Aerosol, Clouds and Trace Gases Research Infrastructure – ACTRIS, the European research infrastructure supporting atmospheric science

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ABSTRACT

The Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) officially became the 33rd European Research Infrastructure Consortium (ERIC) on April 25, 2023 with the support of 17 founding member and observer countries. As a pan-European legal organization, ACTRIS ERIC will coordinate the provision of data and data products on short-lived atmospheric constituents and clouds relevant to climate and air pollution over the next 15-20 years. ACTRIS was designed more than a decade ago, and its development was funded at national and European levels. It was included in the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap in 2016 and subsequently, in the national infrastructure roadmaps of European countries. It became a landmark of the ESFRI roadmap in 2021. The purpose of this paper is to describe the mission of ACTRIS, its added value to the community of atmospheric scientists, providing services to academia as well as the public and private sectors, and to summarize its main achievements. The present publication serves as a reference document for ACTRIS, its users and the scientific community as a whole. It provides the reader with relevant information and an overview on ACTRIS governance and services, as well as a summary of the main scientific achievements of the last 20 years. The paper concludes with an outlook on the upcoming challenges for ACTRIS and the strategy for its future evolution.

SIGNIFICANCE STATEMENT

ACTRIS is the new European Research Infrastructure consortium for short-lived atmospheric constituents and clouds, supporting fundamental research and excellence in Earth system observation. The primary objective of ACTRIS is to produce high-quality integrated datasets in the field of atmospheric sciences and to provide services, including access to instrumented platforms, tailored for scientific and technological use. Established with a long-term perspective, with financial commitments from 17 European countries and the European Commission, ACTRIS services are open to the global community of scientists involved in atmospheric research and beyond. It is expected that ACTRIS will have a strong impact enhancing excellence in Earth system observation and research, providing information and knowledge for the development of sustainable solutions to societal needs.

CAPSULE

ACTRIS, the newly established European research infrastructure enabling research on aerosol, clouds and trace gases.

1. Introduction

Short-lived Atmospheric Constituents (SLACs) and clouds play a key role in regulating the Earth's climate and impacting the quality of air and its effects on human and ecosystem health. Their concentration is controlled not only by the intensity of primary emissions (sources) and removal processes (sinks), but also by a complex set of secondary reactions that are not yet fully understood and that may evolve in the coming decades due to changes in climate. Evolution of terrestrial and marine ecosystems, and changes in the hydrosphere and cryosphere are likely to affect the sources and sinks of SLACs, while warmer temperatures may strongly influence the thermodynamics and chemical processes controlling their formation and removal. Despite evident progress in understanding and modeling atmospheric composition, there are still gaps in our understanding of climate–chemistry interactions that need to be filled to ensure that policy makers are provided with the most appropriate strategies for predicting, mitigating, and adapting to the impacts of climate change.

For understanding sources, sinks, and chemistry of SLACs and their impacts on climate change and air quality, but also the role of clouds, the research community must rely on sustainable infrastructures to enable excellent research: field and laboratory facilities equipped with state-of-the-art instruments to observe, in the long term, the evolution of the natural atmosphere or to experiment processes under controlled conditions, well-dimensioned data centres (DCs) for curation and access to data and data products, and expert centres to harmonize methodologies for probing the atmosphere and test innovative atmospheric measurement techniques.

On April 25, 2023, the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) was officially established as a European Research Infrastructure Consortium (ERIC), one of the specific legal forms that facilitates the establishment and operation of Research Infrastructures (Appendix A provides definitions of acronyms and terminologies). ACTRIS ERIC is supported by 17 countries (Figure 1). As the European organization to facilitate research in the field of atmospheric sciences, its goal is to document variability, to understand processes and to quantify the impacts of SLACs on the Earth's climate, air quality, human health, and ecosystems.
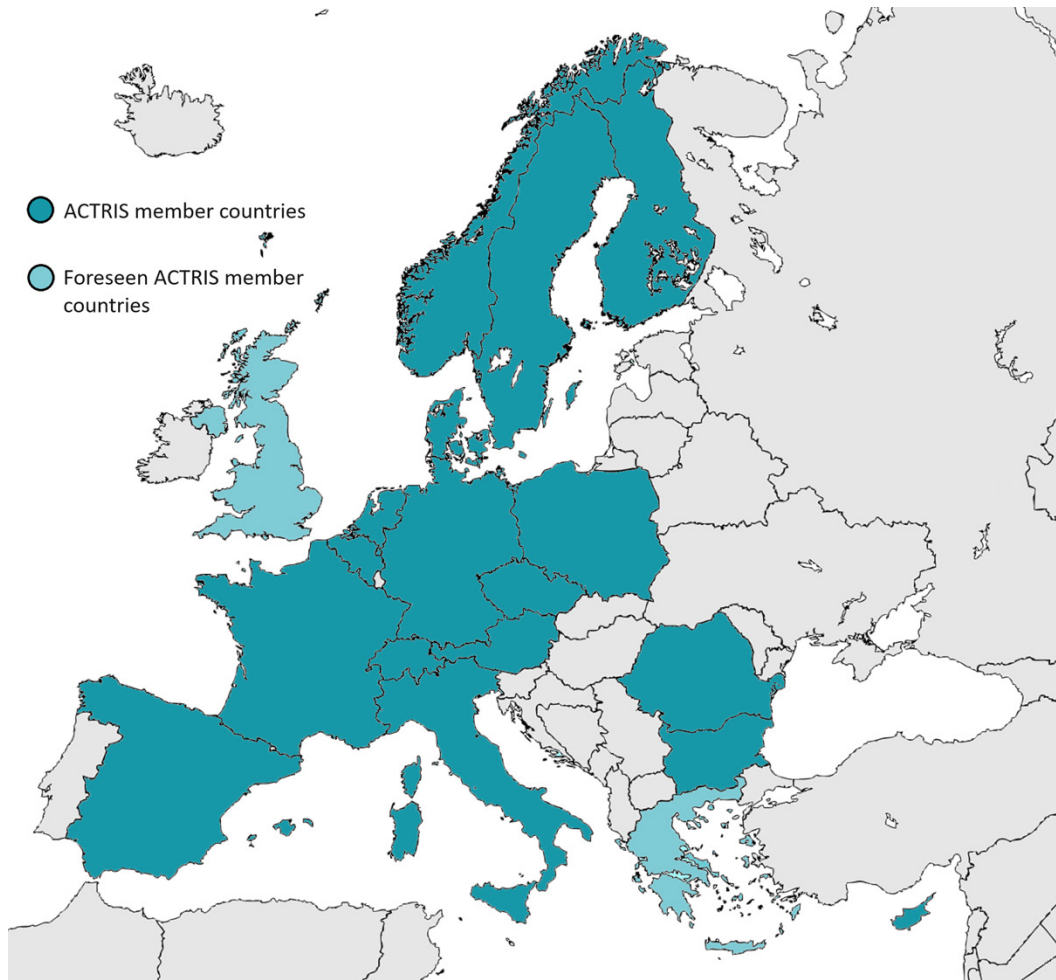
Fig. 1. ACTRIS Member Countries (in cyan), as of September 2023. The United Kingdom and Greece (in light green) are candidates to integrate in ACTRIS ERIC during 2024.

It is the key European initiative that enables and facilitates atmospheric research of SLACs and clouds for the coming decades. Built around large and comprehensive atmospheric research facilities, distributed across Europe and beyond, ACTRIS provides a unique portfolio of services to be used by a large community of scientists to conduct cutting-edge research on aerosols, clouds and reactive trace gases.

The first sections of the paper provide the rationale for the long-term establishment of the research infrastructure (RI) and describe the ACTRIS scientific and technical strategy along with a user-oriented description of its organization. The second part of this document outlines the concept of ACTRIS variables, the data life cycle, from raw data acquisition, quality control and assurance (QA/QC), to data analysis and the policy for data dissemination, access and use of the services. In addition, it explains how ACTRIS collaborates with international networks

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and gives an overview of principal scientific achievements of ACTRIS over the past decades. Despite being established as an ERIC only recently, the ACTRIS research community has produced several key scientific contributions for many years, e.g., on the composition, distribution, and properties of SLACS and clouds, the physico-chemical processes that determine their fate and impacts, the impact of natural hazards such as volcanic eruptions and forest fires on the atmospheric composition, etc. It is within the scope of the paper to review how ACTRIS has contributed to the advancement of knowledge and technologies for the study of the atmosphere and its composition. The final section describes perspectives for the development of ACTRIS over the next years/decade, and illustrates how the perimeter of the RI may evolve according to user needs.

2. The ACTRIS concept

a. The rationale for ACTRIS

The atmosphere is a highly complex system in which properties and concentration levels of gaseous and particulate species are influenced by processes involving dynamics, energy balance, chemistry and interactions with other Earth compartments. Predicting atmospheric behavior across time scales (hours to decades) is essential for society and relies on complex models supported by high quality observations.

ACTRIS focuses on producing high-quality observations of SLACs and clouds, studying processes affecting their variability in space and time, mainly enabling research in:

- Earth's radiative balance, clouds and short-lived climate forcers (SLCFs), including, chemical, microphysical and optical properties of aerosol and chemically reactive gases including ozone, nitrogen oxides, and non-methane volatile organic compounds, all of which are part of ACTRIS.
- Air quality (AQ), with aerosol and trace gases having serious health effects. ACTRIS tools and services contribute to a better understanding of the drivers of AQ levels in Europe.
- The impact of extreme phenomena, such as forest fires, severe weather, volcanic eruptions or the COVID-19 pandemic.
- Improving technologies for measuring SLACs and cloud properties.

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ACTRIS addresses the complex interconnections between aerosols, clouds, and trace gases, with observations spanning four dimensions and time scales ranging from seconds to days, as well as process-oriented studies, that are essential for climate and air pollution research.

b. The specific objectives of ACTRIS

ACTRIS aims at generating high-quality datasets and offering user-friendly services, including access to instrumented platforms. Its objectives include:

- Providing precise, coherent and integrated information on the 4D-composition, variability and properties of SLACs, from surface to stratosphere;
- Understanding the processes driving the formation, transformation and removal of these constituents;
- Granting coordinated open physical and remote access to ACTRIS facilities for scientific, technological and innovative use of ACTRIS tools and services, including the private sector;
- Ensuring open access to data and services with internationally compliant standards and the means for their effective use;
- Enhancing the quality of data and services offered to the community, involving private sector partners;
- Advancing technology development and use within the RI and user community;
- Fostering operator and user training and strengthening research, education and innovation links in atmospheric sciences.

c. ACTRIS in the European research infrastructures framework

ESFRI (European Strategy Forum on Research Infrastructures) is a strategic instrument to strengthen European research and its international outreach, addressing future scientific and societal challenges. It offers guidance on better use and development of RIs on European and international levels through regular roadmaps, addressing RI scientific needs and existing gaps.

ACTRIS, initially an ESFRI Project in 2016, became an ESFRI Landmark in 2021. ACTRIS is part of the ESFRI environment domain, forming the Environmental Research Infrastructures (ENVRI) cluster (Petzold et al., 2024), aiming to observe the Earth as a single system, providing open and FAIR (findable, accessible, interoperable, and reusable) (Wilkinson et al., 2016) environmental data, tools, and services.

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d. The integration of ACTRIS into a Global Observing System for monitoring and forecasting atmospheric composition changes

Strengthened by its history and experience, ACTRIS stands as Europe's preeminent contribution to several networks and frameworks dedicated to observing atmospheric composition and properties, at both European and international scales.

Notably, ACTRIS has evolved from existing networks and facilities, which explains why ACTRIS legacy data (defined in Section 5) span several decades into the past. Global networks of ground-based observations are an essential component to complement Earth observation from space, and provide calibration, validation and ground-truthing of the remote sensing information collected by current and future satellite missions. ACTRIS has actively strengthened the European contribution to existing networks, by continuing to operate in 17 European countries. ACTRIS contributes to international and European networks by either 1) providing observation data or data products, 2) offering support to operating calibration centres, 3) operating data centre (DC) and 4) training to users and data producers in the networks. Considering its wide scope, ACTRIS is actively involved with internationally recognized networks and programmes, namely 1) the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO), 2) the European Monitoring and Evaluation Programme (EMEP), 3) the Network for the Detection of Atmospheric Composition Change (NDACC), 4) the Aerosol Robotic Network AERONET, 5) the European Aerosol Lidar NETwork – EARLINET), and its international dimension GALION (GAW Aerosol Lidar Observing Network), 6) The Cloud Network (CLOUDNET), and 7) the Pandonia Global Network (PGN) .

As detailed in Section 5.5, ACTRIS supports the European Commission's approach "As open as possible, as closed as necessary". This ensures that ACTRIS data and digital tools are freely accessible, with minimal restrictions, and align with the FAIR principles. Thus, ACTRIS data remains accessible through international network portals, while acknowledging its provenance. ACTRIS is therefore aligned with the standards defined in WMO- Integrated Global Observing System (WIGOS) or other international data repositories (more details in Section 5) and its policies in line with recommendations of Carmichael et al. (2023)

ACTRIS collaboration with international networks shows different levels of involvement:

- EARLINET and CLOUDNET: both networks are operated by ACTRIS. A few stations in the networks are in non-member countries and will be serviced through the ACTRIS

access program for external users (defined in Section 4.4), thus maintaining the integrity of both networks.

- The ACTRIS data portal for in-situ aerosol, reactive trace gases and cloud variables is operated jointly with GAW (World Data Centers for Aerosol and Reactive gases) and EMEP.
- ACTRIS provides atmospheric column and vertical profiles data according to NDACC Protocols, accessible through the NDACC portal with the ACTRIS label.
- ACTRIS operates AERONET calibration centres, complementing the National Aeronautics and Space Administration (NASA)'s centre. Data from ACTRIS-serviced AERONET instruments is available through the AERONET portal.
- ACTRIS contributes to the European PANDONIA calibration centre, with data from ACTRIS-serviced PANDORA instruments available through the PGN (Pandonia Global Network) portal.

Furthermore, ACTRIS shares data or data products in Real (or Near) Real Time (see Section 5.3) with other parties, such as the EUMETNET e-profile program and the Copernicus Atmosphere Monitoring Service (CAMS).

3. The organization of ACTRIS

ACTRIS is organized with four main pillars, aimed at service provision: ACTRIS National Facilities (NFs) providing data and access; ACTRIS Topical Centres (TCs) defining measurement methodologies used in the NFs and instrument Quality Assurance / Quality Control (QA/QC) strategy; ACTRIS DC managing data collection, curation and dissemination according to the ACTRIS Data Policy and FAIR principles; and the ACTRIS Head Office (HO) overseeing operational work. TCs, DC and the HO form the ACTRIS Central Facilities (CFs), ensure adherence to ACTRIS procedures and policies, provide support to NFs, and oversee QA/QC from instrument setup to data delivery. In Appendix A, terms used in the organization of ACTRIS are defined in more detail.

a. The National Facilities

NFs are divided into Observational and Exploratory Platforms, developed, managed and operated by national research performing organizations (RPOs). Observational and Exploratory Platforms are proposed by countries participating in ACTRIS and accepted through a labeling process ensuring the compliance with ACTRIS technical requirements.

Criteria for labeling differ between Observational and Exploratory Plaforms but generally include:

- Compliance of the instrumental suite and deployment at the facility with ACTRIS requirements (as defined hereafter);
- Fulfillment of all procedures recommended by ACTRIS TCs and DC, regarding methodologies, instrument QA/QC procedures, data provision;
- Medium- to long-term commitment of stakeholders to support operations.

Their role is to ensure the delivery of coherent and long-term time-series of atmospheric variables and data from short-term experiments, the adequate operation and maintenance of the instruments, and the provision of physical and remote access to the facilities. 87 Observational Platforms and 33 Exploratory Platforms (of which 17 atmospheric simulation chambers) are scheduled to become ACTRIS NF in Europe and beyond in 2026. Most platforms are accessible to provide key support to research projects and training activities for the atmospheric and climate science communities. The capacity to offer combined access to different categories of platforms is a clear added value in ACTRIS.

1) OBSERVATIONAL PLATFORMS

ACTRIS Observational Platforms are fixed ground-based stations applying state-of-the-art measurement techniques, following ACTRIS operation procedures. They are strategically located in diverse climate regions in and outside Europe, delivering high-quality long-term observational data for at least one of six ACTRIS components: aerosol remote sensing (ARS), cloud remote sensing (CRS), reactive trace gases remote sensing (RTGRS), aerosol in situ (AIS), cloud in situ (CIS), and reactive trace gases in situ measurements (RTGIS). Each component is connected to the respective TC (see Sec. 4.2.2) and DC units (see Sec. 4.2.3).

An Observational Platform must meet ACTRIS requirements for instrumentation, calibration and operation procedures, data evaluation and delivery, and QA/QC procedures. Each observational component has minimum (or mandatory, M) and optimum (O) technical requirements, with minimum requirements ensuring valuable quality-assured data. Optimum setups are the most suitable configuration for a large user community and comprehensive data provision. Figure 2 shows the foreseen geographical distribution of existing Observational

Platforms, at fully operational stage of ACTRIS in 2026. Most facilities are already in operation.
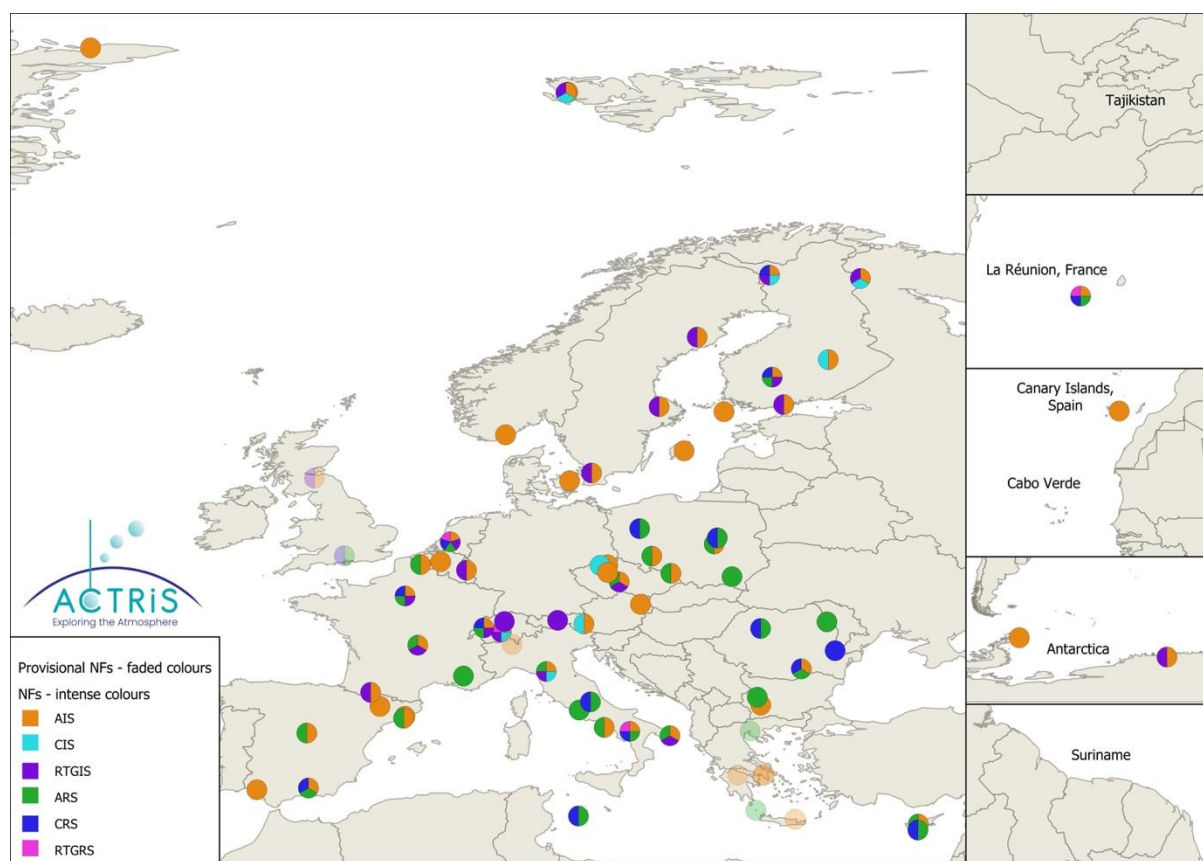

Fig. 2. Geographical distribution of ACTRIS Observational Platforms foreseen for 2026; different colors for different components. Acronyms in the figures: NF = National Facility, AIS = Aerosol In Situ, CIS = Cloud In Situ, RTGIS = Reactive Trace Gases In Situ, ARS = Aerosol Remote Sensing, CRS = Cloud Remote Sensing, RTGRS = Reactive Trace Gases Remote Sensing. The complete list of Observational Platforms is in Appendix B.

2) EXPLORATORY PLATFORMS

Exploratory Platforms complement Observational ones by exploring atmospheric processes of short-lived pollutants and cloud processes related to ACTRIS objectives in controlled experiments in atmospheric simulation chambers and in dedicated experiments using mobile instruments, including aerial platforms. They do not offer continuous observations but follow ACTRIS standards, when possible. Additional measurements (e.g., oxidant concentrations, detailed aerosol chemical composition) not covered by ACTRIS TCs, are often included. Besides, portable instruments operated on mobile platforms typically prioritize size and weight

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over sensitivity. State-of-the-art data processing chains, including consistency checks and dedicated instrument comparisons, ensure a high quality of ACTRIS data products (e.g., Doussin et al. (2023)). Specific QA/QC measures are defined during Exploratory Platform labeling.

Many long-standing ACTRIS simulation chambers (Table 1) have been part of the EUROCHAMP European infrastructure (Section 3.4). The collective European chamber expertise led to a recently published handbook (Doussin et al., 2023) outlining best practices and standard protocols. This is crucial for ensuring realistic reaction time scales and competition between different reaction pathways. Experiments typically involve mixtures of trace gases, aerosols, or real emissions from sources such as plants and combustion engines.

Mobile platforms range from single mobile instruments to transportable laboratories, which can be deployed in targeted experiments and field campaigns to study atmospheric processes related to aerosols, clouds, and reactive trace gases in regions or meteorological or climatic conditions that are not or only partially covered by the ACTRIS observational network. Mobile instruments can be land-based in easy-to-transport, robust housings for operation in remote locations, or placed on moving platforms like vans, ships, drones, or (tethered) balloons requiring specific light-weight instruments. The procedures for establishing and accessing mobile and laboratory platforms within ACTRIS are still in progress, and the platform list will be communicated on the ACTRIS web portal in the future.

Name (country)	Description	Type of process studies	Reference
AIDA (Germany)	Indoor aluminum cylinder (84 m3)	Cloud, gas- and particle phase processes	(Möhler et al., 2003)
LACIS-T (Germany)	Indoor wind tunnel (0.32 m^3)	Cloud processes	(Niedermeier et al., 2020)
AURA (Denmark)	Indoor Teflon cuboid (4.9 m^3)	Particle phase processes	(Kristensen et al., 2017)

AXIC (Denmark)	Indoor Teflon cuboid (4.5 m^3) and flow tube	Particle and gas-phase processes	(Kappelt et al., 2021)
KASC1 ILMARI (Finland)	Indoor Teflon cuboid (29 m3)	Particle phase processes	(Leskinen et al., 2015)
FORTH-ASC (Greece)	Indoor Teflon cuboid (10 m^3)	Particle phase processes	(Kaltsonoudis et al., 2017)
PACS (Switzerland)	Indoor Teflon cuboid (9 m^3)	Particle phase processes	(Platt et al., 2013)
MAC (UK)	Indoor Teflon cuboid (18 m^3)	Particle phase processes	(Shao et al., 2022)
ChAMBRe (Italy)	Indoor stainless-steel cylinder (3 m^3)	(Bio-)Particle phase processes	(Massabò et al., 2018)
CESAM (France)	Indoor stainless-steel cylinder (4.2 m^3)	Particle and gas-phase processes	(Wang et al., 2011)
SAPHIR SAPHIR-STAR (Germany)	Outdoor Teflon cylinder (270 m^3) Indoor quartz cylinder (2 m^3)	Particle and gas-phase processes	(Rohrer et al., 2005)
HELIOS (France)	Outdoor Teflon hemisphere (90 m^3)	Particle and gas-phase processes	(Ren et al., 2017)
EUPHORE (Spain)	2 outdoor Teflon Hemispheres (200 m^3)	Particle and gas-phase processes	(Bloss et al., 2005)
ACD-C (Germany)	2 Indoor Teflon cylinders (19 m^3)	Particle and gas-phase processes	(Iinuma et al., 2004)
QUAREC (Germany)	Indoor quartz cylinder (1.1 m^3)	Gas-phase processes	(Illmann et al., 2021)

ESC-Q-UAIC/CERNESIM (Romania)	Indoor quartz cylinder (0.76 m^3)	Gas-phase processes	(Roman et al., 2022)
RvG-ASIC (UK)	Indoor glass cuboid in stainless steel chamber (3.5 m^3)	Ice-air interface processes	(Thomas et al., 2021)

Table 1. Current atmospheric simulation chambers proposed as ACTRIS Exploratory Platforms. This table illustrates the diversity of simulation chambers within ACTRIS, with variations in chamber volume, materials, and irradiation conditions, offering users the opportunity to investigate atmospheric processes under a wide variety of conditions. Most ACTRIS simulation chambers allow experiments to be performed at (near-) atmospheric conditions with respect to trace gas and aerosol concentrations.

b. The Topical Centres

TCs support the operation of NFs and are responsible for defining procedures and tools, and performing the QA/QC of ACTRIS measurements and data, and evaluating the performance of NFs. The core activities of TCs are to ensure sustainable and traceable high-quality data and data products related to ACTRIS with known uncertainty. These activities include (1) establishing guidelines, defining QA/QC procedures to be applied by NFs, (2) developing, testing and implementing advanced measurement technologies and data evaluation algorithms, (3) enhancing the competence of the operative personnel by training, and (4) evaluating the performance of NFs as part of the NF audit and labeling. They are also the link between ACTRIS and the associated scientific communities, they ensure training and transfer of knowledge to ACTRIS operators and users.

