

# Biennial Report

Zweijahresbericht  
2024/2025



**TROPOS**

Leibniz Institute for  
Tropospheric Research





# TROPPOS

Leibniz Institute for  
Tropospheric Research

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### **TROPOS**

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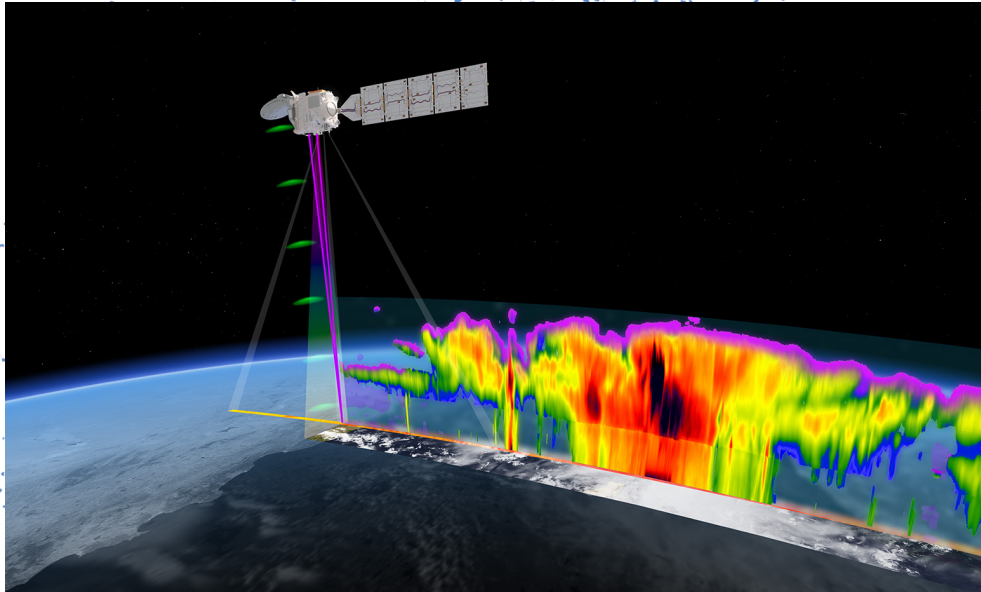
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# Introduction / Einleitung

## Overview / Übersicht





### Introduction

The Leibniz Institute for Tropospheric Research e. V. (TROPOS) has been located in the Leipzig Science Park/Permoserstrasse since 1992 in the neighbourhood of the Helmholtz Centre for Environmental Research, the Leibniz Institute for Surface Modification and other institutions. Its name identifies it as a member of the Leibniz Association.



Fig. / Abb. 1: TROPOS main building. / TROPOS-Hauptgebäude. © Patric Seifert, TROPOS

The institute is funded by the State of Saxony and the Federal Ministry of Research, Technology and Space with an annual basic budget of approx. 11.074 million Euros, and approx. 12.886 million Euros per year in third-party funding.

A total of 234 people are employed at TROPOS (including 37 student/scientific assistants, 3 apprentices), 176 of whom are scientists (as of 31 December 2025). TROPOS was founded to research physical and chemical processes in the polluted troposphere.

TROPOS has developed a clear and globally unique research profile, which today focuses on the physical and chemical interactions between atmospheric small airborne particles (aerosol particles) and cloud particles. Despite the smallest absolute



Fig. / Abb. 2: TROPOS chemistry laboratory. / Das TROPOS-Chemielaborgebäude. © Tilo Arnhold, TROPOS

### Einleitung

Das Leibniz-Institut für Troposphärenforschung e. V. (TROPOS) befindet sich seit 1992 im Wissenschaftspark Leipzig/Permoserstraße in der Nachbarschaft des Helmholtz-Zentrums für Umweltforschung, des Leibniz-Instituts für Oberflächenmodifizierung und anderer Einrichtungen. Sein Name weist es als Mitglied der Leibniz-Gemeinschaft aus.

Das Institut wird vom Freistaat Sachsen und dem Bundesministerium für Forschung, Technologie und Raumfahrt mit einem jährlichen Grundbudget von ca. 11,074 Millionen Euro und ca. 12,886 Millionen Euro pro Jahr an Drittmitteln gefördert.

Insgesamt sind 234 Personen am TROPOS beschäftigt (darunter 37 studentische/wissenschaftliche Hilfskräfte und 3 Auszubildende), davon 176 Wissenschaftler:innen (Stand: 31. Dezember 2025). TROPOS wurde gegründet, um physikalische und chemische Prozesse in der verschmutzten Troposphäre zu erforschen.

TROPOS hat ein klares und weltweit einzigartiges Forschungsprofil entwickelt, das sich heute auf die physikalischen und chemischen Wechselwir-



Fig. / Abb. 3: TROPOS cloud laboratory. / TROPOS-Wolkenlabor. © Tilo Arnhold, TROPOS

kungen zwischen atmosphärischen Schwebeteilchen (Aerosolpartikeln) und Wolkenpartikeln konzentriert. Trotz ihrer geringen absoluten Mengen sind diese Partikel wesentliche Bestandteile der Atmosphäre, da sie den Energie-, Wasser- und Spurenstoffhaushalt des Erdsystems beeinflussen. Menschliche Aktivitäten können die Eigenschaften dieser hochdispersen Systeme verändern und somit sowohl direkte als auch indirekte Auswirkungen auf die menschliche Gesundheit und das Klima haben.

Um diese starken Zusammenhänge aufzuklären, müssen die physikalisch-chemischen Prozesse der Aerosol- und Wolkenbildung sowie die Auswirkungen auf Gesundheit und Klima noch in erheblichem Umfang untersucht werden. Besondere

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Fig. / Abb. 4: EartCARE. © European Space Agency - ESA

quantities, these particles are essential components of the atmosphere because they influence the energy, water and trace substance balance of the earth system. Human activities can change the properties of these highly dispersed systems and thus have both a direct and indirect impact on human health and climate.

In order to clarify these strong connections, the physico-chemical processes of aerosol and cloud formation and the effects on health and climate still need to be investigated to a considerable extent. Particular challenges here are the analysis of the smallest quantities of substances involved and the complex behavior of atmospheric multiphase systems, whose individual processes in the atmosphere cannot be clearly observed separately. In the current state of knowledge on global climate change, this complexity is reflected in the much greater uncertainties in all published figures on aerosol and cloud effects compared to the state of knowledge on the effects of greenhouse gases.

In order to achieve a significant increase in the understanding of tropospheric multiphase processes and to improve their application to the prediction of the consequences of human intervention, TROPOS develops and carries out coordinated field, laboratory and modelling studies to investigate aerosol particles and clouds. The long-term measurements initiated by TROPOS are increasingly making it possible to record trends in regional and large-scale aerosol distribution and their impact on climate and health. The ACTRIS-D research infrastructure coordinated by TROPOS, which is part of the national roadmap and Germany's contribution to the European ACTRIS roadmap programme, plays a central role here and will significantly shape the work at TROPOS as well as national and international collaborations in the long term.

Herausforderungen stellen dabei die Analyse kleinster Stoffmengen und das komplexe Verhalten atmosphärischer Mehrphasensysteme dar, deren einzelne Prozesse in der Atmosphäre nicht klar getrennt beobachtet werden können. Beim aktuellen Wissensstand zum globalen Klimawandel spiegelt sich diese Komplexität wider: So sind die Unsicherheiten bei Aerosol- und Wolkeneffekten deutlich größer als bei den Auswirkungen von Treibhausgasen.

