BAMS Article

Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS): The European Research Infrastructure Supporting Atmospheric Science

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KEYWORDS:
Atmosphere;
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Trace gases

ABSTRACT: The Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) officially became the 33rd European Research Infrastructure Consortium (ERIC) on 25 April 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.

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SIGNIFICANCE STATEMENT: The Aerosol, Clouds and Trace Gases Research Infrastructure (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.

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1. Introduction

Short-lived atmospheric constituents (SLACs) and clouds play a key role in regulating 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. The 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 policymakers are provided with the most appropriate strategies for predicting, mitigating, and adapting to the impacts of climate change.

For understanding the sources, sinks, and chemistry of SLACs and their impacts on climate change and air quality, as well as 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 centers (DCs) for curation and access to data and data products, and expert centers to harmonize methodologies for probing the atmosphere and test innovative atmospheric measurement techniques.

On 25 April 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 (Fig. 1). As the European organization facilitates research in the field of atmospheric sciences, its goal is to document variability, to understand processes, and to quantify the impacts of SLACs on Earth's climate, air quality, human health, and ecosystems.

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 and the data life cycle, from raw data acquisition and quality control/quality 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 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 physicochemical processes that determine their fate and impacts, and the impact of natural hazards such as volcanic eruptions and forest fires on the atmospheric composition. 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.

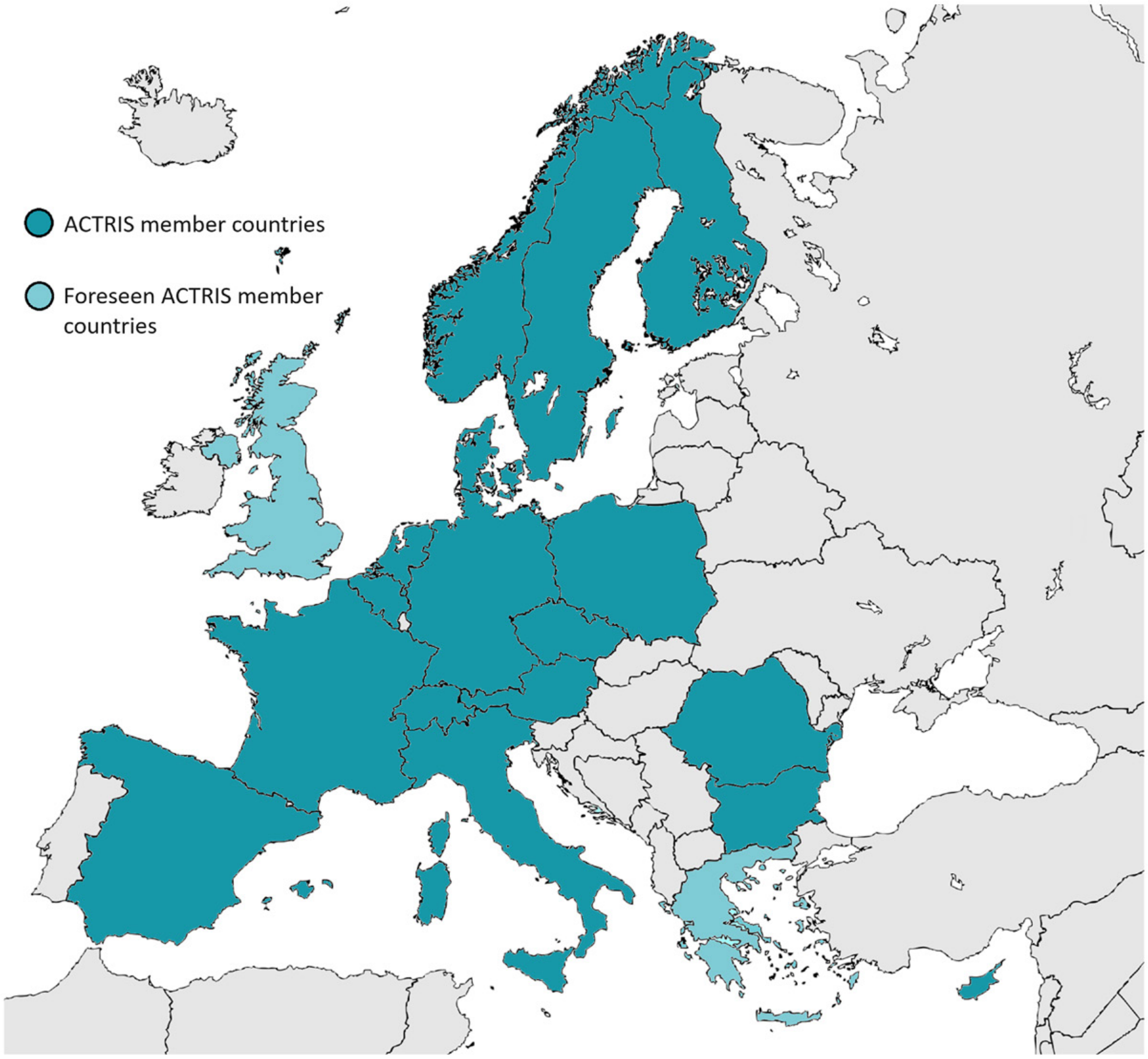

Fig. 1. ACTRIS member countries (cyan), as of September 2023. The United Kingdom and Greece (light green) are candidates to integrate into ACTRIS ERIC during 2024.

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 and 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 aerosols and chemically reactive gases including ozone, nitrogen oxides, and nonmethane 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 coronavirus disease 2019 (COVID-19) pandemic.
- Improving technologies for measuring SLACs and cloud properties.

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 the following:

- 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 infrastructure framework. The European Strategy Forum on Research Infrastructures (ESFRI) 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 (ESFRI 2021). ACTRIS is part of the ESFRI environment domain, forming the Environmental Research Infrastructure (ENVRI) cluster (Petzold et al. 2024), aiming to observe Earth as a single system, providing open and findable, accessible, interoperable, and reusable (FAIR) (Wilkinson et al. 2016) environmental data, tools, and services.

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 (see the sidebar for additional information).

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 1) providing observation data or data products, 2) offering support to operating calibration centers, 3) operating DCs, and 4) providing training to users and data producers in the networks. Considering its wide scope, ACTRIS is actively involved with internationally recognized networks and programs, namely, 1) the Global Atmosphere Watch (GAW) program 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 GAW Aerosol Lidar Observing Network (GALION), 6) the Cloud Network (CLOUDNET), and 7) the Pandonia Global Network (PGN).