The ACTRIS TCs were selected based on their recognized expertise in the field. As such, they are jointly operated as a consortium of several units in two or more countries. TCs are set-up to respond to the scientific and technical needs of ACTRIS, each with a particular focus on either remote sensing (from the ground) or in situ (near-surface) measurements. Table 2 lists the TCs and indicates the countries where the different units are located.

Topical Centre (TC)	Acronym	Countries where the TC units are located
Centre for Aerosol In Situ Measurements - European Center for Aerosol Calibration & Characterization	CAIS-ECAC	DE, CZ, FI, FR, IT
Centre for Cloud Remote Sensing	CCRES	FR, DE, FI, NL
Centre for Cloud In Situ Measurements	CIS	DE, AT
Centre for Reactive Trace Gases Remote Sensing	CREGARS	BE, AT, DE, FR, NL
Centre for Reactive Trace Gases In Situ Measurements	CiGas	DE, CH, FI, FR
Centre for Aerosol Remote Sensing	CARS	RO, CH, DE, ES, FR, IT

Table 2: the ACTRIS Topical Centres and the countries where units are located. Each TC has different specialized units operated by different organizations in different countries, with a total of 36 units (BE: Belgium, AT: Austria, DE: Germany, FR: France, CH: Switzerland, IT: Italy, RO: Romania, ES: Spain, FI: Finland, CZ: Czech Republic, NL: The Netherlands).

c. The Data Centre

ACTRIS DC provides scientists and other user groups with free and open access to all ACTRIS data. It also provides access to data products and tools for QA/QC, data analysis and research. ACTRIS DC ensures the management and organization of ACTRIS data and value-added products. This includes long-term archiving and access to data following the FAIR principles and tools for data production, visualization, evaluation and analysis. The DC compiles, processes, curates, archives, and distributes the data produced by the NFs, in accordance with ACTRIS data policy. DC is responsible for the data citation service, attribution and version control and offers support to NFs on data curation and services to all users of ACTRIS data.

The numerous measurement methodologies applied in ACTRIS result in a considerable diversity of the data collected. In accordance with these requirements, the ACTRIS DC is organized in 6 Units (Figure 3).
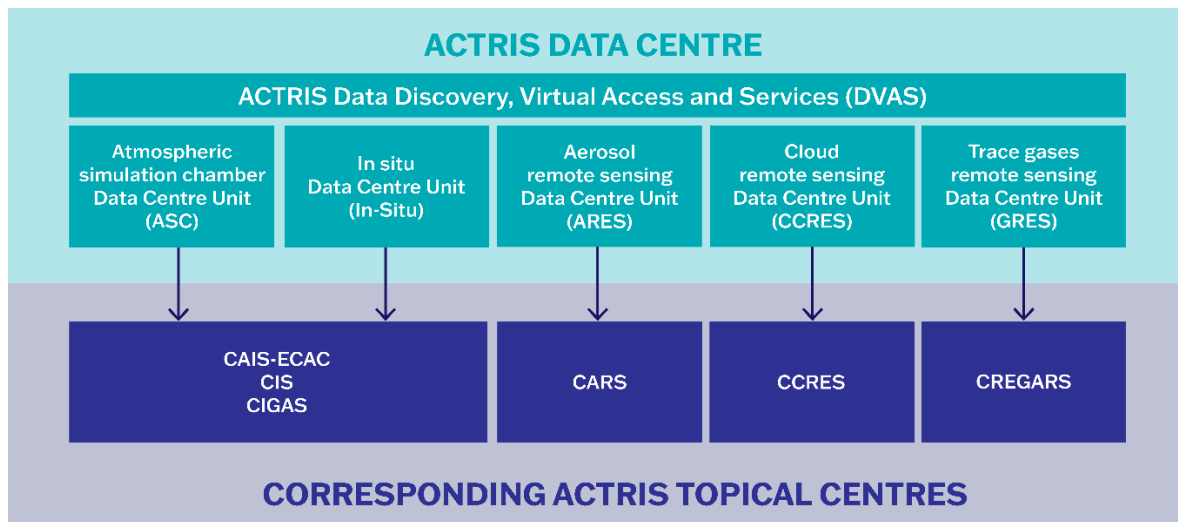
Fig.3. The structure and components of ACTRIS DC, and links between each DC unit and the associated TCs. Five units (In-Situ, ARES, CLU, GRES, ASC) have complementary topic expertise, and one unit (DVAS) deals with integrating activities and coordination. There are defined links and procedures for interaction between the DC Units, NFs and TCs. ACTRIS DC units are operated by established data centers, ensuring trust, long-term sustainability but also security and environmental responsibilities in data management

The ACTRIS DC core tasks are to ensure:

- documented, traceable processing and long-term archiving and preservation of all ACTRIS Real Real Time (RRT), Near Real Time (NRT) and scheduled data, as well as higher level data products;
- documented and traceable processing chain of raw data;
- documentation of data, data flow, citation service, and data attribution, including version control, data traceability, and interoperability of all data;
- access to ACTRIS RRT, NRT and scheduled data and higher-level data products and digital tools through a single point of entry (the ACTRIS data portal);
- data curation and support for campaigns and dedicated research projects and initiatives, external or internal to ACTRIS.

Full implementation of FAIR principles is ongoing over the ACTRIS implementation phase, and the status in spring 2023 is documented in Myhre et al. (2023).

d. The Head Office and the ACTRIS ERIC

The ACTRIS Head Office (HO) coordinates, develops, monitors and integrates RI operations together with facilitating the work of ACTRIS governance and executive bodies. It develops and promotes the long-term sustainability of ACTRIS in all its aspects. It is organized with different units, including the Service and Access Management Unit (SAMU) to connect users with ACTRIS services and access providers (e.g., ACTRIS CFs and NFs). The HO provides outreach and information on ACTRIS and its services, facilitates membership, strengthens international collaboration, and organizes or contributes to workshops and symposia on behalf of ACTRIS and its research community.

ACTRIS ERIC is the legal entity of ACTRIS, responsible for establishing and operating a distributed research infrastructure, including liaison and establishment of long term, sustainable and formal agreements with ACTRIS CFs. ACTRIS ERIC also contracts with the NF hosting organizations, defining the responsibilities of the NF towards ACTRIS and the operation support received from ACTRIS CFs.

e. The ACTRIS Business plan

The ACTRIS business plan is a comprehensive document explaining how the different ACTRIS elements described in 3a-3d are connected, and how the services offered by ACTRIS are structured, operated, managed and funded. The overall organization of ACTRIS is shown in Figure 4.
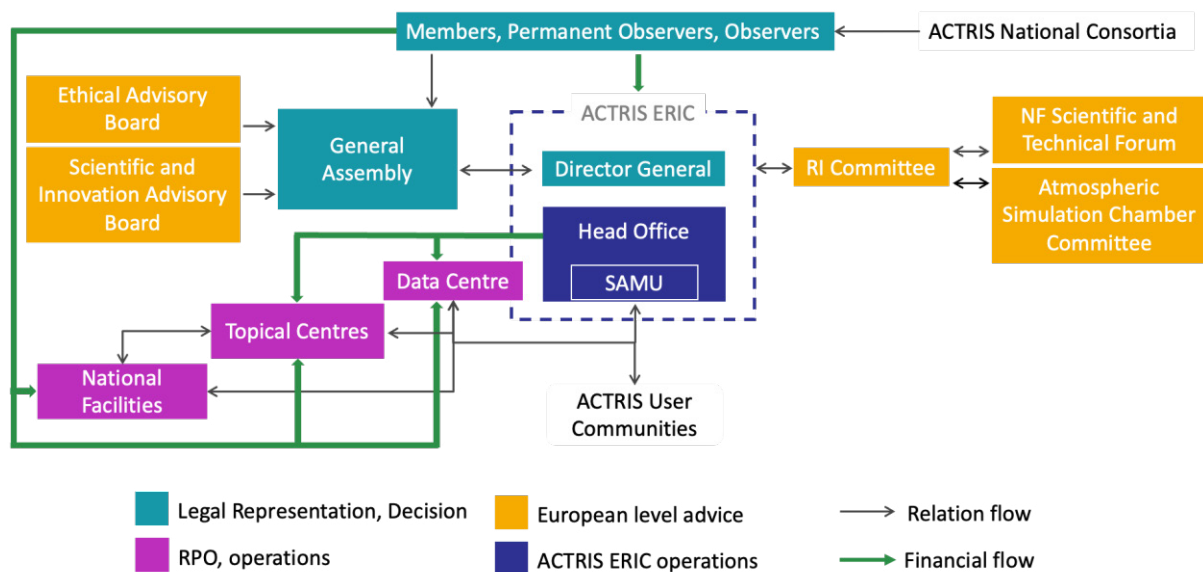

Fig. 4: the ACTRIS Business plan including both the management and governance structures illustrating the components of the organization and their relationships, also including the financial flow. The RI committee, the NF Scientific and Technical Forum (NFSTF) and the Atmospheric Simulation Chamber Committee (ASCC) ensure that the

scientific and strategic development of ACTRIS aligns with user and stakeholder expectations. The Scientific and Innovation Advisory Board and the Ethical Advisory Board are providing advices to the General Assembly. Green arrows are indicating relationship involving financial flow among components, while simple arrows are for relationship without financial flow. Additional revenues from projects and/or user fees are not indicated. All components are defined in the glossary (appendix A)

The main elements of the business plan are the following:

- Financial plan: ACTRIS revenues originate from membership contributions to the ACTRIS ERIC and national contributions by each country. Operation costs of the CFs, including the HO, are shared between ACTRIS ERIC and the CF host institutions while NFs are funded through the national contributions only.

- Management plan: the General Assembly (GA) is the highest decision-making body in ACTRIS, advised by the Scientific and Innovation Advisory Board. The legal entity ACTRIS ERIC is responsible for implementing decisions taken by the GA. Under the leadership of the Director General (DG), it coordinates and operates the distributed research infrastructure and in particular operations at CFs. The main advisory bodies are the RI Committee, the NFTSF and the ASCC, ensuring that the community is engaged in the scientific and strategic development of ACTRIS.

- User plan, including access: ACTRIS services are detailed in the Catalogue of Services (www.actris.eu/catalogue-of-services). All ACTRIS data are openly available at the Data Centre portal while other services, including training, are accessible through a unique entry point and may involve user-fees. ACTRIS actively promotes the services to external users, Worldwide, and including the non-academic and private sectors.

- Communication and Public Relations plan to regularly inform about activities and opportunities through newsletters and social media channels.

4. Description of ACTRIS measurements and data

This section outlines the principles and concepts for ACTRIS data production including information on the ACTRIS variables and the associated methodologies (Appendices C1-C7). This section starts with a description of the ACTRIS variables, data and data production workflow, followed by a section with information on access to data and tools for users and the conditions of use.

a. ACTRIS variables, data and data production workflow

ACTRIS data are data from NFs and comply with the procedures established within ACTRIS. ACTRIS deals with complex processes with 120 atmospheric variables covering aerosol optical and physical properties and chemical composition, various cloud properties and numerous reactive trace gas components. An overview of the types of ACTRIS data produced and their timeliness (delay between data production and data provision to users) is given in Table 3.

Appendix C includes a list of all ACTRIS variables associated to recommended measurement methodology and TC. Overall, ACTRIS includes 35 aerosol variables, 65 trace gas variables and 20 cloud variables, as given in Appendices C1-C7. A number of ACTRIS variables are among those listed as essential climate variables (ECV) defined by the Global Climate Observing System (GCOS, 2021) corresponding to a total of 5 ECVs and 10 ECV products.

The production of ACTRIS data is following a production chain resulting in FAIR data, linking the work and expertise in the TCs to the NFs and the DC. There is a detailed ACTRIS Data Management Plan available describing all aspects of the data flow.

Data production begins with instrument qualification by the associated TC. Data processing happens at NFs, TCs or DC, depending on the type of variable and ACTRIS component (see Figure 3 for the components). Scheduled ACTRIS data undergo QC at NFs, for both Observational and Exploratory Platforms, before submission to the DC and further final QA/QC tests and inspection upon ingestion into databases. For ACTRIS components, following full implementation of all services within the DC and TCs, data from Observational Platforms are uploaded directly to their respective DC units within 1 hour of acquisition. These uploaded data undergo automatic instrumental criteria-based QC, and are paired with pre-calibrations or forecasts (when necessary) to generate RRT data products (potentially final). A second production and QC step is usually performed at scheduled intervals for most components, with final calibrations, and/or re-analysis model output, to create the final "scheduled" data product.

In addition to "scheduled" data, ACTRIS provides NRT/RRT data to programs such as the Copernicus Atmosphere Monitoring Service (CAMS) or E-PROFILE

Attribute	Description
Timeliness	
Real real time (RRT) data	Data provided within 3 hours of production.
Near real time (NRT) data	Data provided within 3 days of production.
Scheduled data	Data provided on a defined, regular schedule, i.e. more than 3 days after production. In the range of 6 months to 1 year depending on type of data from different ACTRIS components
Quality control and compliance attributions	
ACTRIS	This relates to data collected in accordance with ACTRIS procedures, observation is conducted at an ACTRIS National Facility.
ACTRIS compliant	This relates to quality control and compliance. Data are collected in accordance with ACTRIS procedures and comply with the requirements for this variable. The facility component has not necessarily undergone the full ACTRIS labelling process nor is necessarily an ACTRIS National Facility.
ACTRIS associated	This relates to quality control and compliance. Data partly complying with ACTRIS requirements after the start of ACTRIS ERIC.
ACTRIS legacy	This relates to quality control and compliance. Data adheres to ACTRIS procedures in place before ACTRIS RI was established.
Other	This relates to quality control and compliance. Adheres to other types of quality control procedures.

(https://www.eumetnet.eu/activities/observations-programme/current-activities/e-profile/).

Fully responding to FAIR and QA/QC principles, ACTRIS can be used as a fiducial reference measurement network providing a suite of ground-based traceable observations.

Table 3. Timeliness of ACTRIS data and QC attributes of ACTRIS data, associated data and legacy data. ACTRIS data are data from observational or exploratory ACTRIS labeled NFs complying with the procedures established within ACTRIS.

Exploratory Platform data is not centrally produced. Due to instrument and experimental setup diversity, National Facilities process data and the final dataset, corresponding to a complete experiment, is submitted to the DC.

b. Access to data and tools for data users

The ACTRIS DC's mission is to compile, archive and provide open access to well-documented traceable ACTRIS measurement data and data products with rich metadata, documented quality and licenses. ACTRIS data and digital tools are accessible through a single-entry point – the ACTRIS data portal linking all the DC units. All ACTRIS data will be associated with digital object identifiers (DOI).

ACTRIS data and meta data can be accessed via two pathways, a web interface for human users and machine-to-machine (M-2-M) interfaces. The web interface offers a single entry-point for all ACTRIS data products, targeting human users with a structured search interface suitable for cross-domain search, metadata, data visualization, download, as well as a link to a "*Virtual Research Environment (VRE)*". The VRE is a platform aimed at both research and educational purposes where tools such as M-2-M search, data streaming, statistics on data, filtering and plotting are available. It also includes an updated showcase page for ACTRIS RRT and NRT data products. The M-2-M interfaces for (meta)data enable access through standard and metadata interfaces, also linking to the individual DOIs of data items. These interfaces cover all ACTRIS data products, independent of their timeliness (RRT, NRT, scheduled), connecting with customers and collaborating frameworks like WMO Information System (WIS), and WMO Integrated Global Observing System (WIGOS).

ACTRIS DC is not providing computing facilities but virtual tools are available for analyzing source regions of aerosols and reactive trace gases or for FAIR archiving of campaign data.

c. Conditions on use of ACTRIS (meta)data and products and software

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One important requirement for data to be open and FAIR is information on condition of use, and a license. ACTRIS data are offered to users with the CC-BY-4.0 license, which has evolved to be a community standard within the European environmental domain such as the ENVRI community (Petzold et al., 2023). CCBY4.0 will also be recommended on legacy data. This facilitates the scientific use of long time series, not having different licenses on the ACTRIS data and data produced in pre-projects. Briefly, with this license the data user can i) Share — copy and redistribute the material in any medium or format and ii) Adapt — remix, transform, and build upon the material for any purpose, even commercially.

Attribution to ACTRIS is required from users to give appropriate credit, provide a link to the license, and indicate if changes were made. Information on this is included in the files and landing page of the DOI for the ACTRIS data. Within ACTRIS there is also a decision to use the same licenses on metadata (CC-BY-4.0) and for software and digital tools developed by TC and/or DC. GNU Affero General Public License will be used taking the use of web services into account.

5. Major scientific achievements of ACTRIS 2005-2022

ACTRIS has been key in driving atmospheric science in Europe for more than 10 years. It is worth noting that a database of about 1200 scientific articles has been gathered from the Web of Science data records between Jan. 2010 and Aug. 2023, where "ACTRIS" or "pre-ACTRIS" projects are mentioned in the funding or acknowledgements sections. This demonstrates the rich scientific output generated by the use of ACTRIS services and the support provided by the RI through access services and dedicated networking and joint research activities. These activities enhanced the collaboration between ACTRIS partners and external users, maximizing the impact of the RI in terms of scientific outcome. Furthermore, the numerous events organized by ACTRIS during the last 10 years fostered a culture of cooperation between the community (e.g. science conferences, workshops, ACTRIS weeks). These measures enabled the translation of high-quality ACTRIS services to excellent research that increased the impact of the RI. This section highlights some major achievements focusing on key articles.

a. Atmospheric measurement techniques and methodologies

The information needed to address the complex interconnections between aerosols, clouds, and trace gases requires heavily instrumented facilities and the collection of massive amounts of atmospheric measurements. It is, therefore, not surprising that the ACTRIS community has

been instrumental in developing and qualifying new instruments for their application in atmospheric research for both long-term operations and experimentation, in defining suited methodologies for operations and for quality analysis, some of them in collaboration with metrology institutes. Some ACTRIS procedures are now accepted as standards by the European Center for Normalization (CEN) or as reference methods by international organizations such as the WMO.

1) DEVELOPMENT OF TECHNOLOGIES AND METHODOLOGIES FOR IN SITU MEASUREMENTS

For in situ measurements of the physical, chemical and optical properties of aerosol, droplets and ice particles, several ACTRIS-related studies have had a significant impact on a wide community of users who are now adopting the recommended methodologies: e.g. for elemental and organic carbon measurements (Cavalli et al., 2010), mobility particle size spectrometers (Wiedensohler et al., 2012), air ion spectrometers (Gagné et al., 2011), aerosol mass spectrometers (Crenn et al., 2015), levoglucosan measurements (Yttri et al., 2015), condensation nanoparticle counters (Kangasluoma et al., 2017), Black Carbon (BC) measurements (Cuesta-Mosquera et al., 2021), ice nucleation particle counters (Brasseur et al., 2022; Lacher et al., 2021) or in situ cloud spectrometers (Doulgeris et al., 2020).

Studies in ACTRIS are not limited to defining the most appropriate standard operating procedures for specific instruments, but also provide the community with methodologies for processing information. Examples include classifying data from Neutral clusters and Air Ion Spectrometers (Manninen et al., 2016), improving aethalometer measurements (Backman et al., 2017; Drinovec et al., 2015), aerosol mass spectrometer calibration (Freney et al., 2019) or using Particle Size Magnifier and nano-Condensation Nucleus Counters (Lehtipalo et al., 2022). ACTRIS-related studies developing methodologies for the organic aerosol source apportionment (Fröhlich et al., 2015; Chen et al., 2022) are also widely used. For the detection of complex oxygenated molecules in the gas phase or condensable vapors, Holzinger, (2015), Kajos et al., (2015), Fischer et al., (2021), Piel et al. (2021), and Worton et al. (2023) developed advanced methodologies for the use of chemical ionization mass spectrometry techniques now in use at NFs.

Within ACTRIS, large (often international) inter-laboratory comparisons and round-robin exercises ensure equivalence between instruments and methodologies, full traceability and high quality of measurements, such as for absorption photometers (Müller et al., 2011), and NMHC instruments (Hoerger et al., 2015; Holzinger et al., 2019). Many have also been

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performed in simulation chambers under well-characterized and controllable conditions. This was the case for ACTRIS variables, such as organic compounds (Apel et al., 2008; Wisthaler et al., 2008; Glowania et al., 2021), NO_2 (Fuchs et al., 2010a), ice nucleating particles (DeMott et al., 2018), and more specialized instruments for the detection of radicals (Schlosser et al., 2009; Fuchs et al., 2010b; Dorn et al., 2013), glyoxal (Pang et al., 2014), OH reactivity (Fuchs et al., 2017), water vapor (Fahey et al., 2014; Nowak et al., 2022) or ultrafast temperature sensors (Doussin et al., 2023).

2) DEVELOPMENT OF TECHNOLOGIES AND METHODOLOGIES FOR REMOTE SENSING MEASUREMENTS

ACTRIS contributes to remote sensing advancement, by continuously improving, developing and testing (new) measurement techniques, and prototypes, and consolidating new measurement strategies and retrieval algorithms for exploiting instrumental synergies. Examples include: 1) improved daytime Raman profiling (Ortiz-Amezcua et al., 2020), 2) lidar-photometer synergies for higher-level aerosol products (Tsekeri et al., submitted), 3) additional measurements like circular/elliptical depolarization for improved characterization of non-spherical particles and fluorescence for pollen detection and discrimination (Shang et al., 2022). Aerosol remote sensing datasets follow rigorous and centralized QA/QC procedures described in D'Amico et al. (2015).

ACTRIS Cloud Remote Sensing products enhance cloud retrievals and Earth System Models. Kalesse-Los et al. (2022) detected liquid cloud layers within mixed-phase clouds which helps to better understand precipitation formation, cloud lifetime, and the radiation budget. Preißler et al. (2016) developed an algorithm to derive cloud microphysical and optical parameters. Bühl et al. (2019) derived the ice crystal concentration from lidar, radar and wind profiler. Precipitation formation in clouds has been another topic where ACTRIS Cloudnet observations proved to be very useful. Kneifel and Moisseev (2020) investigated riming in clouds which has a strong influence on winter precipitation. Recently, attention has focused on the atmospheric boundary layer (ABL), where Automatic Low-power and Doppler lidars are used to observe cloud formation processes. Manninen et al. (2018) developed an ABL classification algorithm applicable to Doppler lidar observations. ACTRIS remote sensing measurements and expertise played a central role in a recent comprehensive review on the ABL depth and structure by Kotthaus et al. (2023).

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ACTRIS-driven developments also support trace gas column and vertical profile retrievals, notably for improving network-wide harmonized retrieval strategies, in particular for FTIR retrieval of HCHO (Vigouroux et al., 2018) or other species. In the UV-Vis DOAS community, intercomparison campaigns between various UV-VIS (MAX)DOAS-type instruments support the development of measurement guidelines, intercomparability across the network and retrieval algorithm harmonization (e.g., Tirpitz et al., 2021; Kreher et al., 2020).

b) Contribution of ACTRIS to the understanding of atmospheric processes

A fundamental understanding of atmospheric processes is central for air quality and climate studies. With increasing computational power, accurate descriptions of these processes become key for numerical simulations. Many ACTRIS studies have investigated the fundamental processes driving the fate of atmospheric pollutants and their interactions affecting climate and air quality. ACTRIS studies often used both Observational and Exploratory Platforms.