Um das Verständnis der troposphärischen Mehrphasenprozesse spürbar zu verbessern und ihre Anwendung zur Vorhersage der Folgen menschlicher Eingriffe zu optimieren, entwickelt und führt TROPOS koordinierte Feld-, Labor- und Modellstudien zur Untersuchung von Aerosolpartikeln und Wolken durch. Die von TROPOS initiierten Langzeitmessungen ermöglichen es zunehmend, Trends in der regionalen und großräumigen Aerosolverteilung und deren Auswirkungen auf Klima und Gesundheit zu erfassen. Die Forschungsinfrastruktur ACTRIS-D, die unter TROPOS-Koordination Teil der nationalen Roadmap und des deutschen Beitrags zum europäischen ACTRIS-Roadmap-Programm ist, spielt dabei eine zentrale Rolle und wird die Arbeit des TROPOS sowie nationale und internationale Kooperationen langfristig maßgeblich prägen.

### Feldversuche

Die Feldexperimente des Instituts dienen der Aufklärung des atmosphärischen Kreislaufs von Aerosol- und Wolkenpartikeln und der damit verbundenen Prozesse. Die Komplexität des Aerosol-Wolken-Systems wird unter anderem dadurch bestimmt, dass in der Atmosphäre Partikel und Tröpfchen auftreten, deren Durchmesser um mehr als sechs Größenordnungen variieren, vom Nanometer- bis zum Mikrometerbereich. Der Größenbereich von wenigen Nanometern, der unmittelbar nach der Bildung neuer Partikel



Fig. / Abb. 5: Start of construction for the Schmücke Cloud Observatory (SCO). / Baustart für das Schmücke-Wolken-Observatorium (SCO). © Tilo Arnholt, TROPOS

### Field experiments

The Institute's field experiments serve to elucidate the atmospheric cycle of aerosol and cloud particles and the associated processes. The complexity of the aerosol-cloud system is determined, among other things, by the fact that particles and droplets occur in the atmosphere whose diameters vary by more than six orders of magnitude from the nanometre to the micrometre range. The size range of a few nanometres, which occurs directly after the formation of new particles, has been added to the measurement range of aerosol size distributions at TROPOS. In addition, the liquid water droplet and ice crystal forming properties of aerosols interact with a regionally and globally changing Earth system. As a result of the diversity of microphysical, chemical and meteorological processes occurring, there is still a lack of quantitative understanding of the importance of aerosol-cloud interactions in the global climate system.

This uncertainty begins with the particle sources, which are an important subject of research at TROPOS. The combustion of fossil and renewable fuels for energy production and transport is a significant source of aerosols. Measurements taken by the institute at many urban measuring points, including at airports to characterize aircraft emissions, and continental background stations show that the emissions of particles and their precursors are followed by a variety of physical and chemical transformations that need to be analysed with high temporal resolution in order to elucidate the processes involved.

The Leipzig conurbation with the Melpitz background station is repeatedly at the centre of studies on air pollution with a focus on particles, which are often integrated into national and international collaborations. Despite very far-reaching legal regulations, air pollution still exists in Germany and Europe with



Fig. / Abb. 6: Indoor measurements in Rwanda. / Indoor-Messungen in Ruanda. © Leizel Madueno, TROPOS



Fig. / Abb. 7: Preparations for HALO South in Oberpfaffenhofen. / Vorbereitungen für HALO South in Oberpfaffenhofen. © Tilo Arnold, TROPOS

auftritt, wurde in den Messbereich der Aerosolgrößenverteilungen bei TROPOS aufgenommen.

Außerdem stehen die Flüssigwassertropfen- und Eiskristall-bildenden Eigenschaften der Aerosole in Wechselwirkung mit einem sich regional und global ändernden Erdsystem. Aufgrund der Vielfalt der auftretenden mikrophysikalischen, chemischen und meteorologischen Prozesse fehlt es nach wie vor an einem quantitativen Verständnis der Bedeutung von Aerosol-Wolken-Wechselwirkungen im globalen Klimasystem. Diese Unsicherheit beginnt bereits bei den Partikelquellen, die ein wichtiger Gegenstand der Forschung des TROPOS sind.

Die Verbrennung fossiler und erneuerbarer Brennstoffe zur Energieerzeugung und für den Verkehr ist eine bedeutende Quelle für Aerosole. Messungen des Instituts an vielen städtischen Messstellen, darunter auch an Flughäfen zur Charakterisierung von Flugzeugemissionen, und an kontinentalen Hintergrundstationen zeigen, dass auf die Emissionen von Partikeln und ihren Vorläufern eine Vielzahl physikalischer und chemischer Umwandlungen folgt, die mit hoher zeitlicher Auflösung analysiert werden müssen, um die beteiligten Prozesse aufzuklären.

Der Ballungsraum Leipzig mit der Hintergrundstation Melpitz steht immer wieder im Mittelpunkt von Studien zur Luftverschmutzung mit Schwerpunkt auf Partikeln, die häufig in nationale und internationale Kooperationen eingebunden sind. Trotz weitreichender gesetzlicher Regelungen gibt es in Deutschland und Europa nach wie vor Luftverschmutzung mit ihren Folgen für die Morbidität und Mortalität der Bevölkerung. Die Forschungsstation Melpitz wird zunehmend für gezielte Messkampagnen genutzt, auch um physikalisch-chemische hochauflösende In-situ-Charakterisierungen am Boden mit In-situ- und

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Fig. / Abb. 8: TROPOS buildings in Leipzig. / TROPOS-Gebäude in Leipzig. © Ariane Pohlentz, TROPOS

its consequences for the morbidity and mortality of the population. The Melpitz research station is increasingly being used for focused measurement campaigns, also to combine physico-chemical high-resolution in-situ characterisation on the ground with in-situ and remote sensing measurements of the entire column and the associated modelling.

The strongest polluted regions over North America, Europe, Asia with priority on China, Africa, the Indian subcontinent, and South America are far from being sufficiently characterized in terms of aerosol burdens and ensuing climate effects. TROPOS field experiments, including both measurement campaigns as well as long-term measurements are focused on Africa, Asia, South America and the Mediterranean region in international cooperation. The investigation of the increasing number of large forest fires is also becoming increasingly important here. The maritime troposphere over the clean southern and the more polluted northern Atlantic is being observed in long term measurements to better understand aerosol-cloud interactions.

Studies on mineral dust and marine aerosol particles, their interaction and their effects on the radiation budget, cloud formation. Atmospheric ice

Fernerkundungsmessungen der gesamten Säule und der damit verbundenen Modellierung zu kombinieren.

Die am stärksten verschmutzten Regionen über Nordamerika, Europa und Asien mit Schwerpunkt auf China, Afrika, dem indischen Subkontinent und Südamerika sind hinsichtlich der Aerosolbelastung und der daraus resultierenden Klimaauswirkungen bei weitem noch nicht ausreichend charakterisiert. Die Feldexperimente des TROPOS konzentrieren sich in internationaler Zusammenarbeit auf die Regionen Afrika, Asien, Südamerika und den Mittelmeerraum sowohl mit Messkampagnen als auch mit Langzeitmessungen. Auch die Untersuchung der zunehmenden Zahl großer Waldbrände gewinnt hier weiter an Bedeutung.

Die maritime Troposphäre über dem sauberen südlichen und dem eher verschmutzten nördlichen Atlantik wird ebenfalls langfristig beobachtet, um die Wechselwirkungen zwischen Aerosolen und Wolken besser zu verstehen. Studien zu Mineralstaub und marinen Aerosolpartikeln, deren Wechselwirkung und deren Auswirkungen auf den Strahlungshaushalt, die Wolkenbildung, die Eisbildung und die Atmosphärenchemie bleiben ein Kernbestandteil der Arbeit am TROPOS.