As detailed in section 5e, 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 remain accessible through international network portals, while acknowledging its provenance. ACTRIS is therefore aligned with the standards defined in the WMO Integrated Global Observing System (WIGOS) or other international data repositories (more details in section 5) and its policies in line with the 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 nonmember countries and will be serviced through the ACTRIS access program for external users (defined in appendix A), 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 profile data according to NDACC protocols, accessible through the NDACC portal with the ACTRIS label.
- ACTRIS operates AERONET calibration centers, complementing the National Aeronautics and Space Administration (NASA)'s center. Data from ACTRIS-serviced AERONET instruments are available through the AERONET portal.
- ACTRIS contributes to the European Pandonia calibration center, with data from ACTRIS-serviced Pandora instruments available through the PGN portal.
- Furthermore, ACTRIS shares data or data products in real (or near) real time (see section 5c) with other parties, such as the European Meteorological Network (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 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 NFs. 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 Platforms but generally include the following:

- 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, and 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. Eighty-seven 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 (RTGIS) measurements. Each component is connected to the respective TC [see section 3b] and DC [see section 3c] units.

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 the fully operational stage of ACTRIS in 2026. Most facilities are already in operation.

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 and detailed aerosol chemical composition) not covered by ACTRIS TCs are often included. Besides, portable instruments operated on mobile platforms typically prioritize size and weight over sensitivity. State-of-the-art data processing chains, including consistency checks and dedicated instrument comparisons, ensure the 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 European Simulation Chambers for Investigating Atmospheric Processes (EUROCHAMP) European infrastructure (section 3d). 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

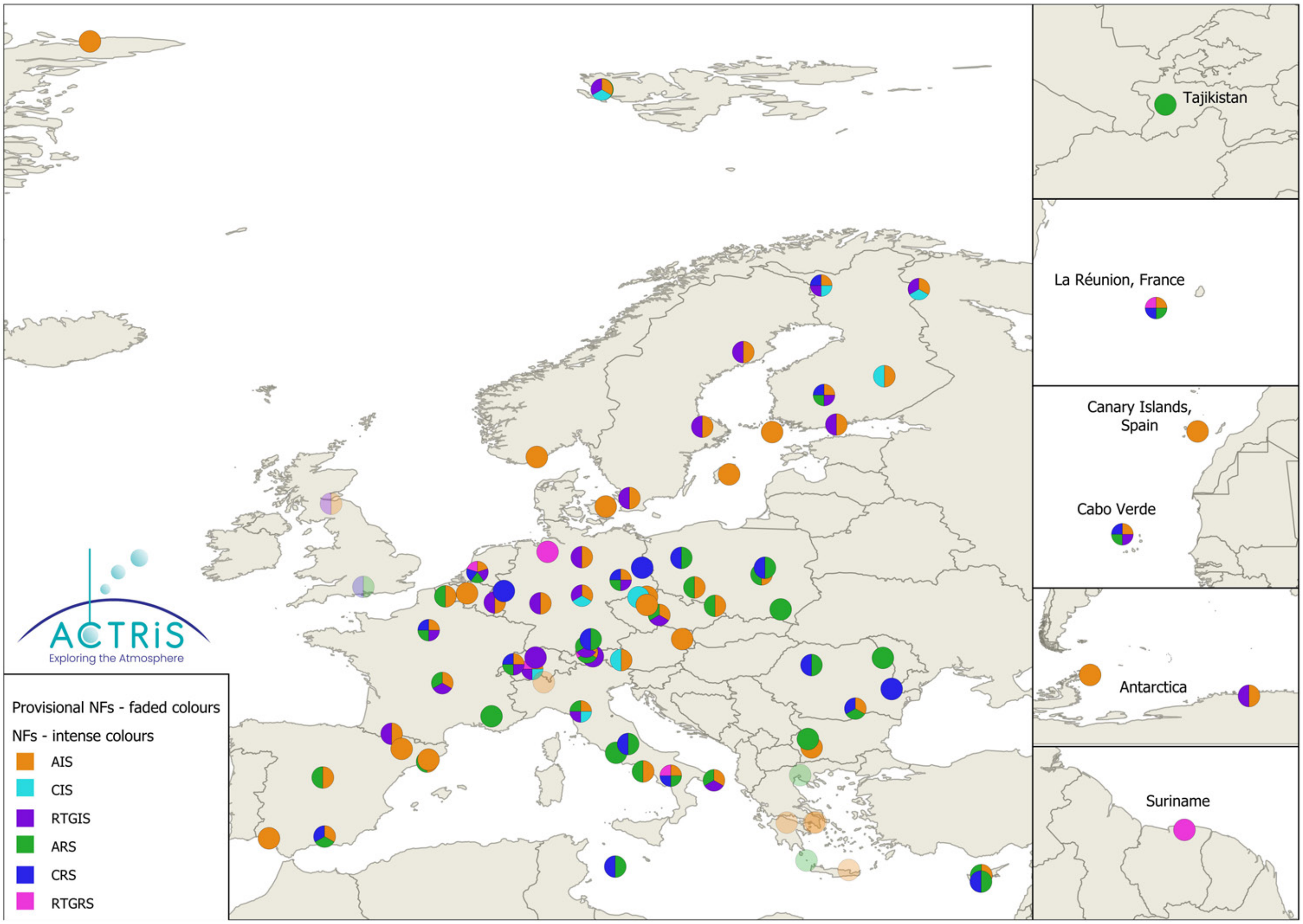

Fig. 2. Geographical distribution of ACTRIS Observational Platforms foreseen for 2026; different colors are used for different components. The complete list of Observational Platforms is in appendix B.

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 lightweight 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.

b. The TCs. TCs support the operation of NFs and are responsible for defining procedures and tools, 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, and 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

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.

Name (country)	Description	Type of process studies	Reference
AIDA (Germany)	Indoor aluminum cylinder (84 m^3)	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 m^3)	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 (United Kingdom)	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)	Two outdoor Teflon hemispheres (200 m^3)	Particle- and gas-phase processes	Bloss et al. (2005)
ACD-C (Germany)	Two 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 (United Kingdom)	Indoor glass cuboid in stainless-steel chamber (3.5 m^3)	Ice–air interface processes	Thomas et al. (2021)

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.

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

Table 2. The ACTRIS TCs 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).

TC	Acronym	Countries where the TC units are located
Centre for Aerosol In Situ Measurements–European Center for Aerosol Calibration and 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

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 into six units (Fig. 3).