Simulation chamber experiments improve our knowledge of chemical reaction mechanisms (e.g. Illmann et al. 2021). Experiments revealed that unimolecular hydrogen-shift reactions of organic peroxy radicals (RO_2) are more competitive than previously thought. They significantly enhance the atmospheric oxidative capacity in the OH oxidation of isoprene (Fuchs et al., 2013; Novelli et al., 2020), lead to a unexpected organic nitrate species in the NO_3 oxidation of isoprene (Carlsson et al., 2023; Vereecken et al., 2021), and are essential for the formation of highly oxygenated organic molecules (HOMs) contributing to secondary organic aerosol (SOA). Mutzel et al. (2015) first reported the fate of highly oxygenated organosulfates (HOOS) upon uptake into the particulate phase and uptake coefficients for numerous HOMs were determined (Poulain et al., 2022). In the real atmosphere, SOA yields depend on the competition between reaction pathways, with RO_2 radicals being possibly scavenged in radical chain-terminating reactions before forming low-volatility compounds (e.g. McFiggans et al. (2019)). Additionally, chamber studies have elucidated new pathways leading to organic acids: e.g. from the photo-oxidation of aromatics (Wang et al., 2020), cloud droplet-mediated oxidation of formaldehyde (Franco et al., 2021), and ozonolysis of α,β-unsaturated ketones (Illmann et al., 2023). An example of results from atmospheric simulation chamber experiment is provided in Figure 5 where new reaction pathways in the oxidation of dimethyl sulfide (DMS) (Veres et al., 2020) are tested. For atmospheric-like chemical composition of the air, the fate of organic peroxy radicals from the oxidation of DMS is mainly

an H-shift reaction leading to the formation of hydroperoxymethyl thioformate (HPMTF) not seen in previous laboratory experiments at high concentrations of reagents (Barnes et al., 1994). Experiments in the chamber show that the subsequent oxidation of HPMTF leads to a higher-than-expected formation of carbonyl sulfide (OCS) (von Hobe et al., 2023).
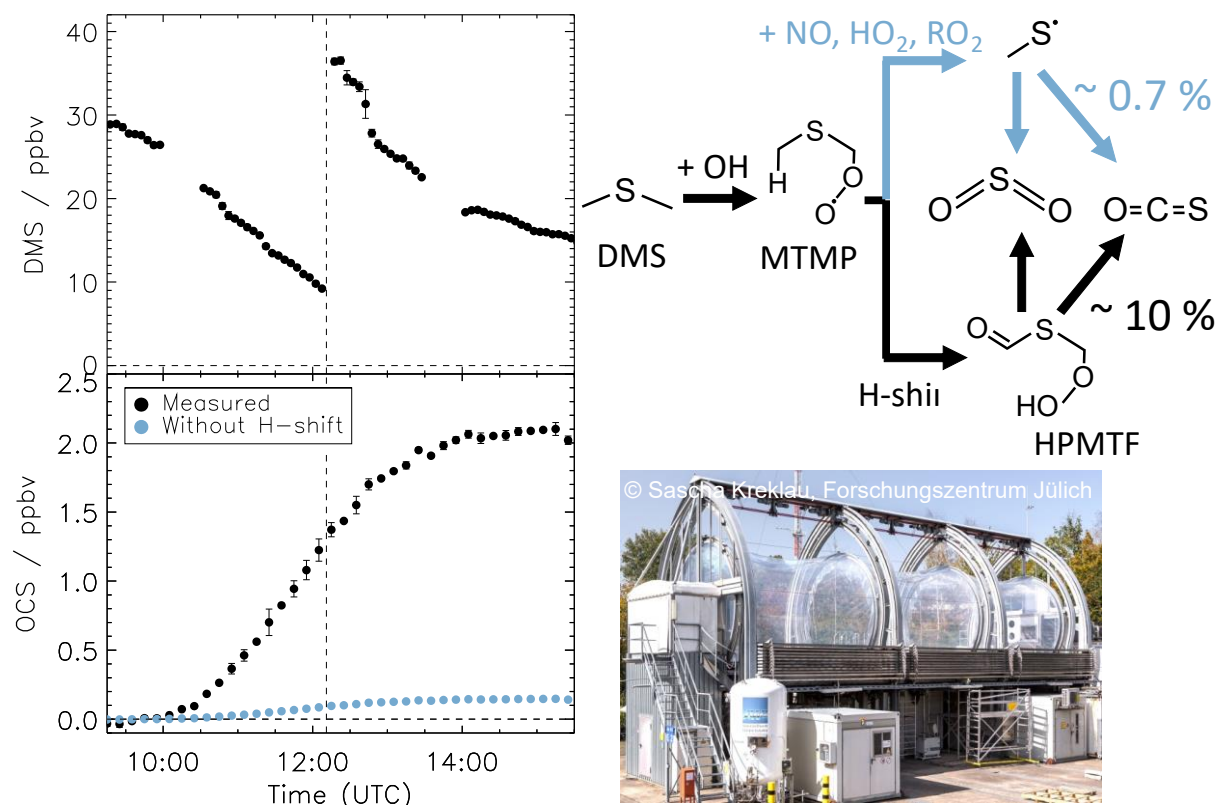

Fig. 5. Evidence for higher-than-expected formation of carbonyl sulfide (OCS) in the OH oxidation of dimethyl sulfide (DMS) due to H-shift reactions following HPMTF formation path (Veres et al., 2020) in experiments carried out in the SAPHIR atmospheric simulation chamber.

Simulation chambers have helped to identify molecular tracers for specific sources. Kalberer et al. (2004) showed that oligomers are major organic aerosol components and Iinuma et al. (2009) how the reaction with SO_2 oxidation products can transform semi-volatile organics into non-volatile aerosol components. Kodros et al. (2020) provided insights into the dark aging of biomass burning aerosol.

ACTRIS has also focused on aerosol-cloud interaction studies. Baars et al. (2017) developed a combined classification for aerosol types and cloud properties. Radenz et al. (2021) found a strong influence of aerosols on the presence of ice in clouds at temperatures between -24°C and -8 °C by comparing polluted and pristine sites worldwide. Marinou et al. (2019) investigated properties of clouds influenced by dust over the Mediterranean Sea using Cloudnet observations in Greece. Biogenic emissions from boreal forests in Finland have a

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substantial influence on cloud formation (Petäjä et al., 2022). Wærsted et al. (2019) and Toledo et al. (2021) developed a new conceptual approach to better understand the fog life cycle based on ACTRIS ground-based remote sensing measurements.

c. ACTRIS studies on trends and variability of atmospheric composition

ACTRIS integrates long-term data from its network of Observational Platforms, providing unique opportunities for detailed insights into Europe's atmospheric composition and trends in constituent concentrations and properties.

The ACTRIS community has published a series of papers characterizing the European aerosol phenomenology. Van Dingenen et al. (2004) and Putaud et al. (2004) first investigated aerosol mass concentrations, number size distributions and chemical composition in traffic, urban, rural and background conditions in Europe, highlighting significant differences between environments due to variable contributions from traffic and other anthropogenic sources, and underlining the importance of organic compounds in all environments. Expanding the analysis to 60 European observation sites, Putaud et al. (2010) identified a decreasing trend of particulate sulfate and nitrate from traffic sites to rural areas. Seasonal variations in organic constituents in Europe were further explored by Cavalli et al. (2016) and more recently by Bressi et al. (2021), using aerosol mass spectrometer data, confirming the dominant role of organics in PM_1 aerosol mass concentrations. A more in-depth analysis with harmonized source apportionment revealed the dominance of oxygenated organic aerosols (Chen et al., 2022). Following a detailed assessment of BC concentrations in Europe by Zanatta et al. (2016), Savadkoohi et al. (2023) investigated the mass concentrations and sources of equivalent-BC (eBC) at about 50 sites influenced by urban activities. Despite a decreasing trend in eBC concentrations between 2006 and 2022, emissions from residential and commercial sources remained fairly stable.

Data integration similarly examined the seasonal and interannual variability of in situ NOx and VOC concentrations at local, regional and global scales. Figure 6 shows an example of time series for specific VOCs at several ACTRIS sites. Helmig et al. (2016) assessed global trends in propane and ethane, showing a reversal in the steady decline of ethane mole fractions in the Northern Hemisphere between 2005 and 2010. Model simulations and observations occasionally revealed discrepancies in ethane and propane (Dalsøren et al., 2018). Long-term measurements of aerosol precursors have been reported from boreal and subarctic forests (Jokinen et al., 2022; Sulo et al., 2021; Kulmala et al., 2023). Additional studies have

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documented their variability at ACTRIS facilities (Debevec et al., 2017; Panopoulou et al., 2020; Verreyken et al., 2021; Simon et al., 2023), linking them to emission sources across diverse environments.
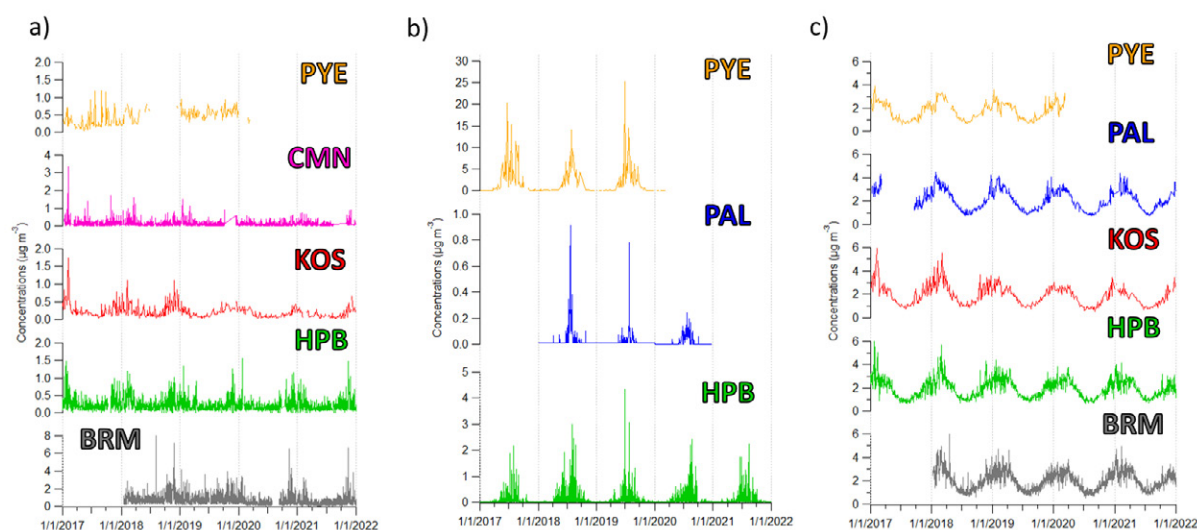

Fig. 6. Mass concentrations (in µg m^{-3}) of a) toluene, b) isoprene and c) ethane measured over the period 2017-2021 at NFs Beromünster (BRM), Monte Cimone (CMN), Hohenpeissenberg (HPB), Košetice (KOS), Pallas (PAL) and EMEP site Peyrusse-Vieille (PYE). The variability illustrates the specific behavior of VOCs associated with (i) regional background, such as ethane, a long lived species, exhibiting similar seasonal pattern and concentration levels related to atmospheric dynamics and lower boundary layer heights in winter; (ii) biogenic emissions (isoprene) which are more intense in summertime; and (iii) short-lived anthropogenic compounds (such as toluene), with no clear seasonal pattern, occasional peaks and highly variable concentration levels from site to site

d. ACTRIS studies relevant to Earth's climate

Twenty-two of the variables measured within ACTRIS are ECV as defined by GCOS (2021). Indeed, ACTRIS Observational Platforms provide spatially and temporally resolved information needed to document the atmospheric burden and radiative properties of aerosol, cloud and trace gases for climate-relevant studies.

ACTRIS products have broad applications in climatology worldwide, both from long-term observations and short-term campaigns. Several studies investigated liquid and mixed-phase clouds in the Arctic (e.g. Gierens et al. (2020)). In this region with only sparse data coverage, the observations brought new insights about cloud processes, especially regarding polar night radiative effects, and helped to evaluate the ICON-Large Eddy Simulation model by simulating Arctic mixed-phase clouds (Schemann and Ebell, 2020).

Building on EARLINET (Pappalardo et al., 2014), ACTRIS has provided aerosol optical property profiles at the continental scale since 2000. Recently, quality-controlled 20-year climatological datasets were released. These datasets have been widely used to identify aerosol types and respective optical properties (Papagiannopoulos et al., 2018), infer microphysical properties through inversion techniques (Müller et al., 2016), increase optical information through lidar/photometer synergies (Chaikovsky et al., 2016), study aerosol hygroscopicity (Bedoya-Velásquez et al., 2018) and aerosol-cloud interactions (Mamouri and Ansmann, 2017; Marinou et al., 2019), optimize satellite product retrievals (Amiridis et al., 2013; Nicolae et al., 2018; Floutsi et al., 2023), and constrain radiative transfer calculations (Granados-Muñoz et al., 2019).

Over the years, ACTRIS in situ observations have been instrumental in global assessments of aerosol radiative forcing and concentrations. Pandolfi et al. (2018) documented aerosol scattering properties at 28 ACTRIS sites. Collaud Coen et al. (2013) and Asmi et al. (2013) highlighted declining decadal trends in aerosol optical properties and size distributions, associated with reduced anthropogenic emissions of primary particles, SO_2, and co-emitted species. Global studies by Collaud Coen et al. (2020) and Laj et al. (2020) showed decreasing aerosol scattering, backscattering, and absorption coefficients in Europe, while several Asian sites displayed positive trends.

e. ACTRIS as a tool for monitoring extreme events and atmospheric hazards

ACTRIS data have been widely used to characterize specific or extreme events affecting the atmosphere either caused by natural or human-induced phenomena. The capacity to be operational 24/7 at most of the Observational Platforms has been essential on many occasions over the past decade.

In 2010, coordinated measurements by Pappalardo et al. (2013) shed light on the processes governing the transport of Icelandic ash plumes from the eruption of the Eyjafjallajökull volcano. Instrumental deployments at ACTRIS NFs have been used for several more recent volcanic eruptions to document the properties of volcanic particles (Lieke et al., 2013), or new particle formation in volcanic plumes (Rose et al., 2019). An ACTRIS-related demonstration study of Amiridis et al. (2023) used synergies between space and ground-based remote sensing for volcanic ash transport forecasting and hence aviation safety.

Furthermore, ACTRIS contributes to atmospheric composition studies related to desert dust in the framework of the Sand and Dust Storm Warning Advisory System (SDS-WAS) of the WMO for the evaluation and optimization of desert dust forecasts (Binietoglou et al., 2015). In addition, exceptionally dense smoke layers from megafires in Canada, Australia, Siberia and from Mediterranean forest fires are monitored and reported by ACTRIS, to appropriately model the smoke transport and respective radiation impacts in both the troposphere and the stratosphere (Figure 7).
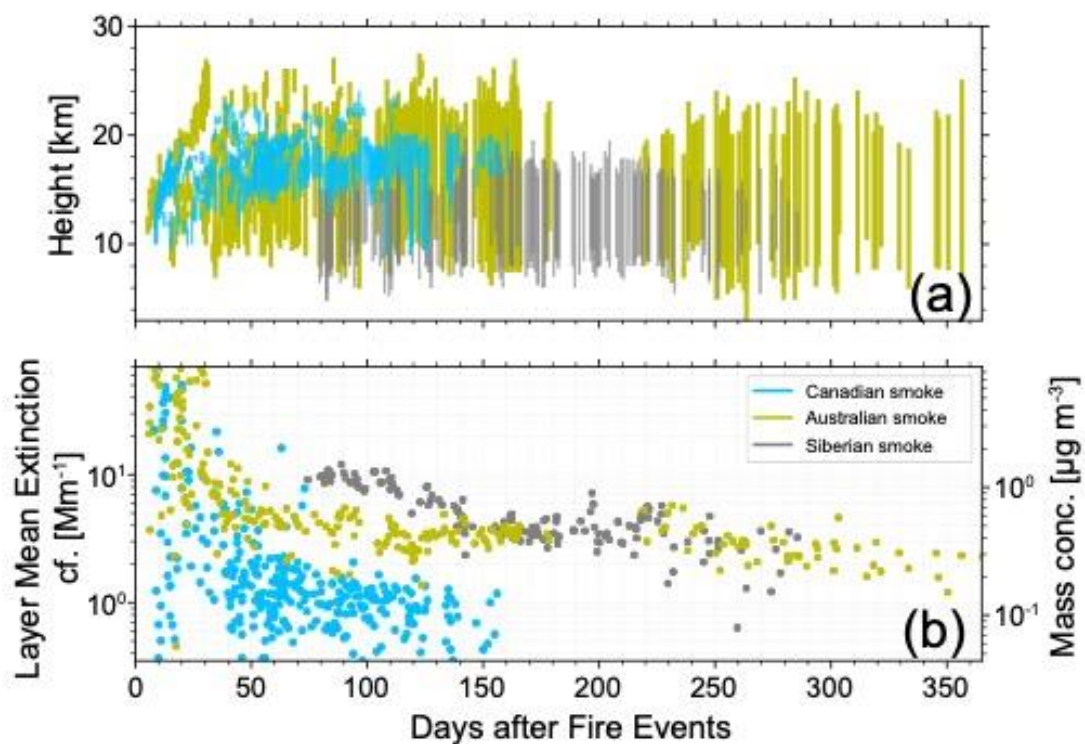

Fig. 7. Stratospheric aerosol burden in the first 365 days after three major fire events as observed with ACTRIS aerosol profiling facilities (high power lidar + sun photometer): (a) Geometrical boundaries (layer bottom to layer top) of the smoke plume. Each vertical bar represents a day-by-day measurement, b) layer mean extinction coefficient (cf) at 532 nm and the respective mass concentration derived with a mass-specific extinction coefficient 8.93 m^2g^{-1} (Baars et al., 2019). Blue dots: Smoke from the record-breaking Canadian wildfires (Pacific Northwest Event) observed over Europe with EARLINET/ACTRIS lidars (Baars et al, 2019), yellow dots: smoke from the Australian New Year Super Outbreak during the Black Summer fire season of 2019–2020 in south-eastern Australia as observed over Punta Arenas, Chile (Ohneiser al, 2022) with the ACTRIS mobile facility LACROS (Radenz et al., 2022) and grey dots: smoke from extremely strong fires in central and eastern Siberia (SIberian Lake Baikal Event) in summer 2019 (Ohneiser et al. 2021) observed over the high Arctic with the ACTRIS shipborne facility OCEANET during the MOSAiC expedition (Engelmann et al.,

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2022). Day 0 represents the 12 August 2017 (Canadian fires), 23 July 2019 (Siberian fires), and 31 December 2019 (Australian fires).

A number of ACTRIS studies related to the COVID-19 pandemic and the series of lockdowns over Europe investigated their impact on air quality both at the European (Putaud et al., 2023), country (Petetin et al., 2020; Putaud et al., 2021) and city scales, e.g. Athens (Eleftheriadis et al., 2021), Paris (Petit et al., 2021), Elche (southeastern Spain) (Clemente et al., 2022), the Po Valley (Cristofanelli et al., 2021), and rural Košetice in the Czech Republic (Mbengue et al., 2023). Interestingly, most studies above documented not only an overall decrease in submicron particulate matter concentrations and primary traffic tracers, but also an increase in ozone. Evangeliou et al. (2021), combining in situ and remote sensing data, provided estimates of BC emission reductions in Europe during lockdowns partly attributed to COVID-19 measures (Figure 8). Finally, ACTRIS services to CAMS had a high impact during the COVID-19 lockdown and relaxation period, when the provision of quality assured measurements helped to characterize the spatial and temporal variations of anthropogenic aerosols (Tsekeri et al., submitted).
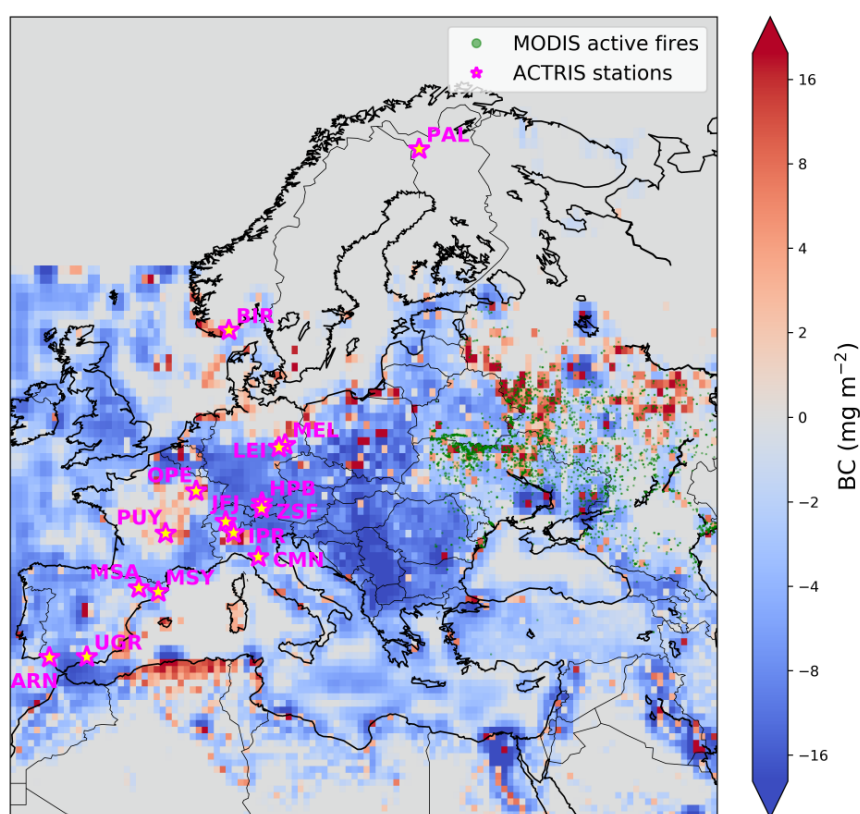
Fig.8: Posterior emission anomaly of black carbon (BC) during the COVID19 lockdown period (15 March – 30 April 2020) with respect to 2015 - 2020 (same period). Circles marked in green show the active fires from NASA MODIS satellite, while stars depict the locations of the ACTRIS stations that were used to calculate the impact of the COVID restriction measures over Europe on black carbon emissions (modified after Evangeliou et al., 2021). The overall net decrease in BC emission is -23kT for the period.

Lastly, the ACTRIS network of observational sites was used by Mayer et al., (2024) to investigate the widespread use of pesticides in Europe during the agricultural application season, which shows that atmospheric transport and persistence of pesticides are underestimated.

6. The evolution of ACTRIS and challenges ahead

Our atmospheric environment is constantly changing, mainly due to direct anthropogenic emissions and climate feedback mechanisms. Our ability to understand the changing environment and make predictions for the future will also evolve with scientific findings supported by new technologies and improved computing capabilities. It is expected that interlinkages and cooperation between different fields of science will become increasingly necessary to deliver services to society that integrate multiple disciplines (e.g., environment, health). To maintain attractiveness, ACTRIS must consider the conditions for maintaining a high and adaptable level of services and address the following challenges in the next 5-15 years of operation.

Challenge 1: Maintaining attractiveness by constantly responding to evolving community needs

ACTRIS services must continue to evolve even after entering its operational phase in 2026. ACTRIS must therefore closely monitor evolution of requirements and needs from the user communities. This implies that ACTRIS must be ready to propose new expertise, extending to new variables and integrating to new available technologies on the market. This comprises, for example, new requests arising for monitoring emerging pollutants or new species. The challenge in ACTRIS will be to be sufficiently agile to rapidly extend its TC perimeter. Given the multi-year process of ACTRIS evolution up till now, much shorter development cycles are expected within ACTRIS to allow for rapid adjustments and continuous improvement in the development of future products or services.

Challenge 2: Ensure regular technology upgrades at ACTRIS facilities

Techniques that now constitute core measurements deployed in almost all ACTRIS facilities were research instruments operated by very few research groups 15 years ago. Similarly, current operating techniques will be obsolete at some stage during the ACTRIS operational phase. ACTRIS will face the need to engage in regular upgrades of its services and products and to maintain attraction to users. Accordingly, it will have to ensure that technologies used in the RI stay on the front-line of the developments, and align with its scientific missions. ACTRIS must serve innovation for the benefit of atmospheric sciences, closely connected to the commercial market as a supplier, technology partner and user. This must clearly come with investments for fostering use of innovative technologies designed as the RIs strategic vision for the next 10 to 20 years.

Challenge 3: Maintaining a sustainable Trans-National Access program to ACTRIS facilities

ACTRIS is service-based and access provision is the core of its activities. The provision of access in ACTRIS has had significant impacts on science and innovation, and contributed to opening its services to more users worldwide. ACTRIS provides its users with various access modalities: virtual (data provision), physical, and remote. Physical access (user(s) moving to the facility for a more or less extended period) or remote access (staff at the facility provide the services remotely without users visiting the facility physically) must continue to be granted. The challenge for ACTRIS is to maintain a permanent scheme for access to most (national and central) facilities, driven by scientific excellence regardless of the country of origin or ability of the proposer to contribute financially, in the international context. In this respect, there is a clear and urgent need for a sustainable funding scheme to ensure that ample user access to facilities is provided and supported independently of European projects.

Challenge 4: Extend the user perimeter by delivering more cross-disciplinary services

Easy and fast access to reliable, long-term, and high-quality environmental data is fundamental for advancing our scientific understanding of the planet Earth and its environment as well as for developing mitigation and adaptation strategies, for fact-based decision-making, and for the development of environment-friendly innovations. It is expected that the demand for integrated, interdisciplinary services beyond the strict atmospheric domain will increase. ACTRIS must adapt to offer more integrated services in addition to the strict atmospheric-specific data production to integrated global services. For that purpose, ACTRIS also liaises

with other research infrastructures beyond the ENVRI cluster and the environmental field. The study of these interactions requires unimpeded use of multidisciplinary data from different spheres of the Earth system, with FAIR digital (meta)data as an absolute prerequisite.

Challenge 5: Establishing ACTRIS as a Research Infrastructure of Global relevance

ACTRIS manages data and data products that are not limited to the European dimension and are of value and utility to a broad scientific community and to policy-makers outside the European political boundaries. ACTRIS must therefore be established as a central element in an international framework addressing global research challenges. The European concept of distributed research infrastructures cannot be directly applied in other regions of the world. For the scope of ACTRIS, counterparts in other nations are often Research Performing Organizations (RPOs) running specific long-term programs but often lack the dimensions of research facilities (such as exploratory Platforms and access). The Atmospheric Radiation Measurement (ARM) program of the Department of Energy in the US provides somewhat similar services to ACTRIS, but without the simulation chamber dimension. Establishment of ACTRIS as a contributor to a global effort to reference and coordinate with similar frameworks under the umbrella of international organizations such as the World Meteorological Organization is essential. The challenge to ACTRIS will then be 1) to develop sustainable partnerships and decision-making processes with the relevant partners worldwide, 2) to demonstrate the benefits of converging interoperability and standards to stakeholders and the global research community, and 3) to establish the mechanisms for providing international access to facilities.