TROPOS ist Konsortialpartner beim Betrieb des deutschen Forschungsflugzeugs HALO und beteiligt sich regelmäßig an Flugkampagnen mit zunehmenden Aktivitäten in wenig erforschten Gebieten wie den Polarregionen. Die Studien zu Mineralstaub sind in die zunehmende Zusammenarbeit mit Ländern auf dem afrikanischen Kontinent wie Cabo Verde, Marokko, Nigeria und Namibia integriert.

Verschiedene bodengestützte Fernerkundungsmethoden werden am TROPOS entwickelt und gekoppelt, um ein synergetisches Bild der vertikalen Verteilung von Aerosolen und Hydrometeoren und deren Verarbeitung zu erhalten. Das Institut ist heute führend in der Entwicklung und Anwendung internationaler Lidar-Netzwerke zur Erfassung



Fig. / Abb. 9: Retirement of the Lidar BERTHA on 22 August 2024. / Außerbetriebnahme vom Lidar BERTHA am 22.08.24. © Beate Richter, TROPOS



Fig. / Abb. 10: ACTRIS-D station in Melpitz. / ACTRIS-D-Station Melpitz. © Tilo Arnhold, TROPOS

formation and atmospheric chemistry remain a core component of the work at TROPOS. TROPOS is a consortium partner in the operation of the German research aircraft HALO and is regularly involved in flight campaigns with increasing activities in understudied areas such as the polar regions. The studies on mineral dust are integrated into increasing co-operation with countries on the African continent, such as Cabo Verde, Morocco, Nigeria and Namibia.

Various ground-based remote sensing methods are developed and coupled at TROPOS in order to obtain a synergistic picture of the vertical distribution of aerosols and hydrometeors and their processing. The institute is now a leader in the development and application of international lidar networks for recording the four-dimensional aerosol distribution. The remote sensing methods developed at TROPOS are also used in international satellite programmes of various space agencies.

On smaller scales, investigations into particle formation and interaction between aerosol particles and clouds and the influence of turbulent mixing processes on cloud development are carried out using airborne measuring platforms. In addition, mountain stations are used for process studies dedicated to understanding individual processes such as the formation of new particles, the physico-chemical changes in aerosol particles during cloud passage and the influence of aerosol particles on the development and freezing of clouds.

TROPOS is significantly involved in regional, national and European in-situ measurement networks for the local recording of atmospheric aerosol and cloud cover. As part of the WMO's Global Atmospheric Watch (GAW) programme, the institute operates the World Calibration Centre for Physical Aerosol Measurements (WCCAP) with the aim of quality assurance of in-situ measurements at national and international measuring stations. Likewise, TROPOS has fully implemented the Organic Tracers and Aerosol

der vierdimensionalen Aerosolverteilung. Die bei TROPOS entwickelten Fernerkundungsmethoden werden auch in internationalen Satellitenprogrammen verschiedener Weltraumagenturen eingesetzt.

In kleinerem Maßstab werden mit Hilfe von luftgestützten Messplattformen Untersuchungen zur Partikelbildung und Wechselwirkung zwischen Aerosolpartikeln und Wolken sowie zum Einfluss turbulenter Mischprozesse auf die Wolkenentwicklung durchgeführt. Darüber hinaus werden Bergstationen für Prozessstudien genutzt, die dem Verständnis einzelner Prozesse wie der Bildung neuer Partikel, den physikalisch-chemischen Veränderungen von Aerosolpartikeln während des Wolkendurchgangs und dem Einfluss von Aerosolpartikeln auf die Entwicklung und Vereisung von Wolken gewidmet sind.

TROPOS ist maßgeblich an regionalen, nationalen und europäischen In-situ-Messnetzen zur lokalen Erfassung von atmosphärischem Aerosol und Wolken beteiligt. Im Rahmen des Global Atmospheric Watch (GAW)-Programms der WMO betreibt das Institut das World Calibration Centre for Physical Aerosol Measurements (WCCAP) mit dem Ziel der Qualitätssicherung von In-situ-Messungen an nationalen und internationalen Messstationen. Ebenso

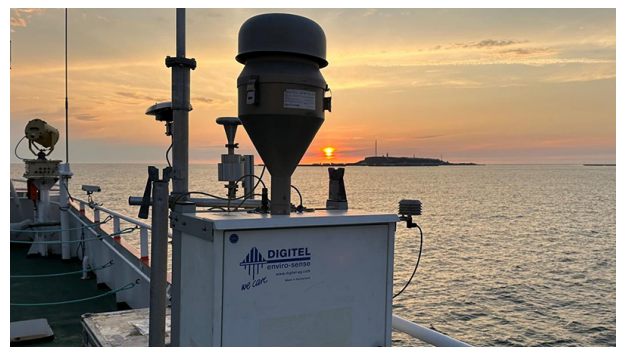


Fig. / Abb. 11: BASS-2024 near Helgoland. / BASS-2024 vor Helgoland. © Olenka Jibaja Valderrama, TROPOS

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Fig. / Abb. 12: Campaign AIDA-BELUGA in Svalbard. / Messkampagne AIDA-BELUGA auf Spitzbergen. © Mona Kellermann, TROPOS

Constituents Calibration Center (OGTAC-CC) harmonizing approaches for the chemical analysis of organic particulate constituents.

TROPOS continues to play a leading role in the development and operation of the networked European and national research infrastructure for recording aerosols, clouds and trace gases (ACTRIS) in order to investigate and understand the processes of short-lived climate components on all relevant scales. WCCAP and OGTAC-CC are part of the ACTRIS Central Facility (CF) Center for Aerosol In-Situ - European Center for Aerosol Calibration and Characterization (CAIS-ECAC) significantly supported by Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).

Field experiments are supported and extended by analyses based on meteorological satellite data. In particular, satellite products are used to analyse the spatiotemporal development of clouds and their radiative forcing, as well as the transport paths of aerosols.

### Laboratory experiments

#### Measurement technology

Numerous measurement methods are being developed in laboratory experiments that are used for particle characterisation in ground-based and airborne field measurement campaigns. This work includes, for example, the further development of aerosol size spectrometers and collection systems for the physical and chemical characterisation of cloud droplets and the interstitial aerosol, i.e. those aerosol particles that are suspended in the gas phase within

hat TROPOS das Organic Tracers and Aerosol Constituents Calibration Center (OGTAC-CC) vollständig implementiert, das die chemische Analyse organischer Partikelbestandteile wie sie in Feldmessungen aber auch in Simulationskammeruntersuchungen angewendet wird, harmonisiert.

TROPOS spielt weiterhin eine führende Rolle bei der Entwicklung und dem Betrieb der vernetzten europäischen und nationalen Forschungsinfrastruktur zur Erfassung von Aerosolen, Wolken und Spurengasen (ACTRIS), um die Prozesse kurzlebiger Klimakomponenten auf allen relevanten Skalen zu untersuchen und zu verstehen. WCCAP und OGTAC-CC sind Teil der ACTRIS Central Facility (CF) Center for Aerosol In-Situ – European Center for Aerosol Calibration and Characterization (CAIS-ECAC), die maßgeblich vom Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (BMUKN) unterstützt wird.

Feldversuche werden durch Analysen auf der Grundlage meteorologischer Satellitendaten unterstützt und erweitert. Insbesondere werden Satellitenprodukte zur Analyse der räumlich-zeitlichen Entwicklung von Wolken und ihrer Strahlungswirkung sowie der Transportwege von Aerosolen verwendet.