The ACTRIS DC core tasks are to ensure the following:

- 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 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

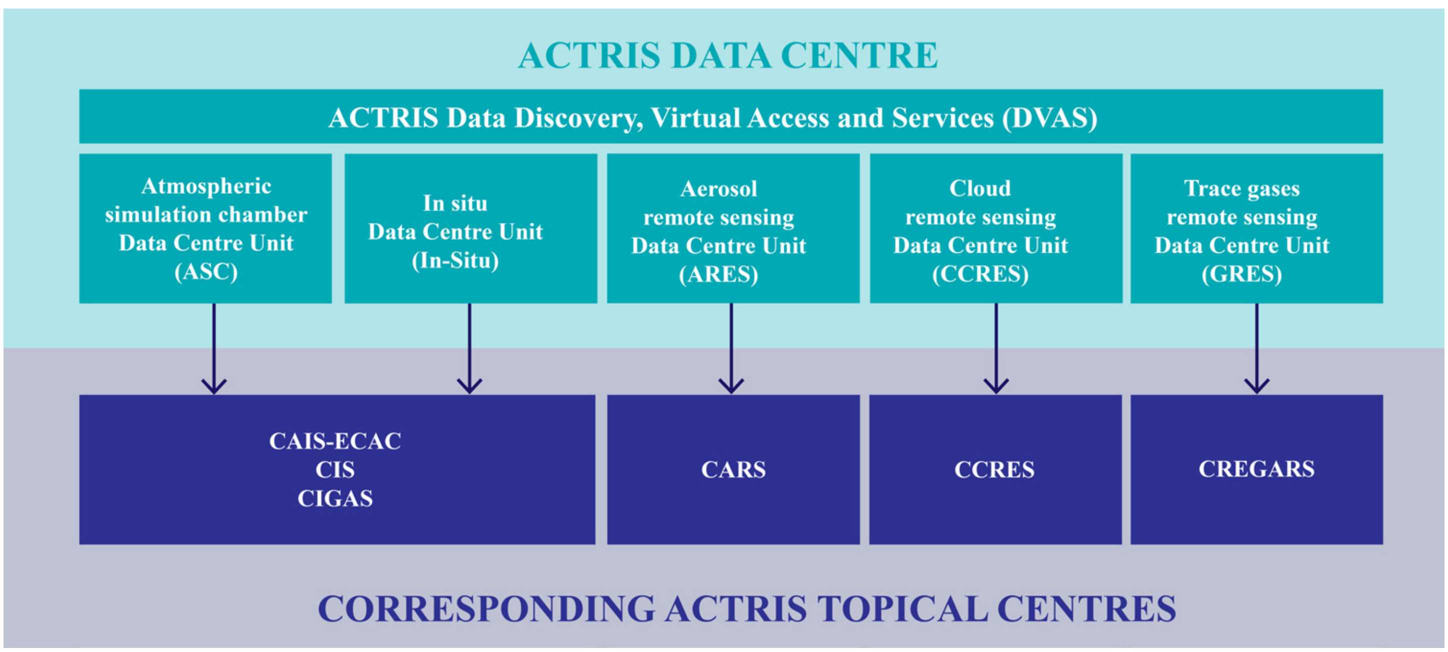

Fig. 3. The structure and components of ACTRIS DC and links between each DC unit and the associated TCs. Five units (in situ, ARES, CCRES, GRES, and ASC) have complementary topic expertise, and one unit (DVAS) deals with integrating activities and coordination. There are defined links and procedures for interaction between the DC units, NFs, and TCs. ACTRIS DC units are operated by established DCs, ensuring trust, and long-term sustainability as well as security and environmental responsibilities in data management.

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 toward 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 sections 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 Fig. 4.

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 NF Scientific and Technical Forum (NFSTF), and the Atmospheric Simulation Chamber Committee (ASCC), ensuring that the community is engaged in the scientific and strategic development of ACTRIS.

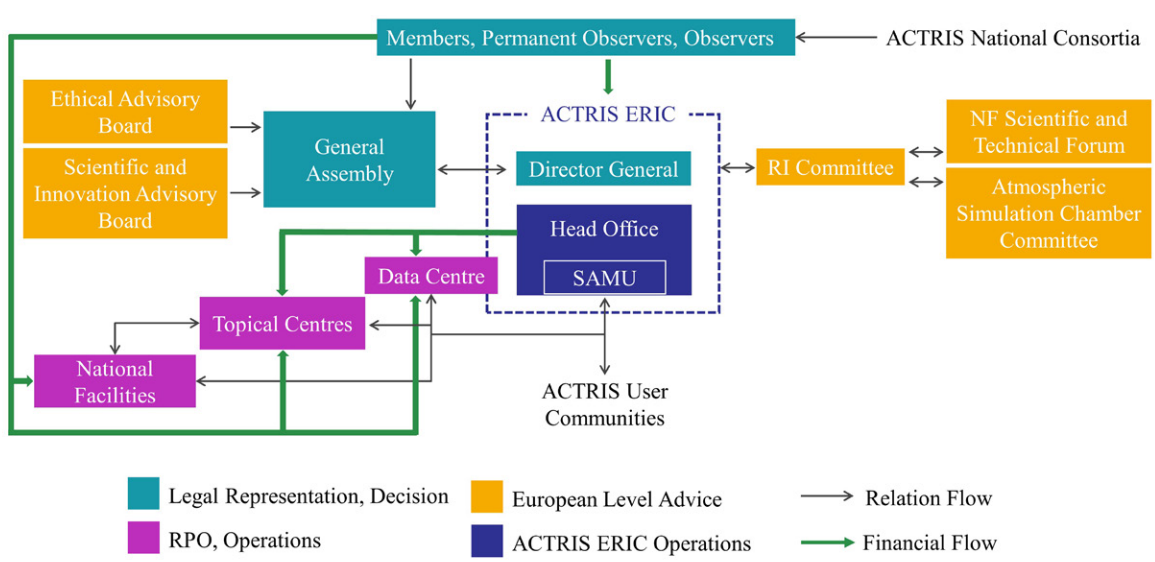

Fig. 4. The ACTRIS business plan including both the management and governance structures illustrating the components of the organization and their relationships, also including the financial flow. The RI Committee, the NFSTF, and the ASCC ensure that the scientific and strategic development of ACTRIS 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 indicate relationships involving financial flow among components, while simple arrows indicate relationships without financial flow. Additional revenues from projects and/or user fees are not indicated. All components are defined in the glossary (appendix A).

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

The production of ACTRIS data follows 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.

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

Attribute	Description
	Timeliness
RRT data	Data provided within 3 h of production
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–1 year depending on the type of data from different ACTRIS components
	QC and compliance attributions
ACTRIS	This relates to data collected in accordance with ACTRIS procedures, and observation is conducted at an ACTRIS NF
ACTRIS compliant	This relates to QC 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 labeling process nor is necessarily an ACTRIS NF
ACTRIS associated	This relates to QC and compliance. Data partly complying with ACTRIS requirements after the start of ACTRIS ERIC
ACTRIS legacy	This relates to QC and compliance. Data adhere to ACTRIS procedures in place before ACTRIS RI was established
Other	This relates to QC and compliance. Adheres to other types of QC procedures

Data production begins with instrument qualification by the associated TC. Data processing happens at NFs, TCs, or DCs, depending on the type of variable and ACTRIS component (see Fig. 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 h of acquisition. These uploaded data undergo automatic instrumental-criteria-based QC and are paired with precalibrations 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 reanalysis model output, to create the final "scheduled" data product.

In addition to scheduled data, ACTRIS provides NRT/RRT data to programs such as CAMS or E-PROFILE (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.

Exploratory Platform data are not centrally produced. Due to instrument and experimental setup diversity, NFs 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 (DOIs).