Challenge 6: Favoring connections to societal needs

Clearly connected to Goal 13 (Take urgent action to combat climate change and its impacts) of the Agenda for Sustainable Development, adopted by the United Nations (UN) General Assembly in 2015, and to the European Green deal, the grand challenge of ACTRIS is also to be recognized as a tool for implementing policies to achieve the SDGs, and to provide decision-makers with the scientific evidence and analyses needed to adapt to climate change impacts and build climate resilience. Science will help guide valuable emission-reduction decisions and actions from local to national and continental scales.

7. Conclusions

ACTRIS reflects a strong desire for global integration from the research community and beyond, to facilitate research through access to high-quality services, from harmonized data provision to access to NFs and CFs. ACTRIS is expected to be fully operational in 2026, with all foreseen services open to users, though ACTRIS is already now regularly used by a large community of scientists with significant impact on research and innovation. Furthermore, ACTRIS is a step forward in providing the advanced tools and platforms required for atmospheric research and long-term collection and archiving of data, making them accessible to the scientific community. It also provides the necessary level of coordination across various disciplines of the atmospheric science, which is crucial for addressing future challenges. While a total of 17 countries are currently contributing to the RI, ACTRIS is actively seeking to extend membership to additional European countries, key to developing a European-wide strategy for the atmospheric science. Through its contribution to several surface-based international observing networks, ACTRIS is a key actor in the global atmosphere monitoring effort.

- in Cyprus by Deputy Ministry of Research, Innovation, and Digital Transition; The establishment and the operation of the ERATOSTHENES CoE NF is supported by 'EXCELSIOR': ERATOSTHENES: EXcellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment H2020 Widespread Teaming project. The project has received funding from the EU H2020 under GA#857510, from the Government of the Republic of Cyprus through the Directorate General for the European Programmes, Coordination and Development and the Cyprus University of Technology.

- In the Czech Republic (CR), the operation costs for the implementation of ACTRIS-CZ and respective NFs were covered by the projects for the support of large research infrastructures (ACTRIS CZ - LM2015037, LM2018122, LM2023030) funded by the Czech Ministry of Education, Youth and Sports of the Czech Republic. ACTRIS-CZ NF instrumentation upgrades were supported by the European Structural and Investment Funds (projects ACTRIS-CR RI, #CZ.02.1.01/0.0/0.0/16_013/0001315 and ACTRIS-CZ RI 2, #CZ.02.1.01/0.0/0.0/18_046/0015968). The costs connected with implementation of ACTRIS-CZ CF unit were funded by the Czech Ministry of Environment (MOSKAL, # CZ.05.2.32/0.0/0.0/18_098/000905).

- In Denmark by the Ministry of Higher Education and Science in Denmark funded ACTRIS-DK (Project. No. 5072-00032B).

- In Finland, ACTRIS-FI projects for the implementation of ACTRIS-FI NFs and ACTRIS TC Units of University of Helsinki funded by Research Council of Finland (grant no. 328616, 328617 and 328823 (INAR RI/ ACTRIS-FI 2020-2024); 329274 (ACTRIS CFs 2020-2024); and 345510, 345527 and 345528 (INAR RI 2022-2025)) and the funding from the Ministry of Transport and Communications. The Atmosphere and Climate Competence Center Flagship funding by the Research Council of Finland (grant # 337549, 337552, 337550 and 337551) and Jane and Aatos Erkko Foundation funding.

- In France, ACTRIS-FR receives support from the French Ministry of Higher Education and Research, from the French National Centre for Scientific Research (CNRS) and 22 further French research performing organizations composing the ACTRIS-FR consortium and contributing to its activities. ACTRIS activities benefit from national funding managed by the French National Research Agency (ANR)

under the "Investments for the Future Programme (PIA)" (EQUIPEX OBS4CLIM, grant n° ANR-21-ESRE-0013).

- In Germany, implementation of ACTRIS-D is funded by the Federal Ministry of Education and Research (BMBF) under the FONA Strategy "Research for Sustainability". The operation of the CFs is supported by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). Contributions of the German Meteorological Service (DWD) are funded by the Federal Ministry of Digital and Transport (BMDV). The implementation and operation of ACTRIS-D is co-funded by 11 German research performing organizations.

- In Greece, ACTRIS-GR is funded by the project ''PANhellenic infrastructure for Atmospheric Composition and climatE change'' (MIS 5021516), implemented under the Action ''Reinforcement of the Research and Innovation Infrastructure'', funded by the Operational Programme ''Competitiveness, Entrepreneurship and Innovation'' (NSRF 2014–2020) and co-financed by Greece and the European Union (European Regional Development Fund).

- In Italy, ACTRIS-IT is funded by the Italian Ministry of University and Research through Ordinary Fund (FOE), with the project (Grant n. 893/2019) for the implementation of ACTRIS-IT funded by the European Regional Development Fund through the Competitiveness Operational Programme 2014–2020, Action II.1 and with the project (Grant n. 1719/2020) to strengthen ACTRIS-IT human capital. ACTRIS is also supported by the Italian research performing organization composing the national consortium.

- In The Netherlands, ACTRIS-NL is supported by the Ministry of Infrastructure and Water management, and Ruisdael Observatory, a large-scale scientific research infrastructure which is financed by the Dutch Research Council (NWO, grant number 184.034.015).

- In Norway, ACTRIS-NO (Pr.no. 322247) and ACTRIS-ESFRI (Pr.no. 320886) funded by the FORINFRA infrastructure program of the Research Council of Norway.

- In Poland support was provided by The National Information Processing Institute - National Research Institute (OPI-BIP) within the Smart Growth Operational Programme (POIR.04.02.00-00-D019/20); the National Science Center of Poland

AVAILABILITY STATEMENT

All ACTRIS data are available https://dc.actris.nilu.no/ and data production software, tools, and data are available from the CFs on various pages from this one.

APPENDIX

Appendix A: ACTRIS glossary (a more complete glossary can be found at:

https://www.actris.eu/sites/default/files/inline-files/ACTRIS_glossary_April2022_0.pdf)

- **ACTRIS ERIC** – The Aerosol, Clouds and Trace Gases Research Infrastructure established by the European Commission as a European Research Infrastructure Consortium (ERIC) in April 2023. ACTRIS ERIC includes all functions of ACTRIS Head Office and part of the Data Centre. Its statutory seat is located in Helsinki, Finland.

- **ACTRIS National Facilities** - The core components of ACTRIS. They comprise the National Facilities, constituting in Observatory and Exploratory Platforms, and the Central Facilities, fundamental for the provision of harmonized high-quality data. Member and observer countries provided an official list of NFs with those not yet in operation called "provisional".

- **ACTRIS Label** – The "ACTRIS National Facility" label is granted through the ACTRIS labelling process to Observational and Exploratory Platforms that comply with the ACTRIS standards.

- **ACTRIS labelling process** – A process that demonstrates, including through audits, the operational capacities of the ACTRIS National Facilities and ensures the high quality of ACTRIS data by granting the label "ACTRIS National Facility".

- **ACTRIS ERIC Member**:   a Member State of the European Union, associated country, third country other than associated country, or an intergovernmental organization that has joined ACTRIS ERIC with full voting rights

- **ACTRIS Permanent Observer and Observer**: a Member State of the European Union, associated country, third country other than associated country, or an intergovernmental organisation that has joined ACTRIS ERIC as an observer or permanent observer, without voting rights. ACTRIS Observers. An observer is admitted for a maximum of three years with the possibility of two one-year extensions

- **ACTRIS observational components** – ACTRIS observational components refer to the classification of measurement techniques. ACTRIS has six observational components: aerosol in situ measurements (AIS), cloud in situ measurements (CIS), reactive trace gases in situ measurements (RTGIS), aerosol remote sensing

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measurements (ARS), cloud remote sensing measurements (CRS), and reactive trace gases remote sensing measurements (RTGRS).

- **Atmospheric Simulation Chamber Committee (ASC Committee)**: supports the operation of ACTRIS atmospheric simulation chambers on matters related to procedures, quality, consistency and relevance.

- **Central Facility Unit** – part of a Central Facility located at and operated by a research performing organization (RPO) or by ACTRIS ERIC.

- **Cooperation Agreement** - an agreement between ACTRIS ERIC and a National Facility or between ACTRIS ERIC and a Central Facility which is not included in ACTRIS ERIC.

- **Data Management Plan** – A document that outlines the strategy and process towards making ACTRIS data FAIR at ACTRIS Data Centre Level.

- **Data producers** – the network of National Facilities producing ACTRIS data (see Table 2) compliant to specified ACTRIS procedures.

- **Director General (DG)** – the legal representative of ACTRIS ERIC, appointed by the General Assembly, responsible for the implementation of the decisions by the General Assembly and ensuring the scientific and strategic development of ACTRIS

- **ENVRI** – A community of European environmental research infrastructures working together to observe the Earth as one system. ENVRI fosters trans-disciplinary collaboration by providing environmental data, tools, and other services that are Open and FAIR, and can be easily used by anyone for free.

- **ERIC** - The European Research Infrastructure Consortium is a specific legal form that facilitates the establishment and operation of Research Infrastructures with European interest. https://eur-lex.europa.eu/EN/legal-content/summary/european-research-infrastructure-consortium-eric.html

- **ESFRI** - The European Strategic Forum on Research Infrastructures is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.

- **ESFRI Landmark** – It is a milestone that demonstrates that an RI has reached an advanced stage of implementation for delivering user access to their facilities, resources, and services.

- **ESFRI Project** – A label that indicates those RIs undergoing through their preparation phase and considered of strategic importance for the European Research Area.

- **ESFRI Roadmap** – A strategy report on Research Infrastructures periodically published by ESFRI. It includes the Roadmap with ESFRI Projects and ESFRI Landmarks and the ESFRI vision of the evolution of Research Infrastructures in Europe, addressing the mandates of the European Council, and identifying strategy goals.

- **Essential Climate Variable (ECV)** - A physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate.

- **Essential Climate Variable Product (ECV product)** - GCOS ECVs are sub-divided into so-called ECV Products. The term "Product" denotes long-term data records of values or fields of ECVs

- **Ethical Advisory Board**: provides feedbacks and recommendations to the DG on aspects related to ethical issues in ACTRIS-ERIC and ACTRIS activities.

- **FAIR** - FAIR stands for Findable, Accessible, Interoperable, and Reusable, which are principles aimed at promoting good data management and stewardship practices.

- **In situ measurements** - in the context of ACTRIS, in situ measurements of aerosol, cloud, and reactive-trace-gas properties refer to techniques that are characterizing a sampling point. They can be performed from Observational Platforms near the surface, from mobile surface based or airborne platforms, and in atmospheric simulation chambers and laboratories.

- **National ACTRIS consortium** – the organization of the ACTRIS community at the national level.

- **National Facility (NF)** - an Observational or Exploratory Platform providing data and/or physical access to the platform within ACTRIS.

- **National Facility (NF) Technical and Scientific Forum** - It is a highly technical and operative forum to develop the RI and ensure the connection of scientific expertise and technological development. It as an advisory body that may provide recommendations to the RI Committee or to the ACTRIS community.

- **Research infrastructure (RI)** - RI are facilities, resources, and related services used by the scientific community to conduct research in all scientific and technological fields.

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- **Research Infrastructure Committee (RI Committee)** - the committee supports the DG on matters related to the RI to ensure consistency, coherence, and sustainability of the operations of the RI.

- **Scientific and Innovation Advisory Board (SIAB)** - consists of independent external members monitoring scientific and operative quality of and advice to develop ACTRIS ERIC and the research infrastructure activities in operation phase.

- **Service and Access Management Unit (SAMU)** - a part of ACTRIS Head Office facilitating access to ACTRIS services other than data for the user communities.

- **Trans-National Access program** - It addresses both physical access to long-term research sites (Transnational Access-TA) and an access mode in which local site staff perform measurements/sampling according to user defined protocols (Remote Access-RA), or a combination of both. Applicants must be affiliated to an organization in a different country from where the site they wish to access is.

- **User** - a person, a team, or an institution making use of ACTRIS data or other ACTRIS services, including access to ACTRIS facilities.

Appendix B: ACTRIS National Facilities

Table B1: The ACTRIS National Facilities and provisional NFs with their WIGOS identifier – when it exists – and their geographical location. Provisional NFs means they are not yet in full operation mode and ready for entering the labelling process. The components (aerosol, clouds and trace gases) observed at the National Facilities via in situ or remote sensing techniques are included with 1 = Aerosol In Situ; 2 = Cloud In Situ; 3 = Reactive Trace Gases In Situ; 4 = Aerosol Remote Sensing; 5 = Cloud Remote Sensing; and 6 = Reactive Trace Gases Remote Sensing.

Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Marambio	0-20008-0-MBI	Antarctica	-64,25	-56,63	198	1
Trollhaugen		Antarctica	-72,01	2,54	1553	1,3
Sonnblick Observatory	0-20000-0-11343	Austria	47,05	12,96	3106	1,2
University Innsbruck		Austria	47,26	11,38	616	3
University Vienna		Austria	48,22	16,36	185	1
Ukkel		Belgium	50,78	4,35	105	1
Vielsalm		Belgium	50,27	5,90	494	1,3
Basic Environmental Observatory Moussala -	0-20008-0-BEO	Bulgaria	42,18	23,59	2925	1

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Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Sofia	0-20008-0-SOF	Bulgaria	42,65	23,38	590	4
Cape Verde Atmospheric Observatory	0-20008-0-CVO	Cape Verde	16,87	-24,87	30	1,3,4,5
Cyprus Atmospheric Observatory (CAO)	0-20008-0-CYP	Cyprus	35,04	33,06	550	1
Cyprus Atmospheric Remote Sensing Observatory CARO	0-20008-0-CYP	Cyprus	34,68	33,04	50	4,5
Lom		Czechia	50,59	14,39	265	1
Milešovka		Czechia	50,56	13,93	837	2
National Atmospheric Observatory Kosetice	0-20000-0-11628	Czechia	49,57	15,08	536	1,3,4
Suchdol		Czechia	50,13	14,39	277	1
Risoe Research Station		Denmark	55,63	12,10	5	1
Villum Research Station		Denmark	81,60	-16,70	24	1
Pallas Atmosphere-Ecosystem Supersite	0-20008-0-PAL	Finland	67,97	24,12	565	1,2,3,5
SMEAR II (Hyytiälä)	0-20008-0-SMR	Finland	61,85	24,28	181	1,3,4,5
SMEAR III (Helsinki)		Finland	60,20	24,97	26	1,3
SMEAR I (Värriö)	0-20008-0-VAR	Finland	67,77	29,58	400	1,2,3
SMEAR IV (Kuopio)		Finland	62,90	27,65	306	1,2

Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Utö Atmospheric and Marine Research Station	0-20008-0-UTO	Finland	59,78	21,38	7	1
Atmospheric Observatory of LiLle (ATOLL)	0-250-1006-598518	France	50,61	3,14	60	1,4
Observatoire de Haute Provence (OHP-GEO)	0-20008-0-OHP	France	43,92	5,72	650	4
Plateforme Pyrénéenne d'Observations Atmosphériques (P2OA)	0-20008-0-PDM	France	42,94	0,14	588	1,3
Site d'observation atmosphériques Puy de Dôme/ Opme/ Cézeaux (COPDD)	0-20008-0-PUY	France	45,77	2,97	1465	1,3,4
Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA)	0-250-1001-07151	France	48,72	2,21	160	1,3,4,5
Observatoire de Physique de l'Atmosphère à La Réunion (OPAR)	0-20008-0-RUN	France	-21,08	55,38	2160	1,4,5,6
Bremen	0-20008-0-BEM	Germany	53,10	8,85	27	6
Garmisch-Partenkirchen/Zugspitze/Schneefernerhaus	0-20008-0-ZSF	Germany	47,48	11,06	743	1,4,6

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Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Jülich Observatory for Cloud Evolution (JOYCE)	0-20008-0-JUE	Germany	50,91	6,41	111	5
Melpitz Research Station	0-20008-0-MEL	Germany	51,53	12,93	86	1,3,4,5
Meteorological Observatory Hohenpeißenberg (DWD)	0-20008-0-HPB	Germany	47,80	11,01	990	1,3,4
Meteorological Observatory Lindenberg	0-20008-0-LIN	Germany	52,21	14,13	104	5
München	no identifier	Germany	48,21	11,26	539	4,5
Schmücke	0-20008-0-SMU	Germany	50,65	10,77	937	1,2,3
Taunus Observatory	0-20008-0-TOB	Germany	50,22	8,45	825	1,3
Waldhof	0-20008-0-WAL	Germany	52,80	10,76	74	1,3
Atmospheric Rome joinT supersitE	0-20008-0-ROM	Italy	41,88	12,68	107	4
CNR–IMAA Atmospheric Observatory (CIAO)	0-20008-0-POT	Italy	40,60	15,72	760	1,4,5,6
Monte Cimone Po Valley San Pietro Capofiume	0-20008-0-CMN	Italy	44,19	10,70	2165	1,2,3,4
Lampedusa	0-20008-0-LMP	Italy	35,52	12,63	50	4,5
Lecce	0-20008-0-ECO	Italy	40,34	18,13	36	1,3,4
Naples Fixed National Facility	0-20008-0-NAP	Italy	40,84	14,18	118	1,4
UNIAQ/CETEMPS	0-20008-0-CEO	Italy	42,37	13,35	656	4,5

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Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Ruisdael Observatory: CABAUW	0-20008-0-CES	Netherlands	51,97	4,93		1,3,4,5,6
Birkenes	0-20008-0-BIR	Norway	58,39	8,25	219	1
Ny-Ålesund, Spitsbergen	0-20008-0-NYA	Norway	78,92	11,92	23	4,6
Zeppelin Mountain observatory	0-20008-0-ZEP	Norway	78,91	11,88	474	1,2,3
Belsk	0-20008-0-COG	Poland	51,84	20,79	173	1,4
Racibórz		Poland	50,08	18,19	215	1,4
Rzecin		Poland	52,76	16,31	59	4,5
Strzyżów		Poland	49,88	21,86	444	4
Warsaw		Poland	52,21	20,98	112	4,5
Wrocław		Poland	51,11	17,04	120	1,4
RADO-Bucharest	0-20008-0-INO	Romania	44,35	26,03	93	1,4,5
RADO-Cluj	0-642-2010-CLJ	Romania	46,77	23,58	352	4,5
RADO-Galati		Romania	45,44	28,06	35	5
RADO-Iasi		Romania	47,17	27,57	66	4
Andalusian Global ObseRvatory of the Atmosphere (AGORA)	0-20008-0-UGR	Spain	37,20	-3,60	680	1,4,5
Barcelona	0-20008-0-BRC	Spain	41,39	2,12	115	1,4
ESAt - El Arenosillo	0-20008-0-ARN	Spain	37,10	-6,70	40	1

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Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Izaña Atmospheric Observatory	0-20008-0-IZO	Spain	28,30	-16,50	2370	1
Madrid	0-20008-0-MAD	Spain	40,50	-3,70	700	1,4
Montsec	0-20008-0-MSA	Spain	42,10	0,70	1571	1
Montseny Supersite	0-20008-0-MSY	Spain	41,50	2,20	720	1
Paramaribo	0-20008-0-PMO	Surinam	5,81	-55,21	7	6
Hyltemossa	0-20008-0-HTM	Sweden	56,10	13,42	115	1,3
Norunda	0-20008-0-NOR	Sweden	60,08	17,48	46	1,3
Östergarnsholm		Sweden	57,43	18,98		1
Svartberget	0-20008-0-SVB	Sweden	64,25	19,77	270	1,3
Jungfraujoch (JFJ)	0-20008-0-JFJ	Switzerland	46,55	7,99	3580	1,2,3,6
Payerne	0-20008-0-PAY	Switzerland	46,81	6,94	489	1,4,5
Beromunster	0-20000-0-06910	Switzerland	47,19	8,18	797	3
Dushanbe, Tajikistan	0-20008-0-DUS	Tajikistan	38,56	68,86	864	4

Provisional facilities

Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m)	Components
Antikythera	0-20008-0-PMO	Greece	35,86	23,30	193	4
Athens supersite NOA	0-20000-0-16714	Greece	37,97	23,72	105	1

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Facility name	WIGOS Station Identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m asl)	Components
Athens supersite Demokritos	0-20008-0-DEM	Greece	38,00	23,82	270	1
Thessaloniki	0-20008-0-THE	Greece	40,63	22,95	50	4
Helmos Mt	0-20008-0-HAC	Greece	37,98	22,20	2314	1
Finokalia	0-20008-0-FKL	Greece	35,33	25,66	250	1
European Commission Atmospheric Observatory	0-20008-0-IPR	Italy	45,82	8,64	209	1
Auchencorth Moss	0-246-0-101462	United Kingdom	55,79	-3,24	267	1,3
Chilbolton Observatory	0-826-300-3	United Kingdom	51,14	-1,44	84	4,5

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Appendix C: ACTRIS variables

Table C1-7: The atmospheric variables included in ACTRIS together with responsible Data Centre unit, the associated Topical Centre and methodology. Variables produced from a single measurement technique is indicated in cyan, variables produced from synergy of measurement techniques in dark blue, and variables produced from synergy of measurement techniques where several combinations are possible in light blue. ECV products are indicated with *.

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Table C1a: The ACTRIS variable produced by Topical Centre ECAC-CAIS and associated measurement technique. Variable produced from a single measurement technique is indicated in cyan, variable produced from synergy of measurement techniques in dark blue, and variable produced from synergy of measurement techniques where several combinations are possible in light blue. ECV products are indicated with *.

ACTRIS CAIS-ECAC measurement guidelines: https://www.actris-ecac.eu/measurement-guidelines.html

ACTRIS aerosol in situ variables	Integrating Nephelometer	Mobility Particle Size Spectrometer	Aerodynamic & Optical Particle Size Spectrometer	Absorption Photometer	Condensation Particle Counter	Scanning PSM, (N)AIS, N-MPSS	Particle Size Magnifier (PSM)	Cloud Condensation Nuclei Counter
Handled by IN-SITU - The aerosol in situ Data Centre unit								
Particle light scattering* and backscattering coefficients	▊ (cyan)							
Particle number size distribution – mobility diameter*		▊ (cyan)						

	Particle number size distribution – optical and aerodynamic diameter	Particle light absorption coefficient* and equivalent black carbon concentration	Particle number concentration	Nanoparticle number size distribution	Nanoparticle number concentration	Cloud condensation nuclei number concentration*
						▉
					▉	
				▉		
			▉			
		▉				
	▉					

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Table C1b: continued

ACTRIS aerosol in situ variables	Filter sampling	Thermal-optical analyser	Offline filter-based IC, GC-MS, HPLC-MS, LC/MS	Aerosol Mass Spectrometer	X-Ray Fluorescence, Particle Induced X-ray Emission
Handled by IN-SITU - The aerosol in-situ Data Centre unit					
Mass concentration of particulate organic and elemental carbon*	■	■			
Mass concentration of particulate organic tracers	■		■		
Mass concentration of non-refractory particulate organics and inorganics				■	
Mass concentration of particulate elements	■				■

Measurement techniques

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Table C2: same as Table C1 for Topical Centre CiGas

CiGas measurement guidelines: https://www.actris.eu/topical-centre/cigas

ACTRIS trace gas in situ variables	On-line GC-FID	On-line GC-MS	On-line GC-FID/MS	On-line GC-Medusa	On-line PTR-MS	On-line Hantzsch	Off-line traps: ads-tubes	Off-line traps: DNPH-cartridge-HPLC	Off-line steel canister	Off-line glass flask	NO-O$_3$ chemiluminescence	Potentially other measurement technique supported by the TC	Cavity Attenuated Phase Shift Spectroscopy (CAPS)	CI-APi-TOF
NMHCs (~50 gases)	■	■	■	■	■		■		▓	▓				
OVOCs (~15 gases)	■	■	■	■	■	■	■	■	▓	▓				
NO											■			
NO$_2$											■	■	■	
Condensable vapors (~4 species)											░		░	■

Measurement techniques

Table C3: same as Table C1 for Topical Centre CIS

CIS measurement guidelines: https://www.actris.eu/topical-centre/cis

ACTRIS cloud in situ variable	Integrating Cloud Probe	Cloud Droplet Probe	Cloud Ice Probe	Aerosol Particle Sampler	Bulk collectors	INP instrument
Liquid droplet mass concentration	■	■				
Liquid droplet effective radius	■	■				
Liquid droplet number concentration		■				
Liquid droplet number size distribution		■				
Ice particle number concentration			■			
Ice particle number size distribution			■			
Ice nucleating particle number concentration				■		■

Measurement techniques

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Table C4: Same as C1 for Topical Centre CARS

Ice nucleating particle temperature spectrum	■		
Liquid droplet inorganic ions mass concentration	■	■	■
Liquid droplet carboxylic acids mass concentration			
Liquid droplet dissolved organic carbon mass concentration			

CARS measurement guidelines: https://www.actris.eu/topical-centre/cars

	Measurement techniques	
ACTRIS aerosol remote sensing variables	High-power aerosol lidar	Automatic sun/sky/lunar photometer
Attenuated backscatter profile	■	
Volume depolarization profile	■	
Particle backscatter coefficient profile	■	
Particle extinction coefficient profile*	■	

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Lidar ratio profile

Ångström exponent profile

Backscatter-related Ångström exponent profile

Particle depolarization ratio profile

Particle layer geometrical properties (height and thickness)

Column integrated extinction

Planetary boundary layer height

Spectral Downward Sky Radiances

Direct Sun/Moon Extinction Aerosol Optical Depth (column)*

Aerosol columnar properties

Aerosol profile microphysical and optical properties

Table C5: Same as C1 for Topical Centre CCRES.