### Laborexperimente

#### Messtechnik

In Laborexperimenten werden zahlreiche Messmethoden entwickelt, die zur Partikelcharakterisierung in bodengestützten und luftgestützten Feldmesskampagnen eingesetzt werden. Diese Arbeit umfasst beispielsweise die Weiterentwicklung von Aerosol-Größenspektrometern und Sammelsystemen zur physikalischen und chemischen Charakterisierung von Wolkentröpfchen und interstitiellen Aerosolen, d. h. jener Aerosolpartikel, die zusätzlich zu den Wolkenpartikeln selbst in der Gasphase innerhalb von Wolken suspendiert sind.



Fig. / Abb. 13: Classroom laboratory of the BeCoLe indoor air project at NEL Leipzig. / Klassenzimmer-Labor des Innenraumluftprojektes BeCoLe bei NEL Leipzig. © Katrin Haase, HTWK

clouds in addition to the cloud particles themselves.

Optical measurement methods are developed and applied to determine the extinction coefficient of particles. Multi-wavelength lidars, a fluorescence lidar and a novel coupled wind and aerosol lidar are being further developed in the laboratory and used in the field to measure aerosol properties, aerosol fluxes and meteorological parameters such as temperature, humidity and wind. The proportions of biogenic and mineral aerosol components in aerosol samples are determined by spectral absorption measurements.

A major contribution of these efforts are the standardization of measurement methods making quality assured atmospheric data interoperable throughout key networks and beyond.

Technologically advanced measurement methods are also being developed for analysing the chemical composition of particles, in particular the EESI-MS (Extractive Electrospray Ionisation Mass Spectrometry) measurement method, which enables the analysis of organic particle components with both high time resolution and high mass spectrometric resolution.

### Process analyses

The activation of cloud droplets and heterogeneous ice formation under realistic turbulent environmental conditions are being investigated at the LACIS-T wind tunnel. The objectives of these investigations are to gain a better understanding of the process at a fundamental level, to identify critical and controlling parameters and to develop suitable parameterisations for describing droplet and ice formation in dynamic models.

Gas-phase reactions of various radicals are investigated in a series of flow reactors developed in-house. These reactions are important components of the tropospheric multiphase system, and the first steps of VOC oxidation convert the initially volatile and poorly water-soluble VOCs into products with lower



Fig. / Abb. 14: Visit by SMWK State Secretary Prof. Dr. Heike Graßmann to TROPOS on 17 June 2025. / Besuch von SMWK-Staatsekretärin Prof. Dr. Heike Graßmann am TROPOS am 17.06.25. © Tilo Arnholt, TROPOS



Fig. / Abb. 15: Mobile measurements during the 'Saxony Wood 2024-25' air measurement campaign in Radeburg near Dresden. / Mobile Messungen bei der Luftmesskampagne „Sachsen Holz 2024-25“ in Radeburg bei Dresden. © Tilo Arnholt, TROPOS

Es werden optische Messverfahren entwickelt und angewendet, um den Extinktionskoeffizienten von Partikeln zu bestimmen. Mehrwellenlängen-Lidare, ein Fluoreszenz-Lidar und ein neuartiges gekoppeltes Wind- und Aerosol-Lidar werden im Labor weiterentwickelt und im Feld eingesetzt, um Aerosoleigenschaften, Aerosolflüsse und meteorologische Parameter wie Temperatur, Feuchte und Wind zu messen. Der Anteil biogener und mineralischer Aerosolkomponenten in Aerosolproben wird durch spektrale Absorptionmessungen bestimmt.

Ein wesentlicher Beitrag dieser Bemühungen ist die Standardisierung von Messmethoden, wodurch qualitätsgesicherte atmosphärische Daten in allen wichtigen Netzwerken und darüber hinaus interoperabel werden.

Technologisch fortgeschrittene Messverfahren werden auch für die Analyse der chemischen Zusammensetzung von Partikeln entwickelt, so insbesondere das EESI-MS (Extractive Electrospray Ionization Mass Spectrometry) Messverfahren, das eine Analyse organischer Partikelbestandteile sowohl mit hoher Zeitauflösung wie auch hoher massenspektrometrischer Auflösung möglich ermöglicht wird.

### Prozessanalysen

Im Windkanal LACIS-T werden die Aktivierung von Wolkentröpfchen und die heterogene Eisbildung unter realistischen turbulenten Umgebungsbedingungen untersucht. Ziel dieser Untersuchungen ist es, ein besseres Verständnis des Prozesses auf fundamentaler Ebene zu erlangen, kritische und

## Introduction / Einleitung

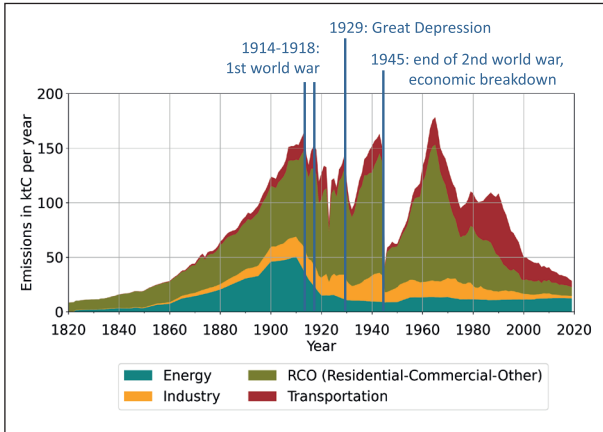


Fig. / Abb. 16: Timeseries of yearly soot emissions (black carbon, BC) in Germany since pre-industrial times, taken from the global emission inventory CEDS (Community Emissions Data System) and separated into different sectors. These emission data are used as an input to air quality modeling for historic periods. / Zeitreihe der jährlichen Rußemissionen (Black Carbon, BC) in Deutschland seit dem Beginn der Industrialisierung, entnommen aus dem globalen Emissionsinventar CEDS (Community Emissions Data System) und unterschieden nach den Sektoren Energie, Industrie, Hausbrand und Transport. Die Daten gehen in Simulationen zur Untersuchung der Luftqualität während der Industrialisierung ein. © Clara Seidel, TROPOS

vapour pressures and greater water solubility, so that they can then be absorbed into particles.

These interactions of trace gases with particles under oxidative conditions are the subject of research in the ACD-C aerosol chamber. These processes are of interest both for ozone formation in the gas phase and for the formation of secondary organic aerosols (SOA) from anthropogenic and biogenic volatile hydrocarbons. The resulting particles are also investigated with regard to their moisture growth and activation behaviour.

In addition to phase transfer parameters for trace gases and radicals, ACD-C is used to systematically analyse the products formed in the particle phase. These form the basis for corresponding model developments. Tropospheric particles are small chemical reactors that further modify the absorbed substances and thus ultimately explain the particle compositions observed in the field.

When particles contain water (for aerosol particles: 'aerosol liquid water (ALW)'), the particle phase reactions can be understood as reactions in aqueous solution. These reactions take place in the droplets of clouds, rain and fog, as well as in aqueous aerosol particles. Therefore, in the field of liquid phase laboratory investigations (in the so-called 'laser laboratory'), mechanisms of reactions with predominantly radical oxidants are investigated using photochemical radical generation and time-resolved optical detection techniques. In order to understand the oxidation of organic trace gases in the tropospheric multiphase system, a large number of reactions involving different radicals

kontrollierende Parameter zu identifizieren und geeignete Parametrisierungen zur Beschreibung der Tröpfchen- und Eisbildung in dynamischen Modellen zu entwickeln.

Gasphasenreaktionen verschiedener Radikale werden in einer Reihe selbst entwickelter Strömungsreaktoren untersucht. Diese Reaktionen sind wichtige Bestandteile des troposphärischen Multiphasensystems und die ersten Schritte der Oxidation von VOC konvertieren die zunächst flüchtigen und schlecht wasserlöslichen VOCs in Produkte mit kleineren Dampfdrücken und größerer Wasserlöslichkeit, so dass diese dann in Partikel aufgenommen werden können.