ACTRIS data and metadata 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, and 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, and scheduled), connecting with customers and collaborating frameworks like WMO Information System (WIS) and 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. One important requirement for data to be open and FAIR is information on the condition of use and a license. ACTRIS data are offered to users with the Creative Commons Attribution 4.0 International (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. 2024). CC BY 4.0 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 whether 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. The GNU Affero General Public License will be used taking the use of web services into account.

5. Major scientific achievements of ACTRIS 2005–22

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 January 2010 and August 2023, where "ACTRIS" or "pre-ACTRIS" projects are mentioned in the funding or acknowledgments 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, and 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., 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, as well as 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), using 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 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) interlaboratory 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 nonmethane hydrocarbon (NMHC) instruments (Hoerger et al. 2015; Holzinger et al. 2019). Many have also been 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), nitrogen dioxide (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), hydroxyl radical (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. 2023), and 3) additional measurements like circular/elliptical depolarization for improved characterization of nonspherical 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 profilers. 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).

ACTRIS-driven developments also support trace gas column and vertical profile retrievals, notably for improving network-wide harmonized retrieval strategies, in particular for Fourier transform infrared (FTIR) retrieval of formaldehyde (HCHO) (Vigouroux et al. 2018) or other species. In the UV–visible (VIS) differential optical absorption spectroscopy (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 an 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 (HOOSs) 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 photooxidation 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 the atmospheric simulation chamber experiment is provided in Fig. 5 where new reaction pathways in the oxidation of dimethyl sulfide (DMS) (Veres et al. 2020) are tested. For the atmospheric-like chemical composition of the air, the fate of RO_2 from the oxidation of DMS is mainly a hydrogen (H)-shift reaction leading to the formation of hydroperoxymethyl thioformate (HPMTF) not seen in previous laboratory experiments at

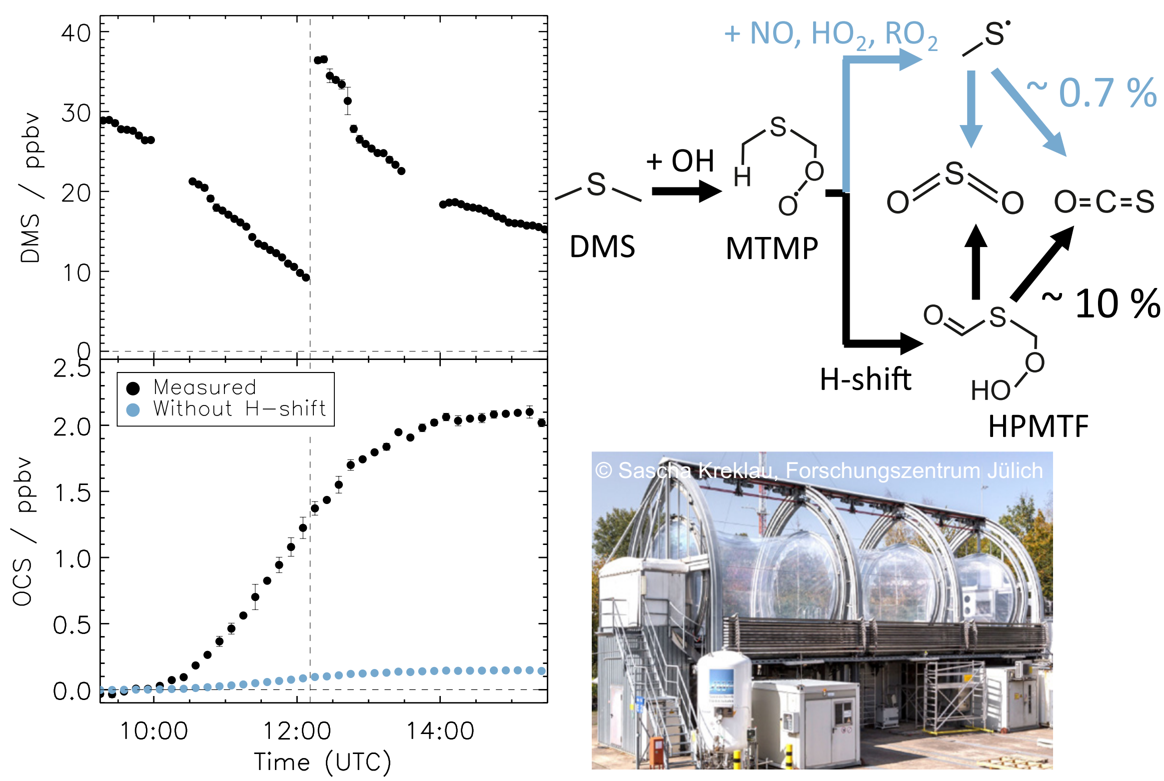

Fig. 5. Evidence for higher-than-expected formation of OCS in the OH oxidation of DMS due to H-shift reactions following the HPMTF formation path (Veres et al. 2020) in experiments carried out in the SAPHIR atmospheric simulation chamber.

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).

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) investigated how the reaction with SO_2 oxidation products can transform semivolatile organics into nonvolatile 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° and −8°C by comparing polluted and pristine sites worldwide. Marinou et al. (2019) investigated the properties of clouds influenced by dust over the Mediterranean Sea using Cloudnet observations in Greece. Biogenic emissions from boreal forests in Finland have a 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 particulate matter 1 (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 volatile organic compound (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 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.