CCRES measurement guidelines: https://www.actris.eu/topical-centre/ccres/

	Measurement techniques							Model
ACTRIS cloud remote sensing variables	Cloud radar	Doppler cloud radar	Lidar/ceilometer	Radiosonde	Microwave radiometer	Drop-counting raingauge	Disdrometer	NWP model input required
Cloud/aerosol target classification	dark blue	light blue	dark blue	light blue	light blue	light blue	light blue	light blue
Drizzle drop size distribution		dark blue	dark blue	light blue	light blue			light blue
Drizzle water content		dark blue	dark blue	light blue	light blue			light blue
Drizzle water flux	dark blue	light blue	dark blue	light blue	light blue			light blue
Ice water content	dark blue	light blue	dark blue	light blue	light blue			light blue
Liquid water content	dark blue		dark blue		dark blue			light blue
Liquid water path*			light blue		teal			light blue

Temperature profile			■	■	
Relative humidity profile			■	■	
Integrated water vapor path			■	■	

Table C6: same as C1 for Topical Centre CREGARS. FTIR (single) stands for FTIR equipped with single detector while FTIR (double) stands for FTIR equipped with dual detectors

CREGARS Measurement guidelines: https://www.actris.eu/topical-centre/cregars/

ACTRIS trace gas remote sensing variables	Measurement techniques					
	FTIR (single)	FTIR (double)	UVVIS – Zenith-Sky	UVVIS-MAXDOAS	UVVIS-PANDORA	O3-DIAL
Ozone profile						■
Ozone partial columns		■				■
Ozone column*		■	■	■	■	

	1	2	3	4	5	6
Formaldehyde column		■	■		■	■
Formaldehyde lower tropospheric profile			■			
NO$_2$ column*		■	■	■	■	■
NO$_2$ partial columns		■	■	■	■	■
NO$_2$ lower tropospheric profile			■			
NH$_3$ column					■	
C$_2$H$_6$ column					■	■

Table C7: Same as Table C1 for simulation chamber variables and products. The phase relates to Topical Centre CiGas (Trace gas), CAIS-ECAC (Aerosol) or CIS (Cloud)

Simulation chamber measurement guidelines: https://link.springer.com/book/10.1007/978-3-031-22277-1

Data product represents a fundamental property from simulation chamber	Aerosol/ Cloud/ Trace gas	Concentration of chemical species in gas-phase	Concentration of chemical species in aerosol phase	Concentration of chemical species in aqueous phase	Aerosol size distribution	Total aerosol mass	Particle number concentration	Particle absorption coefficients	Particle scattering coefficients	Particle extinction coefficients	Actinic flux
Rate constants for gas-phase reactions	Trace gas	■									
Rate constants for condensed phase reactions	Aerosol/cloud		■	■							
Secondary organic aerosol yields	Aerosol	■			■	■	■				
Photolysis frequencies	Trace gas	■									■
Quantum yields	Trace gas	■									■
Vapor pressures	Trace gas /aerosol	■	■								
Henry's constants	Trace gas, cloud	■		■							

	Mass extinction coefficients	Mass absorption coefficients	Mass scattering coefficients	Complex refractive index	Growth factors
	Aerosol	Aerosol	Aerosol	Aerosol	Aerosol
	■				
			■	■	
		■		■	
	■	■	■		
				■	■
				■	

SIDE BAR

A short history of ACTRIS

ACTRIS began as an 'Integrated Activity' project (ACTRIS) funded by the European Commission (EC), under its 7th Framework Programme (2011-2015). Its main objectives were to integrate the European atmospheric ground-based research facilities with advanced atmospheric instrumentation and build a coordinated framework for the provision of observational data for aerosols, clouds and trace gases as well as access of users to these facilities. The project merged existing atmospheric research communities and previous projects funded by the EC's 6th Framework Programme: EUSAAR (European Supersites for Atmospheric Aerosol Research, Asmi et al., 2012 and https://cordis.europa.eu/project/id/26140/fr) and EARLINET (European Aerosol Research Lidar Network, Pappalardo et al. (2014) and https://www.earlinet.org/). This development was crucial for providing the information needed to address the complex interconnections between aerosols, clouds, and trace gases in four dimensions to create climate- and air pollution-relevant research infrastructure services. The consortium integrated the existing EU ground-based monitoring capacity for short-lived reactive trace gases and communities involved in the EC-funded CloudNet project (Illingworth et al., 2007 and https://cloud-net.org/) producing climate-relevant observations of cloud properties. This first phase of ACTRIS can be seen as a phase of integration of European atmospheric research activities and communities.

A second phase of ACTRIS (called ACTRIS-2, https://cordis.europa.eu/project/id/654109), initiated under the EC H2020, further integrated the EU capacity to monitor SLACs and clouds, by consolidating ACTRIS elements such as its DC and Topical centres. ACTRIS-2 further extended the ACTRIS perimeter by opening the research infrastructure to the European communities active in NDACC (Network for the Detection of Atmospheric Composition Changes) and AERONET (Aerosol Robotic Network), completing the integration of ACTRIS to its current state, for its contribution to the atmospheric observing system from near-surface to high altitude (vertical profiles and total column) that is relevant for climate and air quality research.

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In parallel, starting in FP6 (2004-2009), an initiative has been launched to advance and promote the use of atmospheric simulation chambers for understanding atmospheric processes (photochemistry, aerosol formation, etc.) and their impacts on cultural heritage and human health in the EUROCHAMP (the European Simulation Chambers for Investigating Atmospheric Processes (Wiesen, 2006 and https://cordis.europa.eu/project/id/228335) project, shortly followed in FP7 by the EUROCHAMP-2 project (2009-2013, https://cordis.europa.eu/project/id/228335). In H2020, the EUROCHAMP-2020 project (https://www.eurochamp.org/), set guidelines for standard operation of simulation chamber experiments, to promote their interoperability and define best practice protocols ensuring high-quality experiments to improve knowledge of atmospheric processes.

The ACTRIS-2 and EUROCHAMP communities succeeded in integrating ACTRIS as a pan-European research infrastructure in the ESFRI roadmap in 2016. During the ESFRI application process (2014-2015), the vision, mission, and service concepts of ACTRIS were further developed and strengthened. After the ESFRI project status, the ACTRIS Preparatory phase project (ACTRIS-PPP, https://cordis.europa.eu/project/id/739530) in H2020 was the essential instrument to develop the organizational, operational, and strategic frameworks of ACTRIS. The work in ACTRIS-PPP served to establish a legal entity with well-defined operations, a sound business plan and support from different member countries. The first step towards the establishment of the legal entity ACTRIS ERIC was formally requested to the European Commission in September 2021, and the ERIC status was obtained on April 25, 2023 with 17 founding member and observer countries, with the aim of becoming fully operational in 2026. The ACTRIS Implementation project (ACTRIS IMP, https://cordis.europa.eu/project/id/871115), funded under H2020, sets the necessary coordinated structures for coherent implementation actions to be taken at both the national and European levels towards a globally recognized long-term sustainable research infrastructure. The ACTRIS IMP project ended in 2023 with most elements of ACTRIS already in place, and numerous services already operational. These fundamental building blocks of ACTRIS are presented in Figure SB1.
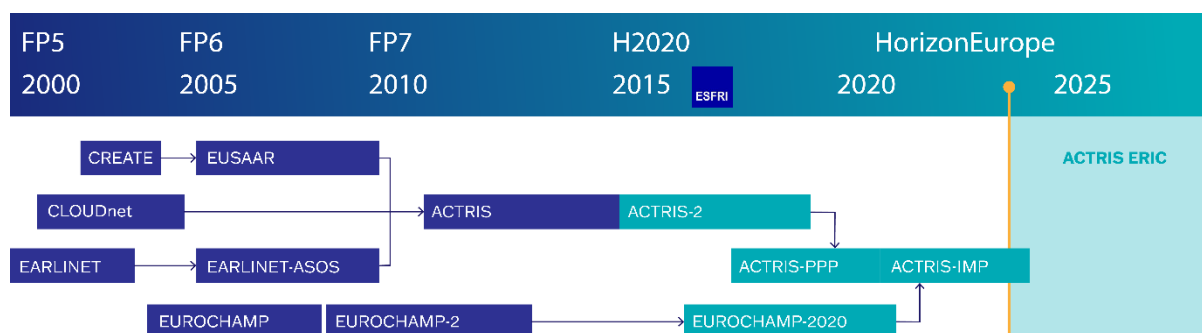
Fig. SB1. The Integrating Activities of the Infrastructure programme of the European Commission, funded under the 5th, 6th and 7th (H2020) and now Horizon Europe Framework Programmes, leading to establishing ACTRIS ERIC in 2023.

The short-term projects have been fundamental for structuring the relevant atmospheric science communities by mobilizing a comprehensive consortium of several key research performing organizations (RPOs) as well as other stakeholders (e.g. public authorities, technological partners) from different EC Member and Associated States to coordinate the development of advanced services in the atmospheric domain.

Overall, ACTRIS has clearly been highly active in integrating initiatives that were initially performed as single community initiatives, when it became evident that pan-European coordination of activities was needed. Indeed, some ACTRIS facilities have been in operation for more than several decades with trace gas remote sensing measurements at the Jungfraujoch dating back to 1950 and among the oldest records in the world. Microphysical and optical aerosol in situ measurements have been operational since 1995 at the Hyytiala facilities (Mäkelä et al., 1997) and at the Jungfraujoch (Collaud Coen et al., 2013), while Birkenes has the longest time series of aerosol chemical properties in Europe (Yttri et al., 2021) and regular observations of aerosol backscatter profiles at the Leipzig observatory were initiated in 1997 (Pappalardo et al., 2014). The use of simulation chamber experiments started in the 1980s but the first steps of integration were taken in Europe in the early 2000s (Becker, 2006). The historical information from the ACTRIS activities is still partly available through the ACTRIS DC.

The creation of ACTRIS ERIC materializes a long-term engagement of a large research community, supported by the European Commission and by strong commitments in many EU Member States and Associated Countries.

REFERENCES

Amiridis, V., Wandinger, U., Marinou, E., Giannakaki, E., Tsekeri, A., Basart, S., Kazadzis, S., Gkikas, A., Taylor, M., Baldasano, J., and Ansmann, A.: Optimizing CALIPSO Saharan dust retrievals, Atmos. Chem. Phys., 13, 12089–12106, https://doi.org/10.5194/acp-13-12089-2013, 2013.

Amiridis, V., Kampouri, A., Gkikas, A., Misios, S., Gialitaki, A., Marinou, E., Rennie, M., Benedetti, A., Solomos, S., Zanis, P., Vasardani, O., Eleftheratos, K., Paschou, P., Georgiou, T., Scollo, S., Mona, L., Papagiannopoulos, N., Retscher, C., Parrinello, T., and Straume, A. G.: Aeolus winds impact on volcanic ash early warning systems for aviation, Sci Rep, 13, 7531, https://doi.org/10.1038/s41598-023-34715-6, 2023.

Apel, E. C., Brauers, T., Koppmann, R., Bandowe, B., Bossmeyer, J., Holzke, C., Tillmann, R., Wahner, A., Wegener, R., Brunner, A., Jocher, M., Ruuskanen, T., Spirig, C., Steigner, D., Steinbrecher, R., Gomez Alvarez, E., Müller, K., Burrows, J. P., Schade, G., Solomon, S. J., Ladstätter-Weissenmayer, A., Simmonds, P., Young, D., Hopkins, J. R., Lewis, A. C., Legreid, G., Reimann, S., Hansel, A., Wisthaler, A., Blake, R. S., Ellis, A. M., Monks, P. S., and Wyche, K. P.: Intercomparison of oxygenated volatile organic compound measurements at the SAPHIR atmosphere simulation chamber, J. Geophys. Res., 113, D20307, 2008.

Asmi, A., Collaud Coen, M., Ogren, J. A., Andrews, E., Sheridan, P., Jefferson, A., Weingartner, E., Baltensperger, U., Bukowiecki, N., Lihavainen, H., Kivekäs, N., Asmi, E., Aalto, P. P., Kulmala, M., Wiedensohler, A., Birmili, W., Hamed, A., O'Dowd, C., G Jennings, S., Weller, R., Flentje, H., Fjaeraa, A. M., Fiebig, M., Myhre, C. L., Hallar, A. G., Swietlicki, E., Kristensson, A., and Laj, P.: Aerosol decadal trends – Part 2: In-situ aerosol particle number concentrations at GAW and ACTRIS stations, Atmos. Chem. Phys., 13, 895–916, https://doi.org/10.5194/acp-13-895-2013, 2013.

Baars, H., Seifert, P., Engelmann, R., and Wandinger, U.: Target categorization of aerosol and clouds by continuous multiwavelength-polarization lidar measurements, Atmos. Meas. Tech., 10, 3175–3201, https://doi.org/10.5194/amt-10-3175-2017, 2017.

Baars, H., Ansmann, A., Ohneiser, K., Haarig, M., Engelmann, R., Althausen, D., Hanssen, I., Gausa, M., Pietruczuk, A., Szkop, A., Stachlewska, I. S., Wang, D., Reichardt, J.,

Skupin, A., Mattis, I., Trickl, T., Vogelmann, H., Navas-Guzmán, F., Haefele, A., Acheson, K., Ruth, A. A., Tatarov, B., Müller, D., Hu, Q., Podvin, T., Goloub, P., Veselovskii, I., Pietras, C., Haeffelin, M., Fréville, P., Sicard, M., Comerón, A., Fernández García, A. J., Molero Menéndez, F., Córdoba-Jabonero, C., Guerrero-Rascado, J. L., Alados-Arboledas, L., Bortoli, D., Costa, M. J., Dionisi, D., Liberti, G. L., Wang, X., Sannino, A., Papagiannopoulos, N., Boselli, A., Mona, L., D'Amico, G., Romano, S., Perrone, M. R., Belegante, L., Nicolae, D., Grigorov, I., Gialitaki, A., Amiridis, V., Soupiona, O., Papayannis, A., Mamouri, R.-E., Nisantzi, A., Heese, B., Hofer, J., Schechner, Y. Y., Wandinger, U., and Pappalardo, G.: The unprecedented 2017–2018 stratospheric smoke event: decay phase and aerosol properties observed with the EARLINET, Atmos. Chem. Phys., 19, 15183–15198, https://doi.org/10.5194/acp-19-15183-2019, 2019.

Backman, J., Schmeisser, L., Virkkula, A., Ogren, J. A., Asmi, E., Starkweather, S., Sharma, S., Eleftheriadis, K., Uttal, T., Jefferson, A., Bergin, M., Makshtas, A., Tunved, P., and Fiebig, M.: On Aethalometer measurement uncertainties and an instrument correction factor for the Arctic, Atmos. Meas. Tech., 10, 5039–5062, https://doi.org/10.5194/amt-10-5039-2017, 2017.

Barnes, I., Becker, K. H., and Patroescu, I.: The tropospheric oxidation of dimethyl sulfide: A new source of carbonyl sulfide, Geophysical Research Letters, 21, 2389–2392, https://doi.org/10.1029/94GL02499, 1994.

Becker, K. H.: Overview on the Development of Chambers for the Study of Atmospheric Chemical Processes, in: Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, vol. 62, edited by: Barnes, I. and Rudzinski, K. J., Kluwer Academic Publishers, Dordrecht, 1–26, https://doi.org/10.1007/1-4020-4232-9_1, 2006.

Bedoya-Velásquez, A. E., Navas-Guzmán, F., Granados-Muñoz, M. J., Titos, G., Román, R., Casquero-Vera, J. A., Ortiz-Amezcua, P., Benavent-Oltra, J. A., De Arruda Moreira, G., Montilla-Rosero, E., Hoyos, C. D., Artiñano, B., Coz, E., Olmo-Reyes, F. J., Alados-Arboledas, L., and Guerrero-Rascado, J. L.: Hygroscopic growth study in the framework of EARLINET during the SLOPE I campaign: synergy of remote sensing and in situ instrumentation, Atmos. Chem. Phys., 18, 7001–7017, https://doi.org/10.5194/acp-18-7001-2018, 2018.

Binietoglou, I., Basart, S., Alados-Arboledas, L., Amiridis, V., Argyrouli, A., Baars, H., Baldasano, J. M., Balis, D., Belegante, L., Bravo-Aranda, J. A., Burlizzi, P., Carrasco, V., Chaikovsky, A., Comerón, A., D'Amico, G., Filioglou, M., Granados-Muñoz, M. J., Guerrero-Rascado, J. L., Ilic, L., Kokkalis, P., Maurizi, A., Mona, L., Monti, F., Muñoz-Porcar, C., Nicolae, D., Papayannis, A., Pappalardo, G., Pejanovic, G., Pereira, S. N., Perrone, M. R., Pietruczuk, A., Posyniak, M., Rocadenbosch, F., Rodríguez-Gómez, A., Sicard, M., Siomos, N., Szkop, A., Terradellas, E., Tsekeri, A., Vukovic, A., Wandinger, U., and Wagner, J.: A methodology for investigating dust model performance using synergistic EARLINET/AERONET dust concentration retrievals, Atmos. Meas. Tech., 8, 3577–3600, https://doi.org/10.5194/amt-8-3577-2015, 2015.

Bloss, C., Wagner, V., Bonzanini, A., Jenkin, M. E., Wirtz, K., Martin-Reviejo, M., and Pilling, M. J.: Evaluation of detailed aromatic mechanisms (MCMv3 and MCMv3.1) against environmental chamber data, Atmos. Chem. Phys., 5, 623–639, https://doi.org/10.5194/acp-5-623-2005, 2005.

Brasseur, Z., Castarède, D., Thomson, E. S., Adams, M. P., Drossaart Van Dusseldorp, S., Heikkilä, P., Korhonen, K., Lampilahti, J., Paramonov, M., Schneider, J., Vogel, F., Wu, Y., Abbatt, J. P. D., Atanasova, N. S., Bamford, D. H., Bertozzi, B., Boyer, M., Brus, D., Daily, M. I., Fösig, R., Gute, E., Harrison, A. D., Hietala, P., Höhler, K., Kanji, Z. A., Keskinen, J., Lacher, L., Lampimäki, M., Levula, J., Manninen, A., Nadolny, J., Peltola, M., Porter, G. C. E., Poutanen, P., Proske, U., Schorr, T., Silas Umo, N., Stenszky, J., Virtanen, A., Moisseev, D., Kulmala, M., Murray, B. J., Petäjä, T., Möhler, O., and Duplissy, J.: Measurement report: Introduction to the HyICE-2018 campaign for measurements of ice-nucleating particles and instrument inter-comparison in the Hyytiälä boreal forest, Atmos. Chem. Phys., 22, 5117–5145, https://doi.org/10.5194/acp-22-5117-2022, 2022.

Bressi, M., Cavalli, F., Putaud, J. P., Fröhlich, R., Petit, J.-E., Aas, W., Äijälä, M., Alastuey, A., Allan, J. D., Aurela, M., Berico, M., Bougiatioti, A., Bukowiecki, N., Canonaco, F., Crenn, V., Dusanter, S., Ehn, M., Elsasser, M., Flentje, H., Graf, P., Green, D. C., Heikkinen, L., Hermann, H., Holzinger, R., Hueglin, C., Keernik, H., Kiendler-Scharr, A., Kubelová, L., Lunder, C., Maasikmets, M., Makeš, O., Malaguti, A., Mihalopoulos, N., Nicolas, J. B., O'Dowd, C., Ovadnevaite, J., Petralia, E., Poulain, L., Priestman, M., Riffault, V., Ripoll, A., Schlag, P., Schwarz, J., Sciare, J., Slowik, J., Sosedova, Y.,

Stavroulas, I., Teinemaa, E., Via, M., Vodička, P., Williams, P. I., Wiedensohler, A., Young, D. E., Zhang, S., Favez, O., Minguillón, M. C., and Prevot, A. S. H.: A European aerosol phenomenology - 7: High-time resolution chemical characteristics of submicron particulate matter across Europe, Atmospheric Environment: X, 10, 100108, https://doi.org/10.1016/j.aeaoa.2021.100108, 2021.

Bühl, J., Seifert, P., Radenz, M., Baars, H., and Ansmann, A.: Ice crystal number concentration from lidar, cloud radar and radar wind profiler measurements, Atmos. Meas. Tech., 12, 6601–6617, https://doi.org/10.5194/amt-12-6601-2019, 2019.

Carlsson, P. T. M., Vereecken, L., Novelli, A., Bernard, F., Brown, S. S., Brownwood, B., Cho, C., Crowley, J. N., Dewald, P., Edwards, P. M., Friedrich, N., Fry, J. L., Hallquist, M., Hantschke, L., Hohaus, T., Kang, S., Liebmann, J., Mayhew, A. W., Mentel, T., Reimer, D., Rohrer, F., Shenolikar, J., Tillmann, R., Tsiligiannis, E., Wu, R., Wahner, A., Kiendler-Scharr, A., and Fuchs, H.: Comparison of isoprene chemical mechanisms under atmospheric night-time conditions in chamber experiments: evidence of hydroperoxy aldehydes and epoxy products from NO$_3$ oxidation, Atmos. Chem. Phys., 23, 3147–3180, https://doi.org/10.5194/acp-23-3147-2023, 2023.

Carmichael, G., Tarasova, O., Hov, H. Barrie, L. and Butler, J. Global atmospheric composition observations, the heart of vital climate and environmental action, Bull. Am. Met. Soc. 104, 3; 10.1175/BAMS-D-22-0016.1

Cavalli, F., Viana, M., Yttri, K. E., Genberg, J., and Putaud, J.-P.: Toward a standardised thermal-optical protocol for measuring atmospheric organic and elemental carbon: the EUSAAR protocol, Atmospheric Measurement Techniques, 3, 79–89, 2010.

Cavalli, F., Alastuey, A., Areskoug, H., Ceburnis, D., Čech, J., Genberg, J., Harrison, R. M., Jaffrezo, J. L., Kiss, G., Laj, P., Mihalopoulos, N., Perez, N., Quincey, P., Schwarz, J., Sellegri, K., Spindler, G., Swietlicki, E., Theodosi, C., Yttri, K. E., Aas, W., and Putaud, J. P.: A European aerosol phenomenology -4: Harmonized concentrations of carbonaceous aerosol at 10 regional background sites across Europe, Atmospheric Environment, 144, 133–145, https://doi.org/10.1016/j.atmosenv.2016.07.050, 2016.

Chaikovsky, A., Dubovik, O., Holben, B., Bril, A., Goloub, P., Tanré, D., Pappalardo, G., Wandinger, U., Chaikovskaya, L., Denisov, S., Grudo, J., Lopatin, A., Karol, Y., Lapyonok, T., Amiridis, V., Ansmann, A., Apituley, A., Allados-Arboledas, L.,

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Binietoglou, I., Boselli, A., D'Amico, G., Freudenthaler, V., Giles, D., Granados-Muñoz, M. J., Kokkalis, P., Nicolae, D., Oshchepkov, S., Papayannis, A., Perrone, M. R., Pietruczuk, A., Rocadenbosch, F., Sicard, M., Slutsker, I., Talianu, C., De Tomasi, F., Tsekeri, A., Wagner, J., and Wang, X.: Lidar-Radiometer Inversion Code (LIRIC) for the retrieval of vertical aerosol properties from combined lidar/radiometer data: development and distribution in EARLINET, Atmos. Meas. Tech., 9, 1181–1205, https://doi.org/10.5194/amt-9-1181-2016, 2016.

Chen, G., Canonaco, F., Tobler, A., Aas, W., Alastuey, A., Allan, J., Atabakhsh, S., Aurela, M., Baltensperger, U., Bougiatioti, A., De Brito, J. F., Ceburnis, D., Chazeau, B., Chebaicheb, H., Daellenbach, K. R., Ehn, M., El Haddad, I., Eleftheriadis, K., Favez, O., Flentje, H., Font, A., Fossum, K., Freney, E., Gini, M., Green, D. C., Heikkinen, L., Herrmann, H., Kalogridis, A.-C., Keernik, H., Lhotka, R., Lin, C., Lunder, C., Maasikmets, M., Manousakas, M. I., Marchand, N., Marin, C., Marmureanu, L., Mihalopoulos, N., Močnik, G., Nęcki, J., O'Dowd, C., Ovadnevaite, J., Peter, T., Petit, J.-E., Pikridas, M., Matthew Platt, S., Pokorná, P., Poulain, L., Priestman, M., Riffault, V., Rinaldi, M., Różański, K., Schwarz, J., Sciare, J., Simon, L., Skiba, A., Slowik, J. G., Sosedova, Y., Stavroulas, I., Styszko, K., Teinemaa, E., Timonen, H., Tremper, A., Vasilescu, J., Via, M., Vodička, P., Wiedensohler, A., Zografou, O., Cruz Minguillón, M., and Prévôt, A. S. H.: European aerosol phenomenology − 8: Harmonised source apportionment of organic aerosol using 22 Year-long ACSM/AMS datasets, Environment International, 166, 107325, https://doi.org/10.1016/j.envint.2022.107325, 2022.