Diese Wechselwirkungen von Spurengasen mit Partikeln unter oxidativen Bedingungen bilden dann das Arbeitsthema der Aerosolkammer ACD-C. Diese Prozesse sind für einerseits für die Ozonbildung in der Gasphase und andererseits für die Bildung des sog. „secondary organic aerosol (SOA)“ sowohl durch anthropogene als auch biogene flüchtige Kohlenwasserstoffe von Interesse. Die entstehenden Partikel werden auch hinsichtlich ihres Feuchtigkeitswachstums und ihres Aktivierungsverhaltens untersucht.

Mit ACD-C werden neben Phasentransferparameter für Spurengase und Radikale insbesondere die in der Partikelphase entstehenden Produkte systematisch analysiert. Diese legen die Grundlage für entsprechende Modellentwicklungen. Troposphärische Partikel sind kleine chemische Reaktoren, die die aufgenommenen Stoffe weiter modifizieren und so schließlich die im Feld beobachteten Partikelzusammensetzungen erklären.

Wenn Partikel Wasser enthalten (für Aerosolpartikel: „Aerosol Liquid Water (ALW)“ können die Partikelphasenreaktionen als Reaktionen in wässriger Lösung verstanden werden. Diese Reaktionen finden in den Tröpfchen von Wolken, Regen und Nebel sowie in wässrigen Aerosolpartikeln statt. Daher werden im Bereich der Flüssigphasen-Laboruntersuchungen (im sog. „Laserlabor“) Mechanismen von Reaktionen mit vorwiegend radikalischen Oxidationsmitteln mit photochemischer Radikalerzeugung und zeitaufgelösten optischen Detektionstechniken untersucht. Um die Oxidation organischer Spurengase im troposphärischen Mehrphasensystem zu verstehen, wird eine Vielzahl von Reaktionen verschiedener Radikale untersucht. Einen aktuellen Schwerpunkt bilden hier Untersuchungen zum Abbau ansonsten langlebiger Verbindungen wie z.B. der so. PFAS (Per- and Polyfluoroalkyl Substances), um zu besseren Einschätzungen der tatsächlichen atmosphärischen Lebensdauern gelangen zu können.

Ein weiterer aktueller Forschungsschwerpunkt ist die Bildung von Radikalen und Oxidationsmitteln

are being investigated. A current focus here is on investigations into the degradation of otherwise long-lived compounds such as PFAS (per- and polyfluoroalkyl substances) in order to arrive at better estimates of their actual atmospheric lifetimes.

Another current research focus is the formation of radicals and oxidants in the so-called Fenton reaction between Fe(II) and  $\text{H}_2\text{O}_2$ . This family of reactions could potentially be the largest source of OH radicals in tropospheric aqueous aerosol particles.

The chemical process investigations described above lead to improvements in the chemical mechanisms used in modelling with the CAPRAM mechanism, initially in box models and then increasingly in higher-scale models.

In analytical measurement technology, methods for better chemical characterisation of the organic components of aerosol particles are being developed and tested in laboratory experiments. These techniques are mostly based on mass spectrometric methods used in various coupling techniques. In the field of sampling techniques, the departments are working closely together to develop a targeted separation of particles of specific sizes and their chemical analysis, as well as to develop inlet systems and reactors.

A further calibration centre for the analysis of multiphase processes and cloud water (CCWAC) is being established as part of ACTRIS.

in der sogenannten Fenton-Reaktion zwischen Fe(II) und  $\text{H}_2\text{O}_2$ . Diese Familie von Reaktionen kann potentiell die größte Quelle von OH Radikalen in troposphärischen wässrigen Aerosolpartikeln sein.

Die beschriebenen chemischen Prozessuntersuchungen führen zu Verbesserungen der chemischen Mechanismen, die in der Modellierung mit dem CAPRAM-Mechanismus des TROPOS verwendet werden, zunächst in Box-Modellen und dann zunehmend in Modellen höherer Skalen. In der analytischen Messtechnik werden Methoden zur besseren chemischen Charakterisierung der organischen Bestandteile von Aerosolpartikeln entwickelt und in Laborexperimenten getestet. Diese Techniken basieren meist auf massenspektrometrischen Methoden, die in verschiedenen Kopplungstechniken eingesetzt werden. Im Bereich der Probenahmetechniken besteht eine enge Zusammenarbeit der Abteilungen zur Entwicklung einer gezielten Abtrennung von Partikeln bestimmter Größen und deren chemischen Analyse sowie zur Entwicklung von Einlasssystemen und Reaktoren.

Im Rahmen von ACTRIS wird ein weiteres Kalibrierzentrum für die Analyse von Mehrphasenprozessen und Wolkenwasser (CCWAC) eingerichtet.

### Modellierung

Um die komplexen atmosphärischen Prozesse zu beschreiben, werden Modellierungssysteme

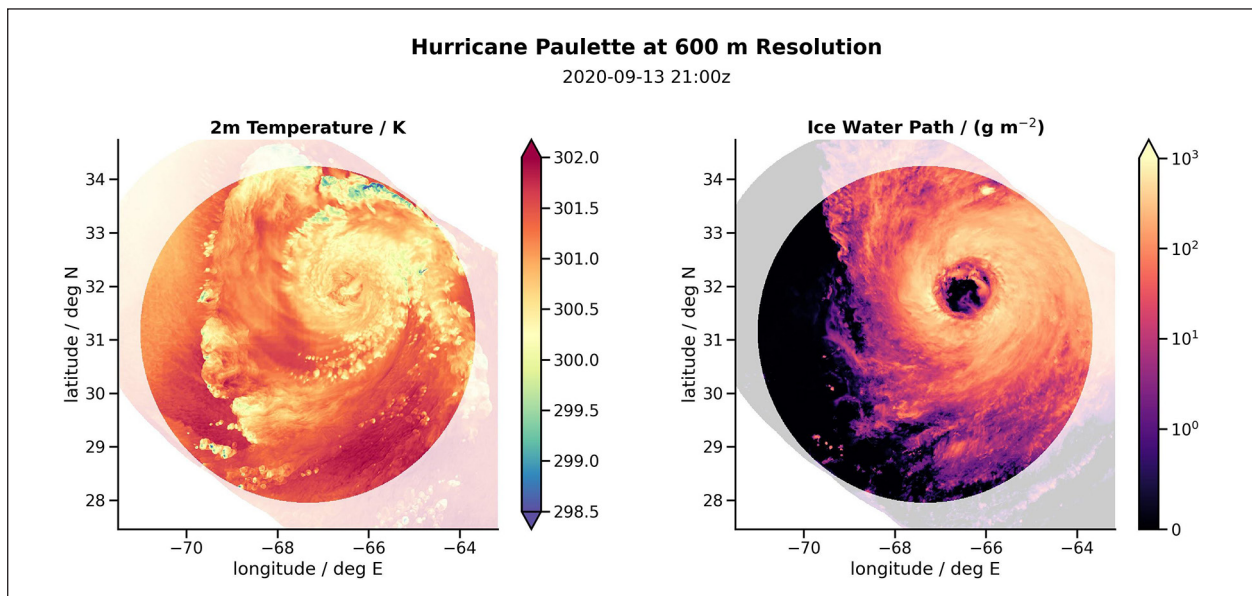


Fig. / Abb. 17: Simulation of the local effects of Hurricane Paulette (2020) on the 2-meter temperature (left) and the ice water path (right). The simulations were created using a newly developed, highly efficient ICON setup that calculates the hurricane's development along its path. A 500 km wide area with a resolution of 600 m was taken into account. / Simulation der lokalen Effekte des Hurrikans Paulette (2020) auf die 2-Meter-Temperatur (links) und den Eiswasserpfad (rechts). Die Simulationen wurden mit einem neuartigen, hocheffizienten ICON-Setup erstellt, das die Entwicklung des Hurrikans entlang seines Pfades berechnet. Dabei wurde ein 500 km breiter Bereich mit einer Auflösung von 600 m berücksichtigt. © Fabian Senf, TROPOS

## Introduction / Einleitung

### Modelling

To describe the complex atmospheric processes, modelling systems of different dimensions, complexity and scales are developed, tested and applied, also in combination with data from field measurements and remote sensing. The modelling studies are intended to describe the atmospheric processes and interactions between aerosol particles, gases and clouds, as well as the direct and indirect influences of aerosol particles on the radiation budget.