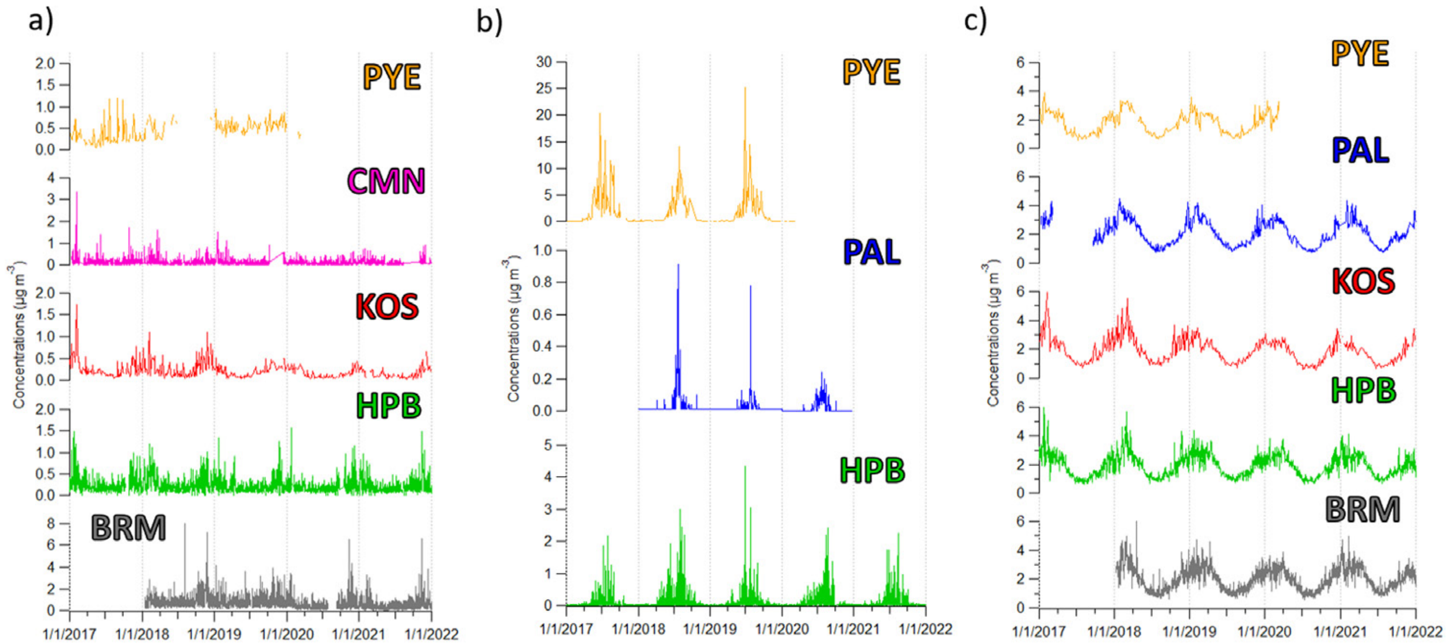

Fig. 6. **Mass concentrations (μg m^{-3}) of (a) toluene, (b) isoprene, and (c) ethane measured over the period 2017–21 at NFs Beromünster (BRM), Monte Cimone (CMN), Hohenpeissenberg (HPB), KOS, Pallas (PAL), and EMEP site Peyrusse-Vieille (PYE). The variability illustrates the specific behavior of VOCs 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, from both 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 Icosahedral Nonhydrostatic (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-yr 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 caused by either natural phenomena 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 (Fig. 7).

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 (KOS) 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 (Fig. 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. 2023).

Last, 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 the 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 and health). To maintain attractiveness, ACTRIS must consider the conditions for maintaining a high and

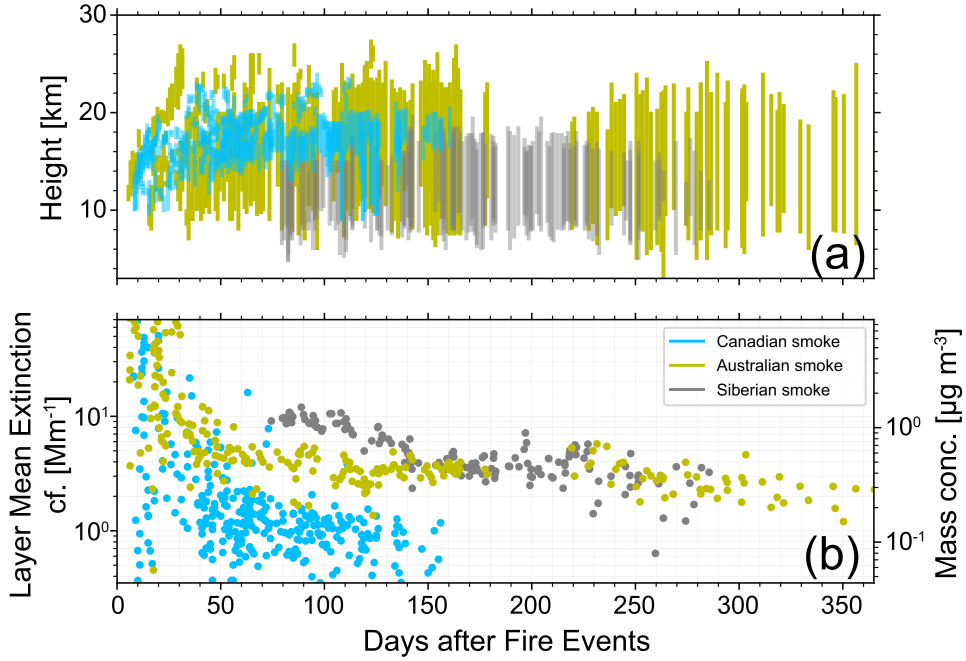

Fig. 7. Stratospheric aerosol burden in the first 365 days after three major fire events as observed with ACTRIS aerosol profiling facilities (high-power lidar + sun photometer): (a) geometrical boundaries (layer bottom to layer top) of the smoke plume. Each vertical bar represents a day-by-day measurement and (b) layer mean extinction coefficient (cf) at 532 nm and the respective mass concentration derived with a mass specific extinction coefficient of 8.93 m^2 g^{-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 2019/20 in southeastern Australia as observed over Punta Arenas, Chile (Ohneiser et al. 2022), with the ACTRIS mobile facility Leipzig Aerosol and Clouds Remote Observations System (LACROS) (Radenz et al. 2021); and gray 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 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Engelmann et al. 2021). Day 0 represents the 12 Aug 2017 (Canadian fires), 23 Jul 2019 (Siberian fires), and 31 Dec 2019 (Australian fires).

adaptable level of services and address the following challenges in the next 5–15 years of operation.

a. Challenge 1: Maintaining attractiveness by constantly responding to evolving community needs. ACTRIS services must continue to evolve even after entering their operational phase in 2026. ACTRIS must therefore closely monitor the 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 multiyear 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.