Clemente, Á., Yubero, E., Nicolás, J. F., Caballero, S., Crespo, J., and Galindo, N.: Changes in the concentration and composition of urban aerosols during the COVID-19 lockdown, Environmental Research, 203, 111788, https://doi.org/10.1016/j.envres.2021.111788, 2022.

Collaud Coen, M., Andrews, E., Asmi, A., Baltensperger, U., Bukowiecki, N., Day, D., Fiebig, M., Fjaeraa, A. M., Flentje, H., Hyvärinen, A., Jefferson, A., Jennings, S. G., Kouvarakis, G., Lihavainen, H., Lund Myhre, C., Malm, W. C., Mihapopoulos, N., Molenar, J. V., O'Dowd, C., Ogren, J. A., Schichtel, B. A., Sheridan, P., Virkkula, A., Weingartner, E., Weller, R., and Laj, P.: Aerosol decadal trends – Part 1: In-situ optical measurements at GAW and IMPROVE stations, Atmos. Chem. Phys., 13, 869–894, https://doi.org/10.5194/acp-13-869-2013, 2013.

Collaud Coen, M., Andrews, E., Alastuey, A., Arsov, T. P., Backman, J., Brem, B. T., Bukowiecki, N., Couret, C., Eleftheriadis, K., Flentje, H., Fiebig, M., Gysel-Beer, M., Hand, J. L., Hoffer, A., Hooda, R., Hueglin, C., Joubert, W., Keywood, M., Kim, J. E., Kim, S.-W., Labuschagne, C., Lin, N.-H., Lin, Y., Lund Myhre, C., Luoma, K., Lyamani, H., Marinoni, A., Mayol-Bracero, O. L., Mihalopoulos, N., Pandolfi, M., Prats, N., Prenni, A. J., Putaud, J.-P., Ries, L., Reisen, F., Sellegri, K., Sharma, S., Sheridan, P., Sherman, J. P., Sun, J., Titos, G., Torres, E., Tuch, T., Weller, R., Wiedensohler, A., Zieger, P., and Laj, P.: Multidecadal trend analysis of in situ aerosol radiative properties around the world, Atmos. Chem. Phys., 20, 8867–8908, https://doi.org/10.5194/acp-20-8867-2020, 2020.

Crenn, V., Sciare, J., Croteau, P. L., Verlhac, S., Fröhlich, R., Belis, C. A., Aas, W., Äijälä, M., Alastuey, A., Artiñano, B., Baisnée, D., Bonnaire, N., Bressi, M., Canagaratna, M., Canonaco, F., Carbone, C., Cavalli, F., Coz, E., Cubison, M. J., Esser-Gietl, J. K., Green, D. C., Gros, V., Heikkinen, L., Herrmann, H., Lunder, C., Minguillón, M. C., Močnik, G., O'Dowd, C. D., Ovadnevaite, J., Petit, J. E., Petralia, E., Poulain, L., Priestman, M., Riffault, V., Ripoll, A., Sarda-Estève, R., Slowik, J. G., Setyan, A., Wiedensohler, A., Baltensperger, U., Prévôt, A. S. H., Jayne, J. T., and Favez, O.: ACTRIS ACSM intercomparison – Part 1: Reproducibility of concentration and fragment results from 13 individual Quadrupole Aerosol Chemical Speciation Monitors (Q-ACSM) and consistency with co-located instruments, Atmospheric Measurement Techniques, 8, 5063–5087, https://doi.org/10.5194/amt-8-5063-2015, 2015.

Cristofanelli, P., Arduni, J., Serva, F., Calzolari, F., Bonasoni, P., Busetto, M., Maione, M., Sprenger, M., Trisolino, P., and Putero, D.: Negative ozone anomalies at a high mountain site in northern Italy during 2020: a possible role of COVID-19 lockdowns?, Environ. Res. Lett., 16, 074029, https://doi.org/10.1088/1748-9326/ac0B7a, 2021.

Cuesta-Mosquera, A., Mocnik, G., Drinovec, L., Muller, T., Pfeifer, S., Minguillon, M., Briel, B., Buckley, P., Dudoitis, V., Fernandez-Garcia, J., Fernandez-Amado, M., De Brito, J., Riffault, V., Flentje, H., Heffernan, E., Kalivitis, N., Kalogridis, A., Keernik, H., Marmureanu, L., Luoma, K., Marinoni, A., Pikridas, M., Schauer, G., Serfozo, N., Servomaa, H., Titos, G., Yus-Diez, J., Ziola, N., and Wiedensohler, A.: Intercomparison and characterization of 23 Aethalometers under laboratory and ambient air conditions:

procedures and unit-to-unit variabilities, ATMOSPHERIC MEASUREMENT TECHNIQUES, 14, 3195–3216, https://doi.org/10.5194/amt-14-3195-2021, 2021.

Dalsøren, S. B., Myhre, G., Hodnebrog, Ø., Myhre, C. L., Stohl, A., Pisso, I., Schwietzke, S., Höglund-Isaksson, L., Helmig, D., Reimann, S., Sauvage, S., Schmidbauer, N., Read, K. A., Carpenter, L. J., Lewis, A. C., Punjabi, S., and Wallasch, M.: Discrepancy between simulated and observed ethane and propanelevels explained by underestimated fossil emissions, Nature Geosci, 11, 178–184, https://doi.org/10.1038/s41561-018-0073-0, 2018.

D'Amico, G., Amodeo, A., Baars, H., Binietoglou, I., Freudenthaler, V., Mattis, I., Wandinger, U., and Pappalardo, G.: EARLINET Single Calculus Chain – overview on methodology and strategy, Atmos. Meas. Tech., 8, 4891–4916, https://doi.org/10.5194/amt-8-4891-2015, 2015.

Debevec, C., Sauvage, S., Gros, V., Sciare, J., Pikridas, M., Stavroulas, I., Salameh, T., Leonardis, T., Gaudion, V., Depelchin, L., Fronval, I., Sarda-Esteve, R., Baisnée, D., Bonsang, B., Savvides, C., Vrekoussis, M., and Locoge, N.: Origin and variability in volatile organic compounds observed at an Eastern Mediterranean background site (Cyprus), Atmos. Chem. Phys., 17, 11355–11388, https://doi.org/10.5194/acp-17-11355-2017, 2017.

DeMott, P. J., Möhler, O., Cziczo, D. J., Hiranuma, N., Petters, M. D., Petters, S. S., Belosi, F., Bingemer, H. G., Brooks, S. D., Budke, C., Burkert-Kohn, M., Collier, K. N., Danielczok, A., Eppers, O., Felgitsch, L., Garimella, S., Grothe, H., Herenz, P., Hill, T. C. J., Höhler, K., Kanji, Z. A., Kiselev, A., Koop, T., Kristensen, T. B., Krüger, K., Kulkarni, G., Levin, E. J. T., Murray, B. J., Nicosia, A., O'Sullivan, D., Peckhaus, A., Polen, M. J., Price, H. C., Reicher, N., Rothenberg, D. A., Rudich, Y., Santachiara, G., Schiebel, T., Schrod, J., Seifried, T. M., Stratmann, F., Sullivan, R. C., Suski, K. J., Szakáll, M., Taylor, H. P., Ullrich, R., Vergara-Temprado, J., Wagner, R., Whale, T. F., Weber, D., Welti, A., Wilson, T. W., Wolf, M. J., and Zenker, J.: The Fifth International Workshop on Ice Nucleation phase 2 (FIN-02): laboratory intercomparison of ice nucleation measurements, Atmos. Meas. Tech., 11, 6231–6257, https://doi.org/10.5194/amt-11-6231-2018, 2018.

Dorn, H.-P., Apodaca, R. L., Ball, S. M., Brauers, T., Brown, S. S., Crowley, J. N., Dubé, W. P., Fuchs, H., Häseler, R., Heitmann, U., Jones, R. L., Kiendler-Scharr, A., Labazan, I.,

Langridge, J. M., Meinen, J., Mentel, T. F., Platt, U., Pöhler, D., Rohrer, F., Ruth, A. A., Schlosser, E., Schuster, G., Shillings, A. J. L., Simpson, W. R., Thieser, J., Tillmann, R., Varma, R., Venables, D. S., and Wahner, A.: Intercomparison of NO_3 radical detection instruments in the atmosphere simulation chamber SAPHIR, Atmos. Meas. Tech., 6, 1111–1140, https://doi.org/10.5194/amt-6-1111-2013, 2013.

Doulgeris, K.-M., Komppula, M., Romakkaniemi, S., Hyvärinen, A.-P., Kerminen, V.-M., and Brus, D.: In situ cloud ground-based measurements in the Finnish sub-Arctic: intercomparison of three cloud spectrometer setups, Atmos. Meas. Tech., 13, 5129–5147, https://doi.org/10.5194/amt-13-5129-2020, 2020.

Doussin, J.-F., Fuchs, H., Kiendler-Scharr, A., Seakins, P., and Wenger, J. (Eds.): A Practical Guide to Atmospheric Simulation Chambers, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-031-22277-1, 2023.

Drinovec, L., Močnik, G., Zotter, P., Prévôt, A. S. H., Ruckstuhl, C., Coz, E., Rupakheti, M., Sciare, J., Müller, T., Wiedensohler, A., and Hansen, A. D. A.: The Aethalometer: an improved measurement of aerosol black carbon with real-time loading compensation, Atmos. Meas. Tech., 8, 1965–1979, https://doi.org/10.5194/amt-8-1965-2015, 2015.

Eleftheriadis, K., Gini, M. I., Diapouli, E., Vratolis, S., Vasilatou, V., Fetfatzis, P., and Manousakas, M. I.: Aerosol microphysics and chemistry reveal the COVID19 lockdown impact on urban air quality, Sci Rep, 11, 14477, https://doi.org/10.1038/s41598-021-93650-6, 2021.

Engelmann, R., Ansmann, A., Ohneiser, K., Griesche, H., Radenz, M., Hofer, J., Althausen, D., Dahlke,, S., Maturilli, M., Veselovskii, I., Jimenez, C., Wiesen, R., Baars, H., Bühl, J., Gebauer, H., Haarig, M., Seifert, P., Wandinger, U., Macke, A., Wildfire smoke, Arctic haze, and aerosol effects on mixed-phase and cirrus clouds over the North Pole region during MOSAiC: An introduction, Atmos. Chem. Phys., 21, 13397-13423, doi:10.5194/acp-21-13397-2021

ESFRI: Strategy Report on Research Infrastructures - Roadmap 2021, 2021.

Evangeliou, N., Platt, S. M., Eckhardt, S., Lund Myhre, C., Laj, P., Alados-Arboledas, L., Backman, J., Brem, B. T., Fiebig, M., Flentje, H., Marinoni, A., Pandolfi, M., Yus-Dìez, J., Prats, N., Putaud, J. P., Sellegri, K., Sorribas, M., Eleftheriadis, K., Vratolis, S., Wiedensohler, A., and Stohl, A.: Changes in black carbon emissions over Europe due to

COVID-19 lockdowns, Atmos. Chem. Phys., 21, 2675–2692, https://doi.org/10.5194/acp-21-2675-2021, 2021.

Fahey, D. W., Gao, R.-S., Möhler, O., Saathoff, H., Schiller, C., Ebert, V., Krämer, M., Peter, T., Amarouche, N., Avallone, L. M., Bauer, R., Bozóki, Z., Christensen, L. E., Davis, S. M., Durry, G., Dyroff, C., Herman, R. L., Hunsmann, S., Khaykin, S. M., Mackrodt, P., Meyer, J., Smith, J. B., Spelten, N., Troy, R. F., Vömel, H., Wagner, S., and Wienhold, F. G.: The AquaVIT-1 intercomparison of atmospheric water vapor measurement techniques, Atmos. Meas. Tech., 7, 3177–3213, https://doi.org/10.5194/amt-7-3177-2014, 2014.

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.

Floutsi, A. A., Baars, H., Engelmann, R., Althausen, D., Ansmann, A., Bohlmann, S., Heese, B., Hofer, J., Kanitz, T., Haarig, M., Ohneiser, K., Radenz, M., Seifert, P., Skupin, A., Yin, Z., Abdullaev, S. F., Komppula, M., Filioglou, M., Giannakaki, E., Stachlewska, I. S., Janicka, L., Bortoli, D., Marinou, E., Amiridis, V., Gialitaki, A., Mamouri, R.-E., Barja, B., and Wandinger, U.: DeLiAn – a growing collection of depolarization ratio, lidar ratio and Ångström exponent for different aerosol types and mixtures from ground-based lidar observations, Atmos. Meas. Tech., 16, 2353–2379, https://doi.org/10.5194/amt-16-2353-2023, 2023.

Franco, B., Blumenstock, T., Cho, C., Clarisse, L., Clerbaux, C., Coheur, P.-F., De Mazière, M., De Smedt, I., Dorn, H.-P., Emmerichs, T., Fuchs, H., Gkatzelis, G., Griffith, D. W. T., Gromov, S., Hannigan, J. W., Hase, F., Hohaus, T., Jones, N., Kerkweg, A., Kiendler-Scharr, A., Lutsch, E., Mahieu, E., Novelli, A., Ortega, I., Paton-Walsh, C., Pommier, M., Pozzer, A., Reimer, D., Rosanka, S., Sander, R., Schneider, M., Strong, K., Tillmann, R., Van Roozendael, M., Vereecken, L., Vigouroux, C., Wahner, A., and Taraborrelli, D.: Ubiquitous atmospheric production of organic acids mediated by cloud droplets, Nature, 593, 233–237, https://doi.org/10.1038/s41586-021-03462-x, 2021.

Freney, E., Zhang, Y., Croteau, P., Amodeo, T., Williams, L., Truong, F., Petit, J.-E., Sciare, J., Sarda-Esteve, R., Bonnaire, N., Arumae, T., Aurela, M., Bougiatioti, A., Mihalopoulos, N., Coz, E., Artinano, B., Crenn, V., Elste, T., Heikkinen, L., Poulain, L.,

Wiedensohler, A., Herrmann, H., Priestman, M., Alastuey, A., Stavroulas, I., Tobler, A., Vasilescu, J., Zanca, N., Canagaratna, M., Carbone, C., Flentje, H., Green, D., Maasikmets, M., Marmureanu, L., Minguillon, M. C., Prevot, A. S. H., Gros, V., Jayne, J., and Favez, O.: The second ACTRIS inter-comparison (2016) for Aerosol Chemical Speciation Monitors (ACSM): Calibration protocols and instrument performance evaluations, Aerosol Science and Technology, 53, 830–842, https://doi.org/10.1080/02786826.2019.1608901, 2019.

Fröhlich, R., Crenn, V., Setyan, A., Belis, C. A., Canonaco, F., Favez, O., Riffault, V., Slowik, J. G., Aas, W., Aijälä, M., Alastuey, A., Artiñano, B., Bonnaire, N., Bozzetti, C., Bressi, M., Carbone, C., Coz, E., Croteau, P. L., Cubison, M. J., Esser-Gietl, J. K., Green, D. C., Gros, V., Heikkinen, L., Herrmann, H., Jayne, J. T., Lunder, C. R., Minguillón, M. C., Močnik, G., O'Dowd, C. D., Ovadnevaite, J., Petralia, E., Poulain, L., Priestman, M., Ripoll, A., Sarda-Estève, R., Wiedensohler, A., Baltensperger, U., Sciare, J., and Prévôt, A. S. H.: ACTRIS ACSM intercomparison – Part 2: Intercomparison of ME-2 organic source apportionment results from 15 individual, co-located aerosol mass spectrometers, Atmospheric Measurement Techniques, 8, 2555–2576, https://doi.org/10.5194/amt-8-2555-2015, 2015.

Fuchs, H., Ball, S. M., Bohn, B., Brauers, T., Cohen, R. C., Dorn, H.-P., Dubé, W. P., Fry, J. L., Häseler, R., Heitmann, U., Jones, R. L., Kleffmann, J., Mentel, T. F., Müsgen, P., Rohrer, F., Rollins, A. W., Ruth, A. A., Kiendler-Scharr, A., Schlosser, E., Shillings, A. J. L., Tillmann, R., Varma, R. M., Venables, D. S., Villena Tapia, G., Wahner, A., Wegener, R., Wooldridge, P. J., and Brown, S. S.: Intercomparison of measurements of NO_2 concentrations in the atmosphere simulation chamber SAPHIR during the NO3Comp campaign, Atmos. Meas. Tech., 3, 21–37, https://doi.org/10.5194/amt-3-21-2010, 2010a.

Fuchs, H., Brauers, T., Dorn, H.-P., Harder, H., Häseler, R., Hofzumahaus, A., Holland, F., Kanaya, Y., Kajii, Y., Kubistin, D., Lou, S., Martinez, M., Miyamoto, K., Nishida, S., Rudolf, M., Schlosser, E., Wahner, A., Yoshino, A., and Schurath, U.: Technical Note: Formal blind intercomparison of HO_2 measurements in the atmosphere simulation chamber SAPHIR during the HOxComp campaign, Atmos. Chem. Phys., 10, 12233–12250, https://doi.org/10.5194/acp-10-12233-2010, 2010b.

Fuchs, H., Hofzumahaus, A., Rohrer, F., Bohn, B., Brauers, T., Dorn, H.-P., Häseler, R., Holland, F., Kaminski, M., Li, X., Lu, K., Nehr, S., Tillmann, R., Wegener, R., and Wahner, A.: Experimental evidence for efficient hydroxyl radical regeneration in isoprene oxidation, Nature Geosci, 6, 1023–1026, https://doi.org/10.1038/ngeo1964, 2013.

Fuchs, H., Novelli, A., Rolletter, M., Hofzumahaus, A., Pfannerstill, E., Kessel, S., Edtbauer, A., Williams, J., Michoud, V., Dusanter, S., Locoge, N., Zannoni, N., Gros, V., Truong, F., Sarda-Esteve, R., Cryer, D., Brumby, C., Whalley, L., Stone, D., Seakins, P., Heard, D., Schoemaecker, C., Blocquet, M., Coudert, S., Batut, S., Fittschen, C., Thames, A., Brune, W., Ernest, C., Harder, H., Muller, J., Elste, T., Kubistin, D., Andres, S., Bohn, B., Hohaus, T., Holland, F., Li, X., Rohrer, F., Kiendler-Scharr, A., Tillmann, R., Wegener, R., Yu, Z., Zou, Q., and Wahner, A.: Comparison of OH reactivity measurements in the atmospheric simulation chamber SAPHIR, ATMOSPHERIC MEASUREMENT TECHNIQUES, 10, 4023–4053, https://doi.org/10.5194/amt-10-4023-2017, 2017.

Gagné, S., Lehtipalo, K., Manninen, H. E., Nieminen, T., Schobesberger, S., Franchin, A., Yli-Juuti, T., Boulon, J., Sonntag, A., Mirme, S., Mirme, A., Hõrrak, U., Petäjä, T., Asmi, E., and Kulmala, M.: Intercomparison of air ion spectrometers: an evaluation of results in varying conditions, Atmos. Meas. Tech., 4, 805–822, https://doi.org/10.5194/amt-4-805-2011, 2011.

GCOS: The Status of the Global Climate Observing System 2021, WMO, Geneva, 2021.

Gialitaki, A., Tsekeri, A., Amiridis, V., Ceolato, R., Paulien, L., Kampouri, A., Gkikas, A., Solomos, S., Marinou, E., Haarig, M., Baars, H., Ansmann, A., Lapyonok, T., Lopatin, A., Dubovik, O., Groß, S., Wirth, M., Tsichla, M., Tsikoudi, I., and Balis, D.: Is the near-spherical shape the "new black" for smoke?, Atmos. Chem. Phys., 20, 14005–14021, https://doi.org/10.5194/acp-20-14005-2020, 2020.

Gierens, R., Kneifel, S., Shupe, M. D., Ebell, K., Maturilli, M., and Löhnert, U.: Low-level mixed-phase clouds in a complex Arctic environment, Atmos. Chem. Phys., 20, 3459–3481, https://doi.org/10.5194/acp-20-3459-2020, 2020.

Glowania, M., Rohrer, F., Dorn, H.-P., Hofzumahaus, A., Holland, F., Kiendler-Scharr, A., Wahner, A., and Fuchs, H.: Comparison of formaldehyde measurements by Hantzsch, CRDS and DOAS in the SAPHIR chamber, Atmos. Meas. Tech., 14, 4239–4253, https://doi.org/10.5194/amt-14-4239-2021, 2021.

Granados-Muñoz, M. J., Sicard, M., Román, R., Benavent-Oltra, J. A., Barragán, R., Brogniez, G., Denjean, C., Mallet, M., Formenti, P., Torres, B., and Alados-Arboledas, L.: Impact of mineral dust on shortwave and longwave radiation: evaluation of different vertically resolved parameterizations in 1-D radiative transfer computations, Atmos. Chem. Phys., 19, 523–542, https://doi.org/10.5194/acp-19-523-2019, 2019.

Helmig, D., Rossabi, S., Hueber, J., Tans, P., Montzka, S. A., Masarie, K., Thoning, K., Plass-Duelmer, C., Claude, A., Carpenter, L. J., Lewis, A. C., Punjabi, S., Reimann, S., Vollmer, M. K., Steinbrecher, R., Hannigan, J. W., Emmons, L. K., Mahieu, E., Franco, B., Smale, D., and Pozzer, A.: Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production, Nature Geosci, 9, 490–495, https://doi.org/10.1038/ngeo2721, 2016.

Hoerger, C. C., Claude, A., Plass-Duelmer, C., Reimann, S., Eckart, E., Steinbrecher, R., Aalto, J., Arduini, J., Bonnaire, N., Cape, J. N., Colomb, A., Connolly, R., Diskova, J., Dumitrean, P., Ehlers, C., Gros, V., Hakola, H., Hill, M., Hopkins, J. R., Jäger, J., Junek, R., Kajos, M. K., Klemp, D., Leuchner, M., Lewis, A. C., Locoge, N., Maione, M., Martin, D., Michl, K., Nemitz, E., O'Doherty, S., Pérez Ballesta, P., Ruuskanen, T. M., Sauvage, S., Schmidbauer, N., Spain, T. G., Straube, E., Vana, M., Vollmer, M. K., Wegener, R., and Wenger, A.: ACTRIS non-methane hydrocarbon intercomparison experiment in Europe to support WMO GAW and EMEP observation networks, Atmos. Meas. Tech., 8, 2715–2736, https://doi.org/10.5194/amt-8-2715-2015, 2015.

Holzinger, R.: PTRwid: A new widget tool for processing PTR-TOF-MS data, Atmos. Meas. Tech., 8, 3903–3922, https://doi.org/10.5194/amt-8-3903-2015, 2015.

Holzinger, R., Acton, W. J. F., Bloss, W. J., Breitenlechner, M., Crilley, L. R., Dusanter, S., Gonin, M., Gros, V., Keutsch, F. N., Kiendler-Scharr, A., Kramer, L. J., Krechmer, J. E., Languille, B., Locoge, N., Lopez-Hilfiker, F., Materić, D., Moreno, S., Nemitz, E., Quéléver, L. L. J., Sarda Esteve, R., Sauvage, S., Schallhart, S., Sommariva, R., Tillmann, R., Wedel, S., Worton, D. R., Xu, K., and Zaytsev, A.: Validity and limitations of simple reaction kinetics to calculate concentrations of organic compounds from ion counts in PTR-MS, Atmos. Meas. Tech., 12, 6193–6208, https://doi.org/10.5194/amt-12-6193-2019, 2019.

Iinuma, Y., Böge, O., Gnauk, T., and Herrmann, H.: Aerosol-chamber study of the α-pinene/O_3 reaction: influence of particle acidity on aerosol yields and products,

Atmospheric Environment, 38, 761–773, https://doi.org/10.1016/j.atmosenv.2003.10.015, 2004.

Iinuma, Y., Böge, O., Kahnt, A., and Herrmann, H.: Laboratory chamber studies on the formation of organosulfates from reactive uptake of monoterpene oxides, Phys. Chem. Chem. Phys., 11, 7985, https://doi.org/10.1039/b904025k, 2009.

Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Brooks, M. E., Delanoé, J., Donovan, D. P., Eastment, J. D., Gaussiat, N., Goddard, J. W. F., Haeffelin, M., Baltink, H. K., Krasnov, O. A., Pelon, J., Piriou, J.-M., Protat, A., Russchenberg, H. W. J., Seifert, A., Tompkins, A. M., Van Zadelhoff, G.-J., Vinit, F., Willén, U., Wilson, D. R., and Wrench, C. L.: Cloudnet, Bulletin of the American Meteorological Society, 88, 883–898, https://doi.org/10.1175/BAMS-88-6-883, 2007.

Illmann, N., Gibilisco, R. G., Bejan, I. G., Patroescu-Klotz, I., and Wiesen, P.: Atmospheric oxidation of α,β-unsaturated ketones: kinetics and mechanism of the OH radical reaction , Atmos. Chem. Phys., 21, 13667–13686, https://doi.org/10.5194/acp-21-13667-2021, 2021.