Model studies of aerosol processes and aerosol-cloud interaction to investigate radiation and climate effects are performed with the global aerosol climate model ECHAM-HAM or, more recently, ICON-HAM. The model parameterisation of aerosol processes developed on high-resolution scales can be directly taken into account in climate studies using coarser resolution. One research focus is the investigation of control factors and effects of natural aerosols such as mineral dust, marine aerosol, smoke particles from forest fires or organic aerosol from plant emissions.

Regional chemical transport modelling for air quality studies is performed with the aerosol-chemistry model MUSCAT that has been developed at TROPOS. Coupled to the regional meteorology model COSMO or the ICON model, it is a suitable transformation for simulating the dispersion behaviour of particles and gases on a regional scale which has been demonstrated in several international model comparisons and in the processing of air quality issues. The dynamics of primary and secondary aerosol particles and their interaction with radiation and clouds are being simulated in several projects. An "urbanised" version of COSMO-MUSCAT, which uses a horizontal grid resolution of up to a few 100 m, has also been developed for further applications, in particular air quality studies.

In addition, one- and two-dimensional process models have been and are being further developed. SPECS (SPECTral bin cloud microphysicS) is used to describe cloud processes. It allows an explicit and very precise calculation of the processes condensation, collision or freezing, and can be used as a box model as well as for case studies coupled with the regional COSMO or ICON model in a regional setup. SPACCIM (SPECTral Aerosol Cloud Chemistry Interaction Model) is a package model for the coupled size-resolved description of microphysics and multiphase chemistry. Process modelling is carried out in conjunction with field studies and laboratory experiments, often mediated by CAPRAM. CAPRAM is disseminated to users around the world through international outreach activities and is used worldwide for modeling the tropospheric multiphase system.

unterschiedlicher Dimensionen, Komplexität und Skalen entwickelt, getestet und angewendet, auch in Kombination mit Daten aus Feldmessungen und Fernerkundung. Die Modellierungsstudien sollen die atmosphärischen Prozesse und Wechselwirkungen zwischen Aerosolpartikeln, Gasen und Wolken sowie die direkten und indirekten Einflüsse von Aerosolpartikeln auf den Strahlungshaushalt beschreiben.

Modellstudien zu Aerosolprozessen und Aerosol-Wolken-Wechselwirkungen zur Untersuchung von Strahlungs- und Klimaeffekten werden mit dem globalen Aerosol-Klimamodell ECHAM-HAM oder, seit kurzem, mit ICON-HAM durchgeführt. Die auf hochauflösenden Skalen entwickelte Modellparameterisierung von Aerosolprozessen kann in Klimastudien mit größerer Auflösung direkt berücksichtigt werden. Ein Forschungsschwerpunkt ist die Untersuchung von Einflussfaktoren und Auswirkungen natürlicher Aerosole wie Mineralstaub, Meeres-Aerosole, Rauchpartikel aus Waldbränden oder organische Aerosole aus Pflanzenemissionen.

Regionale chemische Transportmodellierungen für Luftqualitätsstudien werden mit dem bei TROPOS entwickelten Aerosol-Chemie-Modell MUSCAT durchgeführt. Gekoppelt an das regionale Meteorologiemodell COSMO oder das ICON-Modell hat es sich in mehreren internationalen Modellvergleichen und bei der Bearbeitung von Luftqualitätsfragen als geeignet für die Simulation des Ausbreitungsverhaltens von Partikeln und Gasen auf regionaler Skala erwiesen. Die Dynamik von primären und sekundären Aerosolpartikeln und ihre Wechselwirkung mit Strahlung und Wolken werden in mehreren Projekten simuliert. Für weitere Anwendungen, insbesondere Luftqualitätsstudien, wurde auch eine „urbanisierte“ Version von COSMO-MUSCAT entwickelt, die eine horizontale Gitterauflösung von bis zu einigen 100 m verwendet.

Darüber hinaus wurden und werden ein- und zweidimensionale Prozessmodelle weiterentwickelt. SPECS (SPECTral bin cloud microphysicS) wird zur Beschreibung von Wolkenprozessen verwendet. Es ermöglicht eine explizite und sehr genaue Berechnung der Prozesse Kondensation, Kollision oder Gefrieren und kann sowohl als Box-Modell als auch für Fallstudien in Verbindung mit dem regionalen COSMO- oder ICON-Modell in einem regionalen Setup verwendet werden. SPACCIM (SPECTral Aerosol Cloud Chemistry Interaction Model) ist ein Paketmodell für die gekoppelte größen aufgelöste Beschreibung von Mikrophysik und Mehrphasenchemie. Die Prozessmodellierung erfolgt in Verbindung mit Feldstudien und Laborexperimenten, häufig vermittelt durch CAPRAM.

# Overview of the individual contributions / Übersicht der Einzelbeiträge

## Overview of the individual contributions

This biennial report presents selected scientific TROPOS work from 2024 to 2025 in four long and 20 short articles. As in previous years, a broad spectrum of field, laboratory and modelling work is presented, which investigates both fundamental and novel physical and chemical mechanisms in aerosols and their interactions with clouds and the application fields climate and health. The articles demonstrate the institutes strategy to more deeply explore the role of aerosols and aerosol-cloud interaction in the coupled and anthropogenically affected Earth System where the marine and terrestrial environment in a changing world plays a stronger role.

### Long articles

TROPOS is proud to have established a Leibniz ScienceCampus on the topic of 'Smoke and Bioaerosols in Climate Change' (BioSmoke) together with the University of Leipzig, the German Biomass Research Centre (DBFZ) and the Helmholtz Centre for Environmental Research (UFZ) who contribute expertise in biomass combustion analysis, water and energy cycles, and ecological dynamics. BioSmoke aims to clarify the controlling factors and effects of the release of aerosol particles from vegetation fires. **Tegen et al.** summarize initial scientific results include observational and modelling studies of smoke layers caused by pyroconvection, analyses of dust emission, and the chemical ageing of mineral particles mobilised by strong winds associated with pyroconvective events.

Smoke plumes and their regional to global transports can be observed in great details also from the new EarthCARE satellite, launched in May 2024, with an expected life time of 10 years. EarthCARE provides a unique combination of active and passive instruments for atmospheric observations aerosol and clouds. TROPOS leads the development of data-processing algorithms for two of the four instruments on board the satellite: the Atmospheric Lidar (ATLID) and the Multi-Spectral Imager (MSI). Impressive examples of EarthCARE's capabilities to assess large scale atmospheric aerosol and cloud phenomena like wildfires and hurricanes as well as tremendous efforts to calibrate sensors and to validate products are reported by **Bley et al.**

Another fascinating features visible from satellite are oceanic phytoplankton blooms. These blooms strongly effect the so-called sea surface micro layer (SML) which in turn is a source of emissions of marine biogenic aerosols into the atmosphere. As a biologically highly productive environment that is

## Übersicht der Einzelbeiträge

Dieser Zweijahresbericht präsentiert ausgewählte wissenschaftliche Arbeiten von TROPOS aus den Jahren 2024 bis 2025 in vier langen und 20 kurzen Artikeln. Wie in den Vorjahren wird ein breites Spektrum an Feld-, Labor- und Modellierungsarbeiten vorgestellt, die sowohl grundlegende als auch neuartige physikalische und chemische Mechanismen in Aerosolen und deren Wechselwirkungen mit Wolken sowie die Anwendungsbereiche Klima und Gesundheit untersuchen. Die Artikel veranschaulichen die Strategie des Instituts, die Rolle von Aerosolen und die Wechselwirkungen zwischen Aerosolen und Wolken im gekoppelten und anthropogen beeinflussten Erdsystem, in dem die marine und terrestrische Umwelt in einer sich verändernden Welt eine immer wichtigere Rolle spielt, eingehender zu untersuchen.