b. 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

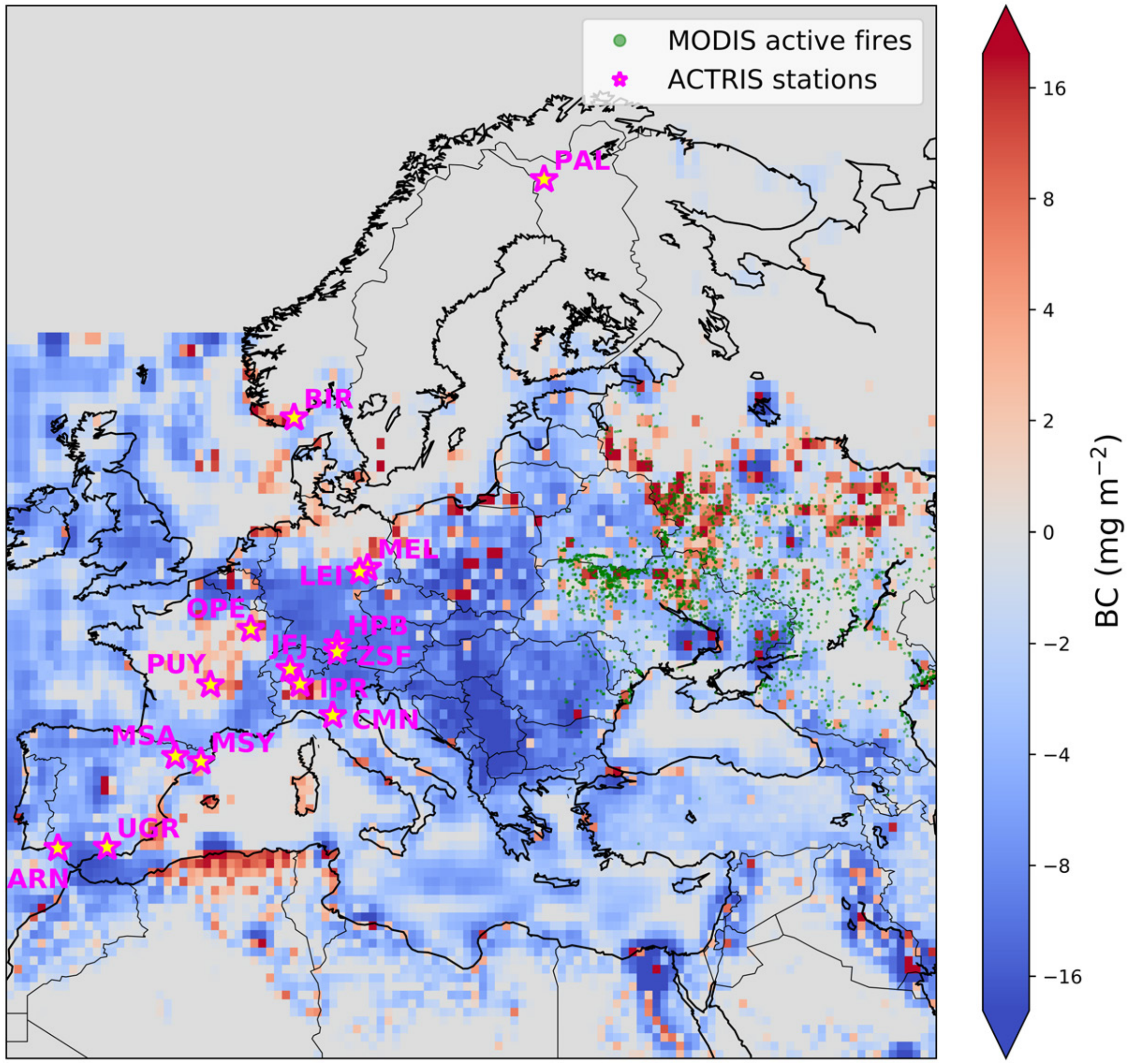

Fig. 8. Posterior emission anomaly of BC during the COVID-19 lockdown period (15 Mar–30 Apr 2020) with respect to 2015–20 (same period). Circles marked in green show the active fires from the NASA MODIS satellite, while stars depict the locations of the ACTRIS stations that were used to calculate the impact of the COVID-19 restriction measures over Europe on BC emissions (modified after Evangeliou et al. 2021). The overall net decrease in BC emission is −23 kT for the period.

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 the fostering use of innovative technologies designed as the RI strategic vision for the next 10–20 years.

c. Challenge 3: Maintaining a sustainable Transnational 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.

d. 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 are 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 the unimpeded use of multidisciplinary data from different spheres of Earth system, with FAIR digital (meta)data as an absolute prerequisite.

e. 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 policymakers 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 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 United States provides somewhat similar services to ACTRIS, but without the simulation chamber dimension. The 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.

f. 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 Sustainable Development Goals (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 a 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 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, which is key to developing a European-wide strategy for atmospheric science. Through its contribution to several surface-based international observing networks, ACTRIS is a key factor in the global atmospheric monitoring effort.

Acknowledgments. The construction of ACTRIS received funding from the European Commission through a number of projects from FP6 to Horizon Europe: ACTRIS-PPP, Grant Agreement (GA) 739530, ACTRIS IMP GA 871115, EUROCHAMP-2020 GA 730997, ACTRIS-2 GA 654109, and ACTRIS GA 262254. The access to the ACTRIS infrastructure got support from ATMO-ACCESS GA 101008004. ACTRIS benefitted from the contract established with Copernicus-ECMWF (CAMS21a, CAMS21b, and CAMS27) and the European Space Agency (FRM4DOAS) and ECMWF-Copernicus (CAMS-27) to support the implementation of the central data processing, QA/QC system, and procedure for NRT and RRT data production. In addition, ACTRIS was established thanks to support to national ACTRIS activities in Austria by the Austrian Federal Ministry of Education, Science and Research and in Belgium by the Belgian Science Policy, Federal and Walloon RPO. The FTIR monitoring program at Jungfraujoch was further supported by the GAW-CH program of MeteoSwiss (Zürich, CH), in Bulgaria by the Ministry of Education and Science of Bulgaria (support for ACTRIS BG, part of the Bulgarian National Roadmap for Research Infrastructure) and in Cyprus by the Deputy Ministry of Research, Innovation, and Digital Transition; the establishment and the operation of the ERATOSTHENES CoE NF are 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 and 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, and 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 the 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, the Ministry of Higher Education and Science funded ACTRIS-DK (Project 5072-00032B). In Finland, ACTRIS-FI projects for the implementation of ACTRIS-FI NFs and ACTRIS TC Units of University of Helsinki are funded by Research Council of Finland [Grants 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 (Grants 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, 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 ANR-21-ESRE-0013). In Germany, the 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 are 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 2014–20), 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 the Ordinary Fund (FOE), with the project (Grant 893/2019) for the implementation of ACTRIS-IT funded by the European Regional Development Fund through the Competitiveness Operational Programme 2014–20, Action II.1, and with the project (Grant 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 184.034.015). In Norway, ACTRIS-NO (Pr. 322247) and ACTRIS-ESFRI (Pr. 320886) are 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 (NCN) within DAINA-2 (2020/38/L/ST10/00480), Weave-UNISONO (2021/03/Y/ST10/00206), Preludium BIS-2 (2020/39/O/ST10/03586), Preludium 19 (2020/37/N/ST10/02682), and Preludium 15 (2018/29/N/ST10/02628); the Polish Foundation of Science and Technology (FNiTP) grant (519/FN-ITP/115/2010); and the Ministry of Education and Science of Poland (MEiN) within the Maintenance of Specialized Research Infrastructures (7/E-340/SPUB/SP/2020). In Romania, ACTRIS-RO is supported by the European Regional Development Fund through the Competitiveness Operational Programme 2014–20, Action 1.1.3 Creating synergies with H2020 Programme, project Strengthen the participation of the ACTRIS-RO consortium in the pan-European Research Infrastructure ACTRIS, ACTRIS-ROC, MYSMIS code 107596 (ctr. 337/2021), and the Core Program within the Romanian National Research Development and Innovation Plan 2022–27, carried out with the support of MCID, Project PN 23 05. In Spain, ACTRIS-SP acknowledges the support of the Ministry for Science and Innovation to ACTRIS ERIC and the contribution of many projects of the State Research Agency (AEI), as well as of funding programs of several regional governments. In Sweden, ACTRIS Sverige is supported by the Swedish Research Council, Project ID: 2021-00177_VR. In Switzerland, financial support for ACTRIS-CH NFs and CF Units during 2021–24 is provided by the Swiss State Secretariat for Education and Research and Innovation (SERI). ACTRIS observations at Jungfraujoch receive support from the Swiss Federal Office for the Environment (FOEN) via the CLIMAGS-CH program, the Federal Office of Meteorology and Climatology MeteoSwiss through the GAW-CH program, and the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG). Observations at Payerne are supported by the Federal Office of Meteorology and Climatology MeteoSwiss through the GAW-CH program, with MeteoSwiss providing the base infrastructure at the Payerne observatory. For the station in Beromünster, funding comes from FOEN through the Swiss National Air Pollution Monitoring Network (NABEL). Partners within the ACTRIS-CH consortium support ACTRIS implementation with their own funds. In the United Kingdom, financial support is provided by the Natural Environment Research Council (NERC), the National Centre for Atmospheric Science (NCAS), and the Centre for Ecology and Hydrology (CEH).