Illmann, N., Patroescu-Klotz, I., and Wiesen, P.: Organic acid formation in the gas-phase ozonolysis of α,β-unsaturated ketones, Phys. Chem. Chem. Phys., 25, 106–116, https://doi.org/10.1039/D2CP03210D, 2023.

Jokinen, T., Lehtipalo, K., Thakur, R. C., Ylivinkka, I., Neitola, K., Sarnela, N., Laitinen, T., Kulmala, M., Petäjä, T., and Sipilä, M.: Measurement report: Long-term measurements of aerosol precursor concentrations in the Finnish subarctic boreal forest, Atmos. Chem. Phys., 22, 2237–2254, https://doi.org/10.5194/acp-22-2237-2022, 2022.

Kajos, M. K., Rantala, P., Hill, M., Hellén, H., Aalto, J., Patokoski, J., Taipale, R., Hoerger, C. C., Reimann, S., Ruuskanen, T. M., Rinne, J., and Petäjä, T.: Ambient measurements of aromatic and oxidized VOCs by PTR-MS and GC-MS: intercomparison between four instruments in a boreal forest in Finland, Atmos. Meas. Tech., 8, 4453–4473, https://doi.org/10.5194/amt-8-4453-2015, 2015.

Kalberer, M., Paulsen, D., Sax, M., Steinbacher, M., Dommen, J., Prevot, A. S. H., Fisseha, R., Weingartner, E., Frankevich, V., Zenobi, R., and Baltensperger, U.: Identification of Polymers as Major Components of Atmospheric Organic Aerosols, Science, 303, 1659–1662, https://doi.org/10.1126/science.1092185, 2004.

Kalesse-Los, H., Schimmel, W., Luke, E., and Seifert, P.: Evaluating cloud liquid detection against Cloudnet using cloud radar Doppler spectra in a pre-trained artificial neural network, Atmos. Meas. Tech., 15, 279–295, https://doi.org/10.5194/amt-15-279-2022, 2022.

Kaltsonoudis, C., Kostenidou, E., Louvaris, E., Psichoudaki, M., Tsiligiannis, E., Florou, K., Liangou, A., and Pandis, S. N.: Characterization of fresh and aged organic aerosol emissions from meat charbroiling, Atmos. Chem. Phys., 17, 7143–7155, https://doi.org/10.5194/acp-17-7143-2017, 2017.

Kangasluoma, J., Hering, S., Picard, D., Lewis, G., Enroth, J., Korhonen, F., Kulmala, M., Sellegri, K., Attoui, M., and Petäjä, T.: Characterization of three new condensation particle counters for sub-3 nm particle detection during the Helsinki CPC workshop: the ADI versatile water CPC, TSI 3777 nano enhancer and boosted TSI 3010, Atmos. Meas. Tech., 10, 2271–2281, https://doi.org/10.5194/amt-10-2271-2017, 2017.

Kappelt, N., Russell, H. S., Kwiatkowski, S., Afshari, A., and Johnson, M. S.: Correlation of Respiratory Aerosols and Metabolic Carbon Dioxide, Sustainability, 13, 12203, https://doi.org/10.3390/su132112203, 2021.

Kneifel, S. and Moisseev, D.: Long-Term Statistics of Riming in Nonconvective Clouds Derived from Ground-Based Doppler Cloud Radar Observations, Journal of the Atmospheric Sciences, 77, 3495–3508, https://doi.org/10.1175/JAS-D-20-0007.1, 2020.

Kodros, J. K., Papanastasiou, D. K., Paglione, M., Masiol, M., Squizzato, S., Florou, K., Skyllakou, K., Kaltsonoudis, C., Nenes, A., and Pandis, S. N.: Rapid dark aging of biomass burning as an overlooked source of oxidized organic aerosol, Proc. Natl. Acad. Sci. U.S.A., 117, 33028–33033, https://doi.org/10.1073/pnas.2010365117, 2020.

Kreher, K., Van Roozendael, M., Hendrick, F., Apituley, A., Dimitropoulou, E., Frieß, U., Richter, A., Wagner, T., Lampel, J., Abuhassan, N., Ang, L., Anguas, M., Bais, A., Benavent, N., Bösch, T., Bognar, K., Borovski, A., Bruchkouski, I., Cede, A., Chan, K. L., Donner, S., Drosoglou, T., Fayt, C., Finkenzeller, H., Garcia-Nieto, D., Gielen, C., Gómez-Martín, L., Hao, N., Henzing, B., Herman, J. R., Hermans, C., Hoque, S., Irie, H., Jin, J., Johnston, P., Khayyam Butt, J., Khokhar, F., Koenig, T. K., Kuhn, J., Kumar, V., Liu, C., Ma, J., Merlaud, A., Mishra, A. K., Müller, M., Navarro-Comas, M., Ostendorf, M., Pazmino, A., Peters, E., Pinardi, G., Pinharanda, M., Piters, A., Platt, U.,

Postylyakov, O., Prados-Roman, C., Puentedura, O., Querel, R., Saiz-Lopez, A., Schönhardt, A., Schreier, S. F., Seyler, A., Sinha, V., Spinei, E., Strong, K., Tack, F., Tian, X., Tiefengraber, M., Tirpitz, J.-L., van Gent, J., Volkamer, R., Vrekoussis, M., Wang, S., Wang, Z., Wenig, M., Wittrock, F., Xie, P. H., Xu, J., Yela, M., Zhang, C., and Zhao, X., Intercomparison of NO2, O4, O3 and HCHO slant column measurements by MAX-DOAS and zenith-sky UV–visible spectrometers during CINDI-2, Atmospheric Measurement Techniques, 13, 2169–2208, https://doi.org/10.5194/amt-13-2169-2020, 2020.

Kristensen, K., Jensen, L. N., Glasius, M., and Bilde, M.: The effect of sub-zero temperature on the formation and composition of secondary organic aerosol from ozonolysis of alpha-pinene, Environ. Sci.: Processes Impacts, 19, 1220–1234, https://doi.org/10.1039/C7EM00231A, 2017.

Kulmala, M., Cai, R., Ezhova, E., Deng, C., Stolzenburg, D., Dada, L., Guo, Y., Yan, C., Peräkylä, O., Lintunen, A., Nieminen, T., Kokkonen, T. V., Sarnela, N., Petäjä, T., and Kerminen, V.-M.: Direct link between the characteristics of atmospheric new particle formation and Continental Biosphere-Atmosphere-Cloud-Climate (COBACC) feedback loop, Boreal Environment Research, 28, 1–13, 2023.

Lacher, L., Clemen, H.-C., Shen, X., Mertes, S., Gysel-Beer, M., Moallemi, A., Steinbacher, M., Henne, S., Saathoff, H., Möhler, O., Höhler, K., Schiebel, T., Weber, D., Schrod, J., Schneider, J., and Kanji, Z. A.: Sources and nature of ice-nucleating particles in the free troposphere at Jungfraujoch in winter 2017, Atmos. Chem. Phys., 21, 16925–16953, https://doi.org/10.5194/acp-21-16925-2021, 2021.

Laj, P., Bigi, A., Rose, C., Andrews, E., Lund Myhre, C., Collaud Coen, M., Lin, Y., Wiedensohler, A., Schulz, M., Ogren, J. A., Fiebig, M., Gliß, J., Mortier, A., Pandolfi, M., Petäjä, T., Kim, S.-W., Aas, W., Putaud, J.-P., Mayol-Bracero, O., Keywood, M., Labrador, L., Aalto, P., Ahlberg, E., Alados Arboledas, L., Alastuey, A., Andrade, M., Artíñano, B., Ausmeel, S., Arsov, T., Asmi, E., Backman, J., Baltensperger, U., Bastian, S., Bath, O., Beukes, J. P., Brem, B. T., Bukowiecki, N., Conil, S., Couret, C., Day, D., Dayantolis, W., Degorska, A., Eleftheriadis, K., Fetfatzis, P., Favez, O., Flentje, H., Gini, M. I., Gregorič, A., Gysel-Beer, M., Hallar, A. G., Hand, J., Hoffer, A., Hueglin, C., Hooda, R. K., Hyvärinen, A., Kalapov, I., Kalivitis, N., Kasper-Giebl, A., Kim, J. E., Kouvarakis, G., Kranjc, I., Krejci, R., Kulmala, M., Labuschagne, C., Lee, H.-J.,

Lihavainen, H., Lin, N.-H., Löschau, G., Luoma, K., Marinoni, A., Martins Dos Santos, S., Meinhardt, F., Merkel, M., Metzger, J.-M., Mihalopoulos, N., Nguyen, N. A., Ondracek, J., Pérez, N., Perrone, M. R., Petit, J.-E., Picard, D., Pichon, J.-M., Pont, V., Prats, N., Prenni, A., Reisen, F., Romano, S., Sellegri, K., Sharma, S., Schauer, G., Sheridan, P., Sherman, J. P., Schütze, M., Schwerin, A., Sohmer, R., Sorribas, M., Steinbacher, M., Sun, J., Titos, G., et al.: A global analysis of climate-relevant aerosol properties retrieved from the network of Global Atmosphere Watch (GAW) near-surface observatories, Atmos. Meas. Tech., 13, 4353–4392, https://doi.org/10.5194/amt-13-4353-2020, 2020.

Lehtipalo, K., Ahonen, L. R., Baalbaki, R., Sulo, J., Chan, T., Laurila, T., Dada, L., Duplissy, J., Miettinen, E., Vanhanen, J., Kangasluoma, J., Kulmala, M., Petäjä, T., and Jokinen, T.: The standard operating procedure for Airmodus Particle Size Magnifier and nano-Condensation Nucleus Counter, Journal of Aerosol Science, 159, 105896, https://doi.org/10.1016/j.jaerosci.2021.105896, 2022.

Leskinen, A., Yli-Pirilä, P., Kuuspalo, K., Sippula, O., Jalava, P., Hirvonen, M.-R., Jokiniemi, J., Virtanen, A., Komppula, M., and Lehtinen, K. E. J.: Characterization and testing of a new environmental chamber, Atmos. Meas. Tech., 8, 2267–2278, https://doi.org/10.5194/amt-8-2267-2015, 2015.

Lieke, K. I., Kristensen, T. B., Korsholm, U. S., Sørensen, J. H., Kandler, K., Weinbruch, S., Ceburnis, D., Ovadnevaite, J., O'Dowd, C. D., and Bilde, M.: Characterization of volcanic ash from the 2011 Grímsvötn eruption by means of single-particle analysis, Atmospheric Environment, 79, 411–420, https://doi.org/10.1016/j.atmosenv.2013.06.044, 2013.

Myhre, C. L., Fiebig, M., Rud, R.O., Mona, L., Dema, C., Pascal, N., Henry, P., Picquet-Varrault, B., Brissebrat, G., Boonne, C., O'Connor, E., Tukiainen, S. (2023). The FAIRness of ACTRIS. (NILU rapport 7/2023). ISBN: 978-82-425-3117-9, Kjeller: NILU.

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, https://doi.org/10.1029/97GL00920, 1997.

Mamouri, R.-E. and Ansmann, A.: Potential of polarization/Raman lidar to separate fine dust, coarse dust, maritime, and anthropogenic aerosol profiles, Atmos. Meas. Tech., 10, 3403–3427, https://doi.org/10.5194/amt-10-3403-2017, 2017.

Manninen, A. J., Marke, T., Tuononen, M., and O'Connor, E. J.: Atmospheric Boundary Layer Classification With Doppler Lidar, JGR Atmospheres, 123, 8172–8189, https://doi.org/10.1029/2017JD028169, 2018.

Manninen, H. E., Mirme, S., Mirme, A., Petäjä, T., and Kulmala, M.: How to reliably detect molecular clusters and nucleation mode particles withNeutral cluster and Air Ion Spectrometer (NAIS), Atmos. Meas. Tech., 9, 3577–3605, https://doi.org/10.5194/amt-9-3577-2016, 2016.

Marinou, E., Tesche, M., Nenes, A., Ansmann, A., Schrod, J., Mamali, D., Tsekeri, A., Pikridas, M., Baars, H., Engelmann, R., Voudouri, K.-A., Solomos, S., Sciare, J., Groß, S., Ewald, F., and Amiridis, V.: Retrieval of ice-nucleating particle concentrations from lidar observations and comparison with UAV in situ measurements, Atmos. Chem. Phys., 19, 11315–11342, https://doi.org/10.5194/acp-19-11315-2019, 2019.

Massabò, D., Danelli, S. G., Brotto, P., Comite, A., Costa, C., Di Cesare, A., Doussin, J. F., Ferraro, F., Formenti, P., Gatta, E., Negretti, L., Oliva, M., Parodi, F., Vezzulli, L., and Prati, P.: ChAMBRe: a new atmospheric simulation chamber for aerosol modelling and bio-aerosol research, Atmos. Meas. Tech., 11, 5885–5900, https://doi.org/10.5194/amt-11-5885-2018, 2018.

Mayer, L., Degrendele, C. enk, P., Kohoutek, J., Pribylovà, P., Kukuƒçka, P., Melymuk, L., Durand, A., Ravier, S., Alastuey, A., Baker, A., R., Baltensperger, U., Baumann-Stanzer, K., Biermann, T., Bohlin-Nizzetto, P., Ceburnis, D., Conil, S., Couret, C., Deg√≥rska, A., Diapouli, E., Eckhardt, S., Eleftheriadis, K., Forster, G., L., Freier, K., Gheusi, F., Gini, M., Hellèn, H.,Henne, S., Herrmann, H., Holubovà Smejkalovà, A., Hürrak, U., Hüeglin, C., Junninen, H., Kristensson, A., Langrene, L., Levula, J., Lothon, M., Ludewig, E., Makkonen, U., Matejovicovà, J., Mihalopoulos, N., Minàrikovà, V., Moche, W., Noe, S., M., Pèrez, N., Petäjä, T., Pont, V., Poulain, L., Quivet, E., Ratz, G., Rehm, T., Reimann, S., Simmons, I., Sonke, J., E., Sorribas, M., Spoor, R., Swart, D., P. J., Vasilatou, V., Wortham, H.,Yela, M., Zarmpas, P., Zellweger, Fägi, C., Torseth, K., Laj, P., Klànovà, J., Lammel, G., Widespread Pesticide Distribution in the European Atmosphere Questions their Degradability in Air, Environ. https://doi.org/10.1021/acs.est.3c08488

Mbengue, S., Vodička, P., Komínková, K., Zíková, N., Schwarz, J., Prokeš, R., Suchánková, L., Julaha, K., Ondráček, J., Holoubek, I., and Ždímal, V.: Different approaches to explore the impact of COVID-19 lockdowns on carbonaceous aerosols at a European rural background site, Science of The Total Environment, 892, 164527, https://doi.org/10.1016/j.scitotenv.2023.164527, 2023.

McFiggans, G., Mentel, T. F., Wildt, J., Pullinen, I., Kang, S., Kleist, E., Schmitt, S., Springer, M., Tillmann, R., Wu, C., Zhao, D., Hallquist, M., Faxon, C., Le Breton, M., Hallquist, Å. M., Simpson, D., Bergström, R., Jenkin, M. E., Ehn, M., Thornton, J. A., Alfarra, M. R., Bannan, T. J., Percival, C. J., Priestley, M., Topping, D., and Kiendler-Scharr, A.: Secondary organic aerosol reduced by mixture of atmospheric vapours, Nature, 565, 587–593, https://doi.org/10.1038/s41586-018-0871-y, 2019.

Müller, D., Böckmann, C., Kolgotin, A., Schneidenbach, L., Chemyakin, E., Rosemann, J., Znak, P., and Romanov, A.: Microphysical particle properties derived from inversion algorithms developed in the framework of EARLINET, Atmos. Meas. Tech., 9, 5007–5035, https://doi.org/10.5194/amt-9-5007-2016, 2016.

Müller, T., Henzing, J. S., de Leeuw, G., Wiedensohler, A., Alastuey, A., Angelov, H., Bizjak, M., Collaud Coen, M., Engström, J. E., Gruening, C., Hillamo, R., Hoffer, A., Imre, K., Ivanow, P., Jennings, G., Sun, J. Y., Kalivitis, N., Karlsson, H., Komppula, M., Laj, P., Li, S.-M., Lunder, C., Marinoni, A., Martins dos Santos, S., Moerman, M., Nowak, A., Ogren, J. A., Petzold, A., Pichon, J. M., Rodriquez, S., Sharma, S., Sheridan, P. J., Teinilä, K., Tuch, T., Viana, M., Virkkula, A., Weingartner, E., Wilhelm, R., and Wang, Y. Q.: Characterization and intercomparison of aerosol absorption photometers: result of two intercomparison workshops, Atmospheric Measurement Techniques, 4, 245–268, https://doi.org/10.5194/amt-4-245-2011, 2011.

Mutzel, A., Poulain, L., Berndt, T., Iinuma, Y., Rodigast, M., Böge, O., Richters, S., Spindler, G., Sipilä, M., Jokinen, T., Kulmala, M., and Herrmann, H.: Highly Oxidized Multifunctional Organic Compounds Observed in Tropospheric Particles: A Field and Laboratory Study, Environ. Sci. Technol., 49, 7754–7761, https://doi.org/10.1021/acs.est.5b00885, 2015.

Möhler, O., Stetzer, O., Schaefers, S., Linke, C., Schnaiter, M., Tiede, R., Saathoff, H., Krämer, M., Mangold, A., Budz, P., Zink, P., Schreiner, J., Mauersberger, K., Haag, W., Kärcher, B., and Schurath, U.: Experimental investigation of homogeneous freezing of

sulphuric acid particles in the aerosol chamber AIDA, Atmos. Chem. Phys., 3, 211–223, https://doi.org/10.5194/acp-3-211-2003, 2003.

Nicolae, D., Vasilescu, J., Talianu, C., Binietoglou, I., Nicolae, V., Andrei, S., and Antonescu, B.: A neural network aerosol-typing algorithm based on lidar data, Atmos. Chem. Phys., 18, 14511–14537, https://doi.org/10.5194/acp-18-14511-2018, 2018.

Niedermeier, D., Voigtländer, J., Schmalfuß, S., Busch, D., Schumacher, J., Shaw, R. A., and Stratmann, F.: Characterization and first results from LACIS-T: a moist-air wind tunnel to study aerosol–cloud–turbulence interactions, Atmos. Meas. Tech., 13, 2015–2033, https://doi.org/10.5194/amt-13-2015-2020, 2020.

Nilsson, E. J. K., Eskebjerg, C., and Johnson, M. S.: A photochemical reactor for studies of atmospheric chemistry, Atmospheric Environment, 43, 3029–3033, https://doi.org/10.1016/j.atmosenv.2009.02.034, 2009.

Novelli, A., Vereecken, L., Bohn, B., Dorn, H.-P., Gkatzelis, G. I., Hofzumahaus, A., Holland, F., Reimer, D., Rohrer, F., Rosanka, S., Taraborrelli, D., Tillmann, R., Wegener, R., Yu, Z., Kiendler-Scharr, A., Wahner, A., and Fuchs, H.: Importance of isomerization reactions for OH radical regeneration from the photo-oxidation of isoprene investigated in the atmospheric simulation chamber SAPHIR, Atmos. Chem. Phys., 20, 3333–3355, https://doi.org/10.5194/acp-20-3333-2020, 2020.

Nowak, J. L., Grosz, R., Frey, W., Niedermeier, D., Mijas, J., Malinowski, S. P., Ort, L., Schmalfuß, S., Stratmann, F., Voigtländer, J., and Stacewicz, T.: Contactless optical hygrometry in LACIS-T, Atmos. Meas. Tech., 15, 4075–4089, https://doi.org/10.5194/amt-15-4075-2022, 2022.

Ohneiser, K., Ansmann, A., Chudnovsky, A., Engelmann, R., Ritter, C., Veselovskii, I., Baars, H., Gebauer, H., Griesche, H., Radenz, M., Hofer, J., Althausen, D., Dahlke, S., Maturilli, M., The unexpected smoke layer in the High Arctic winter stratosphere during MOSAiC 2019–2020, Atmos. Chem. Phys., 21, 15783-15808, doi:10.5194/acp-21-15783-2021

Ohneiser, K., Ansmann, A., Kaifler, B., Chudnovsky, A., Barja, B., Knopf, D. A., Kaifler, N., Baars, H., Seifert, P., Villanueva, D., Jimenez, C., Radenz, M., Engelmann, R., Veselovskii, I., Zamorano, F., Australian wildfire smoke in the stratosphere: The decay

phase in 2020/2021 and impact on ozone depletion, Atmos. Chem. Phys., 22, 7417–7442, doi:10.5194/acp-22-7417-2022

Ortiz-Amezcua, P., Bedoya-Velásquez, A. E., Benavent-Oltra, J. A., Pérez-Ramírez, D., Veselovskii, I., Castro-Santiago, M., Bravo-Aranda, J. A., Guedes, A., Guerrero-Rascado, J. L., and Alados-Arboledas, L.: Implementation of UV rotational Raman channel to improve aerosol retrievals from multiwavelength lidar, Opt. Express, 28, 8156, https://doi.org/10.1364/OE.383441, 2020.

Pandolfi, M., Alados-Arboledas, L., Alastuey, A., Andrade, M., Angelov, C., Artiñano, B., Backman, J., Baltensperger, U., Bonasoni, P., Bukowiecki, N., Collaud Coen, M., Conil, S., Coz, E., Crenn, V., Dudoitis, V., Ealo, M., Eleftheriadis, K., Favez, O., Fetfatzis, P., Fiebig, M., Flentje, H., Ginot, P., Gysel, M., Henzing, B., Hoffer, A., Holubova Smejkalova, A., Kalapov, I., Kalivitis, N., Kouvarakis, G., Kristensson, A., Kulmala, M., Lihavainen, H., Lunder, C., Luoma, K., Lyamani, H., Marinoni, A., Mihalopoulos, N., Moerman, M., Nicolas, J., O'Dowd, C., Petäjä, T., Petit, J.-E., Pichon, J. M., Prokopciuk, N., Putaud, J.-P., Rodríguez, S., Sciare, J., Sellegri, K., Swietlicki, E., Titos, G., Tuch, T., Tunved, P., Ulevicius, V., Vaishya, A., Vana, M., Virkkula, A., Vratolis, S., Weingartner, E., Wiedensohler, A., and Laj, P.: A European aerosol phenomenology – 6: scattering properties of atmospheric aerosol particles from 28 ACTRIS sites, Atmos. Chem. Phys., 18, 7877–7911, https://doi.org/10.5194/acp-18-7877-2018, 2018.

Pang, X., Lewis, A. C., Rickard, A. R., Baeza-Romero, M. T., Adams, T. J., Ball, S. M., Daniels, M. J. S., Goodall, I. C. A., Monks, P. S., Peppe, S., Ródenas García, M., Sánchez, P., and Muñoz, A.: A smog chamber comparison of a microfluidic derivatisation measurement of gas-phase glyoxal and methylglyoxal with other analytical techniques, Atmos. Meas. Tech., 7, 373–389, https://doi.org/10.5194/amt-7-373-2014, 2014.

Panopoulou, A., Liakakou, E., Sauvage, S., Gros, V., Locoge, N., Stavroulas, I., Bonsang, B., Gerasopoulos, E., and Mihalopoulos, N.: Yearlong measurements of monoterpenes and isoprene in a Mediterranean city (Athens): Natural vs anthropogenic origin, Atmospheric Environment, 243, 117803, https://doi.org/10.1016/j.atmosenv.2020.117803, 2020.

Papagiannopoulos, N., Mona, L., Amodeo, A., D'Amico, G., Gumà Claramunt, P., Pappalardo, G., Alados-Arboledas, L., Guerrero-Rascado, J. L., Amiridis, V., Kokkalis, P., Apituley, A., Baars, H., Schwarz, A., Wandinger, U., Binietoglou, I, Nicolae, D., Bortoli, D., Comerón, A., Rodríguez-Gómez, A., Sicard, M., Papayannis, A., and

Wiegner, M.: An automatic observation-based aerosol typing method for EARLINET, Atmos. Chem. Phys., 18, 15879–15901, https://doi.org/10.5194/acp-18-15879-2018, 2018.

Pappalardo, G., Mona, L., D'Amico, G., Wandinger, U., Adam, M., Amodeo, A., Ansmann, A., Apituley, A., Alados Arboledas, L., Balis, D., Boselli, A., Bravo-Aranda, J. A., Chaikovsky, A., Comeron, A., Cuesta, J., De Tomasi, F., Freudenthaler, V., Gausa, M., Giannakaki, E., Giehl, H., Giunta, A., Grigorov, I., Groß, S., Haeffelin, M., Hiebsch, A., Iarlori, M., Lange, D., Linné, H., Madonna, F., Mattis, I., Mamouri, R.-E., McAuliffe, M. A. P., Mitev, V., Molero, F., Navas-Guzman, F., Nicolae, D., Papayannis, A., Perrone, M. R., Pietras, C., Pietruczuk, A., Pisani, G., Preißler, J., Pujadas, M., Rizi, V., Ruth, A. A., Schmidt, J., Schnell, F., Seifert, P., Serikov, I., Sicard, M., Simeonov, V., Spinelli, N., Stebel, K., Tesche, M., Trickl, T., Wang, X., Wagner, F., Wiegner, M., and Wilson, K. M.: Four-dimensional distribution of the 2010 Eyjafjallajökull volcanic cloud over Europe observed by EARLINET, Atmos. Chem. Phys., 13, 4429–4450, https://doi.org/10.5194/acp-13-4429-2013, 2013.