### Langbeiträge

TROPOS ist stolz darauf, gemeinsam mit der Universität Leipzig, dem Deutschen Biomasseforschungszentrum (DBFZ) und dem Helmholtz-Zentrum für Umweltforschung (UFZ), die ihr Fachwissen in den Bereichen Biomasseverbrennungsanalyse, Wasser- und Energiekreisläufe sowie ökologische Dynamik einbringen, einen Leibniz-Wissenschaftscampus zum Thema „Rauch und Bioaerosole im Klimawandel“ (BioSmoke) gegründet zu haben. BioSmoke hat sich zum Ziel gesetzt, die Einflussfaktoren und Auswirkungen der Freisetzung von Aerosolpartikeln aus Vegetationsbränden zu klären. **Tegen et al.** fassen erste wissenschaftliche Ergebnisse zusammen, darunter Beobachtungs- und Modellstudien zu Rauchsichten, die durch Pyrokonvektion entstehen, Analysen der Staubemission und die chemische Alterung von Mineralpartikeln, die durch starke Winde im Zusammenhang mit pyrokonvektiven Ereignissen mobilisiert werden.

Rauchwolken und ihre regionalen bis globalen Transportwege können auch vom neuen Satelliten EarthCARE, der im Mai 2024 gestartet wurde und eine erwartete Lebensdauer von 10 Jahren hat, detailliert beobachtet werden. EarthCARE bietet eine einzigartige Kombination aus aktiven und passiven Instrumenten für atmosphärische Beobachtungen von Aerosolen und Wolken. TROPOS leitet die Entwicklung der Algorithmen für die Datenprozessoren für zwei der vier Instrumente an Bord des Satelliten: das Atmospheric Lidar (ATLID) und den Multi-Spectral Imager (MSI). Beeindruckende Beispiele für die Fähigkeiten von EarthCARE zur Bewertung großräumiger atmosphärischer Aerosol- und Wolkenphänomene wie Waldbrände und Hurrikane sowie

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simultaneously exposed to strong actinic radiation, the SML represents a potential hotspot for photochemical reactions. **Jibaja Valderrama et al.** introduce TROPOS' strong contributions to the international project BASS (Biogeochemical processes and Air-sea exchange in the Sea-Surface microlayer) with investigations of photochemical production and degradation of carbonyl compounds, as well as photochemical oxidation capacity in samples of natural SML and underlying water (ULW).

Ocean regions are characterised by high cloud cover, which has a significant impact on the Earth's radiation budget. The latter also varies with the ice fraction in these clouds which in the case of remote ocean regions strongly depend on local marine ice-nucleating particles (INPs). **Hartmann et al.** report on polysaccharides from the marine biosphere that are produced, among others, by marine fungi which act as ice-nucleating macromolecules (INMs). By applying a new physically based INM parameterization on model simulations, it was shown that a considerable fraction of marine INPs result from polysaccharides, which is another example of atmosphere-ocean interaction in the field of aerosols and clouds.

### Short articles

#### *Fundamentals*

Physical and chemical processes in the atmosphere are complex due to numerous interactions on all scales and a multitude of reaction pathways in all phases. Therefore, much of the work at TROPOS consists of fundamental process studies of varying complexity in order to understand processes and parameterise them from small to larger scales. Furthermore, fundamental work must be carried out in measurement technology in order to develop standards, without which long-term comparable recording of the tropospheric system would not be possible.

Disperse multiphase flows are ubiquitous in natural phenomena such as aerosol dispersion, sediment transport, and cloud formation, as well as in technological applications like inhalers, mixing processes, and internal combustion engines. With SCALE-TRACK, **Schmalfuß et al.** provided a breakthrough in Euler-Lagrange-based disperse multiphase modelling with unprecedented scalability and performance speed.

On a larger scale hurricanes are probably the most impressive example of disperse fluid flows in the atmosphere. **Cremer and Senf** managed to simulate the tropical hurricane Paulette with high spatiotemporal and microphysical particle resolution in such

die enormen Anstrengungen zur Kalibrierung der Sensoren und Validierung der Produkte werden von **Bley et al.** beschrieben.

Ein weiteres faszinierendes Merkmal, das vom Satelliten aus sichtbar ist, sind die Blüten des ozeanischen Phytoplanktons. Diese Blüten haben einen starken Einfluss auf die sogenannte Meeresoberflächenmikroschicht (SML), die wiederum eine Quelle für Emissionen von marinen biogenen Aerosolen in die Atmosphäre ist. Als biologisch hochproduktive Umgebung, die gleichzeitig starker aktinischer Strahlung ausgesetzt ist, stellt die SML einen potenziellen Hotspot für photochemische Reaktionen dar. **Jibaja Valderrama et al.** stellen die wichtigen Beiträge von TROPOS zum internationalen Projekt BASS (Biogeochemical processes and Air-sea exchange in the Sea-Surface microlayer) vor, das sich mit der photochemischen Produktion und dem Abbau von Carbonylverbindungen sowie der photochemischen Oxidationskapazität in Proben der natürlichen SML und des darunter liegenden Wassers (ULW) befasst.

Ozeanregionen sind durch eine hohe Bewölkung gekennzeichnet, die einen erheblichen Einfluss auf den Strahlungshaushalt der Erde hat. Letztere variiert auch mit dem Eisanteil in diesen Wolken, der im Falle entlegener Meeresregionen stark von lokalen marinen Eiskeimbildenden Partikeln (INPs) abhängt. **Hartmann et al.** berichten über Polysaccharide aus der marinen Biosphäre, die unter anderem von marinen Pilzen produziert werden, die als Eiskeimbildende Makromoleküle (INMs) fungieren. Durch die Anwendung einer neuen physikalisch basierten INM-Parameterisierung auf Modellsimulationen wurde gezeigt, dass ein beträchtlicher Anteil der marinen INPs aus Polysacchariden stammt, was ein weiteres Beispiel für die Wechselwirkung zwischen Atmosphäre und Ozean im Bereich von Aerosolen und Wolken ist.

### Kurzbeiträge

#### *Grundlagen*

Physikalische und chemische Prozesse in der Atmosphäre sind aufgrund zahlreicher Wechselwirkungen auf allen Skalen und einer Vielzahl von Reaktionswegen in allen Phasen komplex. Daher besteht ein Großteil der Arbeit bei TROPOS aus grundlegenden Prozessstudien unterschiedlicher Komplexität, um Prozesse zu verstehen und sie von kleinen bis zu größeren Skalen zu parametrisieren. Darüber hinaus müssen grundlegende Arbeiten in der Messtechnik durchgeführt werden, um Standards zu entwickeln, ohne die eine langfristig vergleichbare Erfassung des troposphärischen Systems nicht möglich wäre.

Disperse Mehrphasenströmungen sind in Naturphänomenen wie Aerosoldispersion,

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details, creating a new dataset in a way that has not been possible before.