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

A short history of ACTRIS

ACTRIS began as an "Integrated Activity" project (ACTRIS) funded by the European Commission (EC), under its 7th Framework Programme (2011–15). 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 sixth Framework Programme: European Supersites for Atmospheric Aerosol Research (EUSAAR; Asmi et al. 2013 and https://cordis.europa.eu/project/id/26140/fr) and EARLINET (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 RI 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 TCs. ACTRIS-2 further extended the ACTRIS perimeter by opening the RI to the European communities active in the NDACC and AERONET, 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 AQ research.

In parallel, starting in FP6 (2004–09), 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 (Wiesen 2006 and https://cordis.europa.eu/project/id/228335) project, shortly followed in FP7 by the EUROCHAMP-2 project (2009–13, https://cordis.europa.eu/project/id/228335). In H2020, the EUROCHAMP-2020 project (https://www.eurochamp.org/) set guidelines for the 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 RI in the ESFRI roadmap in 2016. During the ESFRI application process (2014–15), 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 toward the establishment of the legal entity ACTRIS ERIC was formally requested by the European Commission in September 2021, and the ERIC status was obtained on 25 April 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 toward a globally recognized long-term sustainable RI. 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 Fig. SB1.

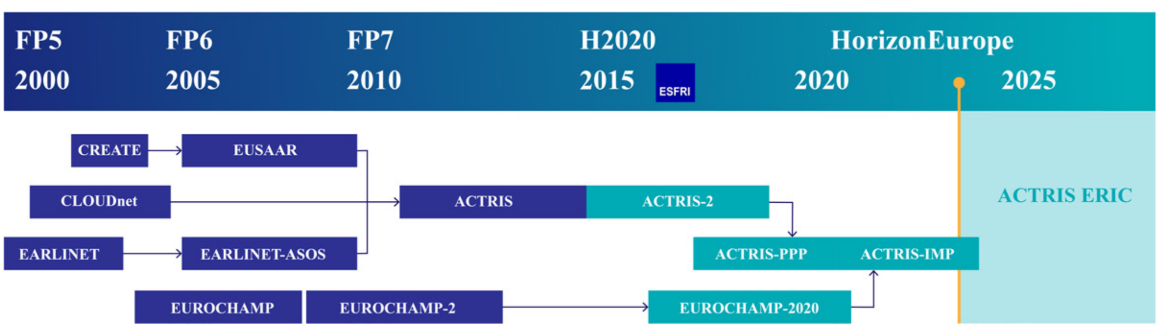

Fig. SB1. The Integrating Activities of the Infrastructure Program of the European Commission, funded under the fifth, sixth, and seventh (H2020) and now Horizon Europe Framework Programmes, leading to establishing ACTRIS ERIC in 2023.

The short-term projects have been fundamental for structuring the relevant atmospheric science communities by mobilizing a comprehensive consortium of several key RPOs as well as other stakeholders (e.g., public authorities and 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 AIS measurements have been operational since 1995 at the Hyytiälä 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 EC and by strong commitments in many EU member states and associated countries.

APPENDIX A
ACTRIS Glossary

A more complete glossary can be found online (https://www.actris.eu/sites/default/files/inline-files/ACTRIS_glossary_April2022_0.pdf).

- ACTRIS ERIC—The Aerosol, Clouds and Trace Gases Research Infrastructure was 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 Observational 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 labeling process to Observational and Exploratory Platforms that comply with the ACTRIS standards.
- ACTRIS labeling process—It is 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 the 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 the associated country, or an intergovernmental organization that has joined ACTRIS ERIC as an observer or permanent observer, without voting rights. ACTRIS Observers: An observer is admitted for a maximum of 3 years with the possibility of two 1-yr extensions.
- ACTRIS observational components—ACTRIS observational components refer to the classification of measurement techniques. ACTRIS has six observational components: aerosol in situ (AIS), cloud in situ (CIS), reactive trace gases in situ (RTGIS), aerosol remote sensing (ARS), cloud remote sensing (CRS), and reactive trace gases remote sensing (RTGRS) measurements.
- Atmospheric Simulation Chamber Committee (ASC Committee)—It supports the operation of ACTRIS atmospheric simulation chambers on matters related to procedures, quality, consistency, and relevance.
- Central Facility Unit—It is part of a Central Facility located at and operated by a research performing organization (RPO) or by ACTRIS ERIC.
- Cooperation Agreement—It is 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—It is a document that outlines the strategy and process toward making ACTRIS data FAIR at the ACTRIS Data Centre Level.
- Data producers—It is the network of National Facilities producing ACTRIS data (see Table 2) compliant with specified ACTRIS procedures.
- Director General (DG)—It is 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—It is a community of European environmental research infrastructures working together to observe Earth as one system. ENVRI fosters transdisciplinary 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—It is a label that indicates those RIs undergoing their preparation phase and is considered of strategic importance for the European Research Area.
- ESFRI roadmap—It is 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)—It is 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 subdivided into so-called ECV products. The term "product" denotes long-term data records of values or fields of ECVs.
- Ethical Advisory Board—It provides feedbacks and recommendations to the DG on aspects related to ethical issues in ACTRIS ERIC and ACTRIS activities.
- FAIR—It 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—It is the organization of the ACTRIS community at the national level.
- National Facility (NF)—It is 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 between scientific expertise and technological development. It is an advisory body that may provide recommendations to the RI Committee or to the ACTRIS Community.

- Research infrastructure (RI)—RI includes facilities, resources, and related services used by the scientific community to conduct research in all scientific and technological fields.
- 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)—It consists of independent external members monitoring the scientific and operative quality of and providing advice to develop ACTRIS ERIC and the research infrastructure activities in the operation phase.
- Service and Access Management Unit (SAMU)—It is a part of ACTRIS Head Office facilitating access to ACTRIS services other than data for the user communities.
- Transnational 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 located.
- User—It is 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 lists the ACTRIS National Facilities categorized by country and their geographical locations. It also details the components observed at these facilities, including aerosols, clouds, and trace gases, using both in situ and remote sensing techniques.

