducing Secondary Organic Aerosol Formation from Gasoline Vehicle Exhaust, P. Natl. Acad. Sci. USA, 114, 6984, https://doi.org/10.1073/pnas.1620911114, 2017.

Zhu, Y., Shen, Y., Meng, H., Sun, Y., Yao, X., Gao, H., Xue, L., and Wang, W.: Investigation of particle number concentrations and new particle formation with largely reduced air pollutant emissions at a coastal semi-urban site in Northern China, J. Geophys. Res.-Atmos., 126, e2021JD035419, https://doi.org/10.1029/2021JD035419, 2021.