Pappalardo, G., Amodeo, A., Apituley, A., Comeron, A., Freudenthaler, V., Linné, H., Ansmann, A., Bösenberg, J., D'Amico, G., Mattis, I., Mona, L., Wandinger, U., Amiridis, V., Alados-Arboledas, L., Nicolae, D., and Wiegner, M.: EARLINET: towards an advanced sustainable European aerosol lidar network, Atmos. Meas. Tech., 7, 2389–2409, https://doi.org/10.5194/amt-7-2389-2014, 2014.

Petäjä, T., Tabakova, K., Manninen, A., Ezhova, E., O'Connor, E., Moisseev, D., Sinclair, V. A., Backman, J., Levula, J., Luoma, K., Virkkula, A., Paramonov, M., 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, https://doi.org/10.1038/s41561-021-00876-0, 2022.

Petetin, H., Bowdalo, D., Soret, A., Guevara, M., Jorba, O., Serradell, K., and Pérez García-Pando, C.: Meteorology-normalized impact of the COVID-19 lockdown upon NO<sub>2</sub> pollution in Spain, Atmos. Chem. Phys., 20, 11119–11141, https://doi.org/10.5194/acp-20-11119-2020, 2020.

Petit, J.-E., Dupont, J.-C., Favez, O., Gros, V., Zhang, Y., Sciare, J., Simon, L., Truong, F., Bonnaire, N., Amodeo, T., Vautard, R., and Haeffelin, M.: Response of atmospheric

composition to COVID-19 lockdown measures during spring in the Paris region (France), Atmos. Chem. Phys., 21, 17167–17183, https://doi.org/10.5194/acp-21-17167-2021, 2021.

Petzold, A., Bundke, U., Hienola, A., Laj, P., Lund Myhre, C., Vermeulen, A., Adamaki, A., Kutsch, W., Thouret, V., Boulanger, D., Fiebig, M., Stocker, M., Zhao, Z., and Asmi, A.: Opinion: New directions in atmospheric research offered by research infrastructures combined with open and data-intensive science, https://doi.org/10.5194/egusphere-2023-1423, 2023

Piel, F., Müller, M., Winkler, K., Skytte Af Sätra, J., and Wisthaler, A.: Introducing the extended volatility range proton-transfer-reaction mass spectrometer (EVR PTR-MS), Atmos. Meas. Tech., 14, 1355–1363, https://doi.org/10.5194/amt-14-1355-2021, 2021.

Platt, S. M., El Haddad, I., Zardini, A. A., Clairotte, M., Astorga, C., Wolf, R., Slowik, J. G., Temime-Roussel, B., Marchand, N., Ježek, I., Drinovec, L., Močnik, G., Möhler, O., Richter, R., Barmet, P., Bianchi, F., Baltensperger, U., and Prévôt, A. S. H.: Secondary organic aerosol formation from gasoline vehicle emissions in a new mobile environmental reaction chamber, Atmos. Chem. Phys., 13, 9141–9158, https://doi.org/10.5194/acp-13-9141-2013, 2013.

Poulain, L., Tilgner, A., Brüggemann, M., Mettke, P., He, L., Anders, J., Böge, O., Mutzel, A., and Herrmann, H.: Particle-Phase Uptake and Chemistry of Highly Oxygenated Organic Molecules (HOMs) From α -Pinene OH Oxidation, JGR Atmospheres, 127, e2021JD036414, https://doi.org/10.1029/2021JD036414, 2022.

Preißler, J., Martucci, G., Saponaro, G., Ovadnevaite, J., Vaishya, A., Kolmonen, P., Ceburnis, D., Sogacheva, L., De Leeuw, G., and O'Dowd, C.: Six years of surface remote sensing of stratiform warm clouds in marine and continental air over Mace Head, Ireland, JGR Atmospheres, 121, https://doi.org/10.1002/2016JD025360, 2016.

Putaud, J.-P., Raes, F., Van Dingenen, R., Brüggemann, E., Facchini, M. C., Decesari, S., Fuzzi, S., Gehrig, R., Hüglin, C., Laj, P., Lorbeer, G., Maenhaut, W., Mihalopoulos, N., Müller, K., Querol, X., Rodriguez, S., Schneider, J., Spindler, G., Brink, H. ten, Tørseth, K., and Wiedensohler, A.: A European aerosol phenomenology - 2: chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe, Atmospheric Environment, 38, 2579–2595, 2004.

Putaud, J.-P., Van Dingenen, R., Alastuey, A., Bauer, H., Birmili, W., Cyrys, J., Flentje, H., Fuzzi, S., Gehrig, R., Hansson, H.-C., Harrison, R. M., Herrmann, H., Hitzenberger, R., Hüglin, C., Jones, A. M., Kasper-Giebl, A., Kiss, G., Kousa, A., Kuhlbusch, T. A. J., Löschau, G., Maenhaut, W., Molnar, A., Moreno, T., Pekkanen, J., Perrino, C., Pitz, M., Puxbaum, H., Querol, X., Rodriguez, S., Salma, I., Schwarz, J., Smolik, J., Schneider, J., Spindler, G., ten Brink, H., Tursic, J., Viana, M., Wiedensohler, A., and Raes, F.: A European aerosol phenomenology - 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe, Atmospheric Environment, 44, 1308–1320, 2010.

Putaud, J.-P., Pozzoli, L., Pisoni, E., Martins Dos Santos, S., Lagler, F., Lanzani, G., Dal Santo, U., and Colette, A.: Impacts of the COVID-19 lockdown on air pollution at regional and urban background sites in northern Italy, Atmos. Chem. Phys., 21, 7597–7609, https://doi.org/10.5194/acp-21-7597-2021, 2021.

Putaud, J.-P., Pisoni, E., Mangold, A., Hueglin, C., Sciare, J., Pikridas, M., Savvides, C., Ondracek, J., Mbengue, S., Wiedensohler, A., Weinhold, K., Merkel, M., Poulain, L., Van Pinxteren, D., Herrmann, H., Massling, A., Nordstroem, C., Alastuey, A., Reche, C., Pérez, N., Castillo, S., Sorribas, M., Adame, J. A., Petaja, T., Lehtipalo, K., Niemi, J., Riffault, V., De Brito, J. F., Colette, A., Favez, O., Petit, J.-E., Gros, V., Gini, M. I., Vratolis, S., Eleftheriadis, K., Diapouli, E., Denier Van Der Gon, H., Yttri, K. E., and Aas, W.: Impact of 2020 COVID-19 lockdowns on particulate air pollution across Europe, Aerosols/Field Measurements/Troposphere/Physics (physical properties and processes), https://doi.org/10.5194/egusphere-2023-434, 2023.

Radenz, M., Bühl, J., Seifert, P., Baars, H., Engelmann, R., Barja González, B., Mamouri, R.-E., Zamorano, F., and Ansmann, A.: Hemispheric contrasts in ice formation in stratiform mixed-phase clouds: disentangling the role of aerosol and dynamics with ground-based remote sensing, Atmos. Chem. Phys., 21, 17969–17994, https://doi.org/10.5194/acp-21-17969-2021, 2021.

Ren, Y., Grosselin, B., Daële, V., and Mellouki, A.: Investigation of the reaction of ozone with isoprene, methacrolein and methyl vinyl ketone using the HELIOS chamber, Faraday Discuss., 200, 289–311, https://doi.org/10.1039/C7FD00014F, 2017.

Rohrer, F., Bohn, B., Brauers, T., Brüning, D., Johnen, F.-J., Wahner, A., and Kleffmann, J.: Characterisation of the photolytic HONO-source in the atmosphere simulation chamber

SAPHIR, Atmos. Chem. Phys., 5, 2189–2201, https://doi.org/10.5194/acp-5-2189-2005, 2005.

Roman, C., Arsene, C., Bejan, I. G., and Olariu, R. I.: Investigations into the gas-phase photolysis and OH radical kinetics of nitrocatechols: implications of intramolecular interactions on their atmospheric behaviour, Atmos. Chem. Phys., 22, 2203–2219, https://doi.org/10.5194/acp-22-2203-2022, 2022.

Rose, C., Foucart, B., Picard, D., Colomb, A., Metzger, J.-M., Tulet, P., and Sellegri, K.: New particle formation in the volcanic eruption plume of the Piton de la Fournaise: specific features from a long-term dataset, Atmos. Chem. Phys., 19, 13243–13265, https://doi.org/10.5194/acp-19-13243-2019, 2019.

Savadkoohi, M., Pandolfi, M., Reche, C., Niemi, J. V., Mooibroek, D., Titos, G., Green, D. C., Tremper, A. H., Hueglin, C., Liakakou, E., Mihalopoulos, N., Stavroulas, I., Artiñano, B., Coz, E., Alados-Arboledas, L., Beddows, D., Riffault, V., De Brito, J. F., Bastian, S., Baudic, A., Colombi, C., Costabile, F., Chazeau, B., Marchand, N., Gómez-Amo, J. L., Estellés, V., Matos, V., Van Der Gaag, E., Gille, G., Luoma, K., Manninen, H. E., Norman, M., Silvergren, S., Petit, J.-E., Putaud, J.-P., Rattigan, O. V., Timonen, H., Tuch, T., Merkel, M., Weinhold, K., Vratolis, S., Vasilescu, J., Favez, O., Harrison, R. M., Laj, P., Wiedensohler, A., Hopke, P. K., Petäjä, T., Alastuey, A., and Querol, X.: The variability of mass concentrations and source apportionment analysis of equivalent black carbon across urban Europe, Environment International, 178, 108081, https://doi.org/10.1016/j.envint.2023.108081, 2023.

Schemann, V. and Ebell, K.: Simulation of mixed-phase clouds with the ICON large-eddy model in the complex Arctic environment around Ny-Ålesund, Atmos. Chem. Phys., 20, 475–485, https://doi.org/10.5194/acp-20-475-2020, 2020.

Schlosser, E., Brauers, T., Dorn, H.-P., Fuchs, H., Häseler, R., Hofzumahaus, A., Holland, F., Wahner, A., Kanaya, Y., Kajii, Y., Miyamoto, K., Nishida, S., Watanabe, K., Yoshino, A., Kubistin, D., Martinez, M., Rudolf, M., Harder, H., Berresheim, H., Elste, T., Plass-Dülmer, C., Stange, G., and Schurath, U.: Technical Note: Formal blind intercomparison of OH measurements: results from the international campaign HOxComp, Atmos. Chem. Phys., 9, 7923–7948, https://doi.org/10.5194/acp-9-7923-2009, 2009.

Shang, X., Baars, H., Stachlewska, I. S., Mattis, I., and Komppula, M.: Pollen observations at four EARLINET stations during the ACTRIS-COVID-19 campaign, Atmos. Chem. Phys., 22, 3931–3944, https://doi.org/10.5194/acp-22-3931-2022, 2022.

Shao, Y., Wang, Y., Du, M., Voliotis, A., Alfarra, M. R., O'Meara, S. P., Turner, S. F., and McFiggans, G.: Characterisation of the Manchester Aerosol Chamber facility, Atmos. Meas. Tech., 15, 539–559, https://doi.org/10.5194/amt-15-539-2022, 2022.

Simon, L., Gros, V., Petit, J.-E., Truong, F., Sarda-Estève, R., Kalalian, C., Baudic, A., Marchand, C., and Favez, O.: Two years of volatile organic compound online in situ measurements at the Site Instrumental de Recherche par Télédétection Atmosphérique (Paris region, France) using proton-transfer-reaction mass spectrometry, Earth Syst. Sci. Data, 15, 1947–1968, https://doi.org/10.5194/essd-15-1947-2023, 2023.

Sulo, J., Sarnela, N., Kontkanen, J., Ahonen, L., Paasonen, P., Laurila, T., Jokinen, T., Kangasluoma, J., Junninen, H., Sipilä, M., Petäjä, T., Kulmala, M., and Lehtipalo, K.: Long-term measurement of sub-3 nm particles and their precursor gases in the boreal forest, Atmos. Chem. Phys., 21, 695–715, https://doi.org/10.5194/acp-21-695-2021, 2021.

Tirpitz, J.-L., U. Frieß, F. Hendrick, C. Alberti, M. Allaart, A. Apituley, A. Bais, S. Beirle, S. Berkhout, K. Bognar, T. Bösch, I. Bruchkouski, A. Cede, K.L. Chan, M. den Hoed, S. Donner, T. Drosoglou, C. Fayt, M.M. Friedrich, A. Frumau, L. Gast, C. Gielen, L. Gomez-Martín, N. Hao, A. Hensen, B. Henzing, C. Hermans, J. Jin, K. Kreher, J. Kuhn, J. Lampel, A. Li, C. Liu, H. Liu, J. Ma, A. Merlaud, E. Peters, G. Pinardi, A. Piters, U. Platt, O. Puentedura, A. Richter, S. Schmitt, E. Spinei, D. Stein Zweers, K. Strong, D. Swart, F. Tack, M. Tiefengraber, R. van der Hoff, M. van Roozendael, T. Vlemmix, J. Vonk, T. Wagner, Y. Wang, Z. Wang, M. Wenig, M. Wiegner, F. Wittrock, P. Xie, C. Xing, J. Xu, M. Yela, C. Zhang, and X. Zhao, Intercomparison of MAX-DOAS vertical profile retrieval algorithms: studies on field data from the CINDI-2 campaign, Atmospheric Measurement Techniques, 14, 1–35, https://doi.org/10.5194/amt-14-1-2021, 2021.

Thomas, M., France, J., Crabeck, O., Hall, B., Hof, V., Notz, D., Rampai, T., Riemenschneider, L., Tooth, O. J., Tranter, M., and Kaiser, J.: The Roland von Glasow Air-Sea-Ice Chamber (RvG-ASIC): an experimental facility for studying ocean–sea-ice–

atmosphere interactions, Atmos. Meas. Tech., 14, 1833–1849, https://doi.org/10.5194/amt-14-1833-2021, 2021.

Toledo, F., Haeffelin, M., Wærsted, E., and Dupont, J.-C.: A new conceptual model for adiabatic fog, Atmos. Chem. Phys., 21, 13099–13117, https://doi.org/10.5194/acp-21-13099-2021, 2021.

Tsekeri, A., Gialitaki, A., Di Paolantonio, M., Dionisi, D., Liberti, G. L., Fernandes, A., Szkop, A., Pietruczuk, A., Pérez-Ramírez, D., Granados Muñoz, M. J., Guerrero-Rascado, J. L., Alados-Arboledas, L., Bermejo Pantaleón, D., Bravo-Aranda, J. A., Kampouri, A., Marinou, E., Amiridis, V., Sicard, M., Comerón, A., Muñoz-Porcar, C., Rodríguez-Gómez, A., Romano, S., Perrone, M. R., Shang, X., Komppula, M., Mamouri, R.-E., Nisantzi, A., Hadjimitsis, D., Navas-Guzmán, F., Haefele, A., Szczepanik, D., Tomczak, A., Stachlewska, I. S., Belegante, L., Nicolae, D., Voudouri, K. A., Balis, D., Floutsi, A. A., Baars, H., Miladi, L., Pascal, N., Dubovik, O., and Lopatin, A.: Combined sun-photometer–lidar inversion: lessons learned during the EARLINET/ACTRIS COVID-19 campaign, Atmos. Meas. Tech., 16, 6025–6050, https://doi.org/10.5194/amt-16-6025-2023, 2023.

Van Dingenen, R., Raes, F., Putaud, J.-P., Baltensperger, U., Charron, A., Facchini, M.-C., Decesari, S., Fuzzi, S., Gehrig, R., Hansson, H.-C., Harrison, R. M., Hüglin, C., Jones, A. M., Laj, P., Lorbeer, G., Maenhaut, W., Palmgren, F., Querol, X., Rodriguez, S., Schneider, J., Brink, H. T., Tunved, P., Tørseth, K., Wehner, B., Weingartner, E., Wiedensohler, A., and Wåhlin, P.: A European aerosol phenomenology—1: physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe, Atmospheric Environment, 38, 2561–2577, https://doi.org/10.1016/j.atmosenv.2004.01.040, 2004.

Vereecken, L., Carlsson, P. T. M., Novelli, A., Bernard, F., Brown, S. S., Cho, C., Crowley, J. N., Fuchs, H., Mellouki, W., Reimer, D., Shenolikar, J., Tillmann, R., Zhou, L., Kiendler-Scharr, A., and Wahner, A.: Theoretical and experimental study of peroxy and alkoxy radicals in the NO$_3$-initiated oxidation of isoprene, Phys. Chem. Chem. Phys., 23, 5496–5515, https://doi.org/10.1039/D0CP06267G, 2021.

Veres, P. R., Neuman, J. A., Bertram, T. H., Assaf, E., Wolfe, G. M., Williamson, C. J., Weinzierl, B., Tilmes, S., Thompson, C. R., Thames, A. B., Schroder, J. C., Saiz-Lopez, A., Rollins, A. W., Roberts, J. M., Price, D., Peischl, J., Nault, B. A., Møller, K. H.,

Miller, D. O., Meinardi, S., Li, Q., Lamarque, J.-F., Kupc, A., Kjaergaard, H. G., Kinnison, D., Jimenez, J. L., Jernigan, C. M., Hornbrook, R. S., Hills, A., Dollner, M., Day, D. A., Cuevas, C. A., Campuzano-Jost, P., Burkholder, J., Bui, T. P., Brune, W. H., Brown, S. S., Brock, C. A., Bourgeois, I., Blake, D. R., Apel, E. C., and Ryerson, T. B.: Global airborne sampling reveals a previously unobserved dimethyl sulfide oxidation mechanism in the marine atmosphere, Proceedings of the National Academy of Sciences, 117, 4505–4510, https://doi.org/10.1073/pnas.1919344117, 2020.

Verreyken, B., Amelynck, C., Schoon, N., Müller, J.-F., Brioude, J., Kumps, N., Hermans, C., Metzger, J.-M., Colomb, A., and Stavrakou, T.: Measurement report: Source apportionment of volatile organic compounds at the remote high-altitude Maïdo observatory, Atmos. Chem. Phys., 21, 12965–12988, https://doi.org/10.5194/acp-21-12965-2021, 2021.

Vigouroux, C., Bauer Aquino, C. A., Bauwens, M., Becker, C., Blumenstock, T., De Mazière, M., García, O., Grutter, M., Guarin, C., Hannigan, J., Hase, F., Jones, N., Kivi, R., Koshelev, D., Langerock, B., Lutsch, E., Makarova, M., Metzger, J.-M., Müller, J.-F., Notholt, J., Ortega, I., Palm, M., Paton-Walsh, C., Poberovskii, A., Rettinger, M., Robinson, J., Smale, D., Stavrakou, T., Stremme, W., Strong, K., Sussmann, R., Té, Y., and Toon, G.: NDACC harmonized formaldehyde time series from 21 FTIR stations covering a wide range of column abundances, Atmos. Meas. Tech., 11, 5049–5073, https://doi.org/10.5194/amt-11-5049-2018, 2018.

von Hobe, M., Taraborrelli, D., Alber, S., Bohn, B., Dorn, H.-P., Fuchs, H., Li, Y., Qiu, C., Rohrer, F., Sommariva, R., Stroh, F., Tan, Z., Wedel, S., and Novelli, A.: Measurement report: Carbonyl sulfide production during dimethyl sulfide oxidation in the atmospheric simulation chamber SAPHIR, Atmospheric Chemistry and Physics, 23, 10609–10623, https://doi.org/10.5194/acp-23-10609-2023, 2023.

Wærsted, E. G., Haeffelin, M., Steeneveld, G., and Dupont, J.: Understanding the dissipation of continental fog by analysing the LWP budget using idealized LES and in situ observations, Quart J Royal Meteoro Soc, 145, 784–804, https://doi.org/10.1002/qj.3465, 2019.

Wagner, R., Bunz, H., Linke, C., Möhler, O., Naumann, K.-H., Saathoff, H., Schnaiter, M., and Schurath, U.: Chamber Simulations of Cloud Chemistry: The AIDA Chamber, in: Environmental Simulation Chambers: Application to Atmospheric Chemical Processes,

vol. 62, edited by: Barnes, I. and Rudzinski, K. J., Kluwer Academic Publishers, Dordrecht, 67–82, https://doi.org/10.1007/1-4020-4232-9_5, 2006.

Wang, J., Doussin, J. F., Perrier, S., Perraudin, E., Katrib, Y., Pangui, E., and Picquet-Varrault, B.: Design of a new multi-phase experimental simulation chamber for atmospheric photosmog, aerosol and cloud chemistry research, Atmos. Meas. Tech., 4, 2465–2494, https://doi.org/10.5194/amt-4-2465-2011, 2011.

Wang, S., Newland, M. J., Deng, W., Rickard, A. R., Hamilton, J. F., Muñoz, A., Ródenas, M., Vázquez, M. M., Wang, L., and Wang, X.: Aromatic Photo-oxidation, A New Source of Atmospheric Acidity, Environ. Sci. Technol., 54, 7798–7806, https://doi.org/10.1021/acs.est.0c00526, 2020.

Wiedensohler, A., Birmili, W., Nowak, A., Sonntag, A., Weinhold, K., Merkel, M., Wehner, B., Tuch, T., Pfeifer, S., Fiebig, M., Fjäraa, A. M., Asmi, E., Sellegri, K., Depuy, R., Venzac, H., Villani, P., Laj, P., Aalto, P., Ogren, J. A., Swietlicki, E., Williams, P., Roldin, P., Quincey, P., Hüglin, C., Fierz-Schmidhauser, R., Gysel, M., Weingartner, E., Riccobono, F., Santos, S., Grüning, C., Faloon, K., Beddows, D., Harrison, R., Monahan, C., Jennings, S. G., O'Dowd, C. D., Marinoni, A., Horn, H.-G., Keck, L., Jiang, J., Scheckman, J., McMurry, P. H., Deng, Z., Zhao, C. S., Moerman, M., Henzing, B., De Leeuw, G., Löschau, G., and Bastian, S.: Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions, Atmos. Meas. Tech., 5, 657–685, https://doi.org/10.5194/amt-5-657-2012, 2012.

Wiesen, P.: The EUROCHAMP Integrated Infrastructure Initiative Environmental, in: Environmental Simulation Chambers: Application to Atmospheric Chemical Processes, vol. 62, edited by: Barnes, I. and Rudzinski, K. J., Kluwer Academic Publishers, Dordrecht, 295–299, https://doi.org/10.1007/1-4020-4232-9_26, 2006.

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. 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.

Wisthaler, A., Apel, E. C., Bossmeyer, J., Hansel, A., Junkermann, W., Koppmann, R., Meier, R., Müller, K., Solomon, S. J., Steinbrecher, R., Tillmann, R., and Brauers, T.: Technical Note: Intercomparison of formaldehyde measurements at the atmosphere simulation chamber SAPHIR, Atmos. Chem. Phys., 8, 2189–2200, https://doi.org/10.5194/acp-8-2189-2008, 2008.

Worton, D. R., Moreno, S., O'Daly, K., and Holzinger, R.: Development of an International System of Units (SI)-traceable transmission curve reference material to improve the quantitation and comparability of proton-transfer-reaction mass-spectrometry measurements, Atmos. Meas. Tech., 16, 1061–1072, https://doi.org/10.5194/amt-16-1061-2023, 2023.

Yttri, K. E., Schnelle-Kreis, J., Maenhaut, W., Abbaszade, G., Alves, C., Bjerke, A., Bonnier, N., Bossi, R., Claeys, M., Dye, C., Evtyugina, M., García-Gacio, D., Hillamo, R., Hoffer, A., Hyder, M., Iinuma, Y., Jaffrezo, J.-L., Kasper-Giebl, A., Kiss, G., López-Mahia, P. L., Pio, C., Piot, C., Ramirez-Santa-Cruz, C., Sciare, J., Teinilä, K., Vermeylen, R., Vicente, A., and Zimmermann, R.: An intercomparison study of analytical methods used for quantification of levoglucosan in ambient aerosol filter samples, Atmos. Meas. Tech., 8, 125–147, https://doi.org/10.5194/amt-8-125-2015, 2015.

Yttri, K. E., Canonaco, F., Eckhardt, S., Evangeliou, N., Fiebig, M., Gundersen, H., Hjellbrekke, A.-G., Lund Myhre, C., Platt, S. M., Prévôt, A. S. H., Simpson, D., Solberg, S., Surratt, J., Tørseth, K., Uggerud, H., Vadset, M., Wan, X., and Aas, W.: Trends, composition, and sources of carbonaceous aerosol at the Birkenes Observatory, northern Europe, 2001–2018, Atmos. Chem. Phys., 21, 7149–7170, https://doi.org/10.5194/acp-21-7149-2021, 2021.

Zanatta, M., Gysel, M., Bukowiecki, N., Müller, T., Weingartner, E., Areskoug, H., Fiebig, M., Yttri, K. E., Mihalopoulos, N., Kouvarakis, G., Beddows, D., Harrison, R. M., Cavalli, F., Putaud, J. P., Spindler, G., Wiedensohler, A., Alastuey, A., Pandolfi, M., Sellegri, K., Swietlicki, E., Jaffrezo, J. L., Baltensperger, U., and Laj, P.: A European aerosol phenomenology-5: Climatology of black carbon optical properties at 9 regional

background sites across Europe, Atmospheric Environment, 145, 346–364,
https://doi.org/10.1016/j.atmosenv.2016.09.035, 2016.