Table B1. The ACTRIS NFs and provisional NFs with their WIGOS identifier—when it exists—and their geographical location. Provisional NFs mean they are not yet in full operation mode and ready for entering the labeling process. The components (aerosol, clouds, and trace gases) observed at the NFs via in situ or remote sensing techniques are included with 1 = AIS; 2 = CIS; 3 = RTGIS; 4 = ARS; 5 = CRS; and 6 = RTGRS.

Facility name	WIGOS station identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m MSL)	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
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 (KOS)	0-20000-0-11628	Czechia	49.57	15.08	536	1, 3, 4
Suchdol		Czechia	50.13	14.39	277	1
Risø Research Station		Denmark	55.63	12.10	5	1

(*Continued*)

Table B1. (*Continued*).

Facility name	WIGOS station identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m MSL)	Components
Villum Research Station		Denmark	81.60	–16.70	24	1
PAL 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
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
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
CMN 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 NF	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
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

(*Continued*)

Table B1. (*Continued*).

Facility name	WIGOS station identifier	Country of location	Lat (°N)	Lon (°E)	Alt (m MSL)	Components
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
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
BRM	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						
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
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

APPENDIX C
ACTRIS Variables

Tables C1–C7: The atmospheric variables are included in ACTRIS together with the responsible Data Centre unit, the associated TC, and methodology. Variables produced from a single measurement technique are indicated in cyan, variables produced from the synergy of measurement techniques are indicated in dark blue, and variables produced from the synergy of measurement techniques where several combinations are possible are indicated in light blue. ECV products are indicated with the symbol "*."

Table C1. The ACTRIS variable produced by TC ECAC–CAIS and associated measurement technique. The variable produced from a single measurement technique is indicated in cyan, the variable produced from the synergy of measurement techniques is indicated in dark blue, and the variable produced from the synergy of measurement techniques where several combinations are possible is indicated in light blue. ECV products are indicated with the symbol "*." ACTRIS CAIS–ECAC measurement guidelines: https://www.actris-ecac.eu/measurement-guidelines.html.

ACTRIS AIS variables	Measurement techniques							
	Integrating nephelometer	Mobility particle size spectrometer	Aerodynamic and optical particle size spectrometer	Absorption photometer	Condensation particle counter	Scanning PSM, (N) AIS, N-MPSS	Particle size magnifier (PSM)	Cloud condensation nucleus counter
Handled by in situ–the AIS 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			[cyan]					
Particle light absorption coefficient* and equivalent BC concentration				[cyan]				
Particle number concentration					[cyan]			
Nanoparticle number size distribution						[cyan]		
Nanoparticle number concentration							[cyan]	
Cloud condensation nucleus number concentration*								[cyan]

ACTRIS AIS variables	Measurement techniques				
	Filter sampling	Thermal–optical analyzer	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 AIS Data Centre unit					
Mass concentration of particulate organic and elemental carbon*	[dark blue]	[dark blue]			
Mass concentration of particulate organic tracers	[dark blue]		[dark blue]		
Mass concentration of nonrefractory particulate organics and inorganics				[cyan]	
Mass concentration of particulate elements	[dark blue]				[dark blue]

Table C2. **As in Table C1, but for TC CiGas. CiGas measurement guidelines: https://www.actris.eu/topical-centre/cigas.**

ACTRIS trace gas in situ variables	Measurement techniques: Online GC–FID	Online GC–MS	Online GC–FID/MS	Online GC–Medusa	Online PTR–MS	Online Hantzsch	Offline traps: ads-tubes	Offline traps: DNPH cartridge–HPLC	Offline steel canister	Offline glass flask	$NO–O_3$ chemilu-minescence	Potentially other measurement technique supported by the TC	Cavity-attenuated phase shift spectroscopy (CAPS)	CI–APi–TOF
NMHCs (~50 gases)	teal	teal	teal	teal	teal		teal		dark blue	dark blue				
OVOCs (~15 gases)	teal	teal	teal	teal	teal	teal	teal	teal	dark blue	dark blue				
NO											teal			
NO_2											teal	teal	teal	
Condensable vapors (~4 species)											grey	grey	grey	teal

Table C3. **As in Table C1, but for TC CIS. CIS measurement guidelines: https://www.actris.eu/topical-centre/cis.**

ACTRIS CIS variable	Measurement techniques: Integrating cloud probe	Cloud droplet probe	Cloud ice probe	Aerosol particle sampler	Bulk collectors	INP instrument
Liquid droplet mass concentration	teal	teal				
Liquid droplet effective radius	teal	teal				
Liquid droplet number concentration		teal				
Liquid droplet number size distribution		teal				
Ice particle number concentration			teal			
Ice particle number size distribution			teal			
Ice nucleating particle number concentration				blue		blue
Ice nucleating particle temperature spectrum				blue		blue
Liquid droplet inorganic ion mass concentration					teal	
Liquid droplet carboxylic acid mass concentration					teal	
Liquid droplet dissolved organic carbon mass concentration					teal	

Table C4. As in Table C1, but for TC CARS. CARS measurement guidelines: https://www.actris.eu/topical-centre/cars.

	Measurement techniques	
ACTRIS ARS variables	High-power aerosol lidar	Automatic sun/sky/lunar photometer
Attenuated backscatter profile		
Volume depolarization profile		
Particle backscatter coefficient profile		
Particle extinction coefficient profile*		
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. As in Table C1, but for TC CCRES. CCRES measurement guidelines: https://www.actris.eu/topical-centre/ccres/.

	Measurement techniques							Model
ACTRIS CRS variables	Cloud radar	Doppler cloud radar	Lidar/ceilometer	Radiosonde	Microwave radiometer	Drop-counting rain gauge	Disdrometer	NWP model input required
Cloud/aerosol target classification								
Drizzle drop size distribution								
Drizzle water content								
Drizzle water flux								
Ice water content								
Liquid water content								
Liquid water path*								
Temperature profile								
Relative humidity profile								
Integrated water vapor path								

Table C6. As in Table C1, but for TC 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/.

	Measurement techniques					
ACTRIS trace gas remote sensing variables	FTIR (single)	FTIR (double)	UV–Vis-Zenith-Sky	UV–Vis-MAXDOAS	UV–Vis-Pandora	O3-DIAL
Ozone profile						■
Ozone partial columns		■				■
Ozone column*		■	■	■	■	
Formaldehyde column	■	■		■	■	
Formaldehyde lower-tropospheric profile				■		
NO_2 column*	■	■	■	■	■	
NO_2 partial columns	■	■	■	■	■	
NO_2 lower-tropospheric profile				■		
NH_3 column		■				
C_2H_6 column	■	■				

Table C7. As in Table C1, but for simulation chamber variables and products. The phase relates to TC 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	Aerosol					■				■	
Mass absorption coefficients	Aerosol					■		■			
Mass scattering coefficients	Aerosol					■			■		
Complex refractive index	Aerosol		■		■			■	■		
Growth factors	Aerosol				■						

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