Such high-resolution cloud modelling, together with ground-based and satellite-based remote sensing, provides spatial cloud fields that are used in the DFG research group "Cloud 3d Structure And Radiation" C3SAR to investigate the role of 3D cloud variability in the cloud radiation budget and in cloud remote sensing. **Macke et al.** present the overall concept of C3SAR and initial results.

Another example of including high-resolution process modelling is presented by **Bran et al.**, who studied Cl atom activation via iron-chloride multiphase chemistry using the TROPOS aqueous-phase chemical mechanism CAPRAM, coupled with the gas-phase Master Chemical Mechanism (MCM) within the box model SPACCIM to arrive at a better understanding of chemical methane removal in the atmosphere.

**Mothes and Herrmann** demonstrate that the newly established ACTRIS calibration centre (CC) for OrGanic Tracers and Aerosol Constituents (OGTAC-CC) has successfully performed an inter-laboratory comparison to assess the readiness of European laboratories to provide harmonized measurements for the key biomass burning tracers levoglucosan, mannosan and galactosan in PM<sub>2.5</sub>.

### *Aerosols and aerosol-cloud interaction in cold regions*

In recent years both the Arctic and Antarctica have been in the focus of in-situ, remote sensing as well as modelling process studies of aerosols and clouds due to the special conditions in these strongly either marine or continental co-located areas with extreme seasonality, which stands in contrast to the situation in the mid-latitudes and the tropics.

From multi-year measurements of ice nucleating particles (INPs) taken at Antarctic observatories together with ship-based observations **Wex et al.** found extremely low INP concentration showing no annual cycle and no measurable biogenic components. This is attributed to the fact that there is hardly any biosphere in Antarctica.

An important source of aerosols in the otherwise pristine polar regions is due to new particle formation, especially during the Arctic spring and summer. **Kellermann et al.** performed and analysed balloon-borne.

The TROPOS mobile remote sensing facility OCEANET has been deployed both in the Arctic during MOSAiC and in Antarctica on the AWI Neumayer-Station for more than one year. From these data, **Griesche et al.** demonstrate that free-tropospheric Arctic mixed-phase clouds are usually not

Sedimenttransport und Wolkenbildung sowie in technologischen Anwendungen wie Inhalatoren, Mischprozessen und Verbrennungsmotoren allgegenwärtig. Mit SCALE-TRACK gelang **Schmalfuß et al.** ein Durchbruch in der Euler-Lagrange-basierten dispersen Mehrphasenmodellierung mit beispielloser Skalierbarkeit und Leistungsgeschwindigkeit.

In größerem Maßstab sind Hurrikane wahrscheinlich das eindrucksvollste Beispiel für disperse Strömungen in der Atmosphäre. **Cremer und Senf** gelang es, den tropischen Hurrikan Paulette mit hoher räumlicher und zeitlicher Auflösung sowie mikrophysikalischer Partikelauflösung so detailliert zu simulieren, dass sie einen neuen Datensatz schufen, der in dieser Form bisher nicht möglich war.

Eine solche hochauflösende Wolkenmodellierung liefert zusammen mit bodengestützter und satellitengestützter Fernerkundung räumliche Wolkenfelder, die in der DFG-Forschungsgruppe „Cloud 3d Structure And Radiation“ (C3SAR) verwendet werden, um die Rolle der 3D-Wolkenvariabilität im Wolkenstrahlungshaushalt und in der Wolkenfernerkundung zu untersuchen. **Macke et al.** stellen das Gesamtkonzept von C3SAR und erste Ergebnisse vor.

Ein weiteres Beispiel für die Einbeziehung hochauflösender Prozessmodellierung wird von **Bran et al.** geliefert, die die Aktivierung von Cl-Atomen durch Eisen-Chlorid-Mehrphasenchemie unter Verwendung des TROPOS-Wasserphasen-Chemie-Mechanismus CAPRAM in Verbindung mit dem Gasphasen-Master-Chemie-Mechanismus (MCM) innerhalb des Box-Modells SPACCIM untersuchten, um ein besseres Verständnis der chemischen Methanentfernung in der Atmosphäre zu erlangen.

**Mothes und Herrmann** zeigen, dass das neu eingerichtete ACTRIS-Kalibrierungszentrum (CC) für organische Tracer und Aerosolbestandteile (OGTAC-CC) erfolgreich einen Laborvergleich durchgeführt hat, um die Fähigkeit europäischer Labore zu bewerten, harmonisierte Messungen für die wichtigsten Tracer für die Verbrennung von Biomasse, Levoglucosan, Mannosan und Galactosan in PM<sub>2,5</sub>, durchzuführen.

### *Aerosole und Wechselwirkungen zwischen Aerosolen und Wolken in kalten Regionen*

In den letzten Jahren standen sowohl die Arktis als auch die Antarktis im Mittelpunkt von In-situ-, Fernerkundungs- und Modellierungsstudien zu Aerosolen und Wolken aufgrund der besonderen Bedingungen in diesen stark marinen oder kontinental geprägten Gebieten mit extremer Saisonalität, die im Gegensatz zur Situation in den mittleren Breiten und den Tropen stehen.

Aus mehrjährigen Messungen von Eiskeimpartikeln (INPs) an antarktischen Observatorien sowie

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limited by the supply of CCN (cloud-condensation nuclei) and INP whereas Antarctica clouds form under aerosol-limited conditions.

The latter could also be the case for continental mixed-phase clouds. To investigate this, TROPOS collaborated with ETH Zurich to conduct silver iodide cloud seeding experiments and accompanied them numerically in a model with new nucleation parameterisations. **Schimmel et al.** present the model simulations and their good agreement with observations.

### *Aerosol characterization*

Aerosol varies strongly in size, concentration and type which all determine their effects on health and climate, the latter either directly or indirectly via aerosol-cloud interaction. Recent developments at TROPOS in modelling and observations have considerably improved our capabilities to distinguish between different aerosol types and to assess their corresponding effects on cloud formation.

As many aerosol processes have a strong regional character, like desert dust and wildfire smoke, **Heinold et al.** developed a limited-area configuration of the ICON Earth System Model coupled to the reduced-complexity aerosol module HAM-lite for computationally efficient, convection-permitting aerosol simulations. The explicit representation of convection enables consistent aerosol-cloud-radiation coupling and has been successfully applied to desert dust and major wildfire events in Australia.

The major challenge in dust remote sensing is to correctly account for the irregularly shaped dust particles. **Haarig et al.** report on the new Leibniz Junior Research Group “Optical LABORatory for Lidar Applications” (OLALA) that for the first time provides a laboratory basis for determining the lidar properties of real dust particles in exact backscattering direction to improve lidar retrieval algorithms.

Promising areas of application of these retrieval lie in the northern hemisphere dust belt stretching from West Africa over Central Asia to China. **Hofer et al.** present the first long-term analysis from the permanently operated lidar station in Central Asia, run by TROPOS in cooperation with local partners in Dushanbe, Tajikistan. This reveals, for example, characteristic seasonal patterns in mineral dust loading.

Another type of aerosol that is attracting increasing attention in the study of the coupled biosphere/atmosphere system is biogenic particles. Using the example of soot emissions from severe forest fires, **Gast et al.** show how these can be detected high up in the stratosphere and thus their global long-range transport using fluorescence lidar technology.

aus Beobachtungen von Schiffen aus haben **Wex et al.** eine extrem niedrige INP-Konzentration festgestellt, die keinen Jahreszyklus und keine messbaren biogenen Komponenten aufweist. Dies wird darauf zurückgeführt, dass es in der Antarktis kaum eine Biosphäre gibt.

Eine wichtige Quelle für Aerosole in den ansonsten unberührten Polarregionen ist die Bildung neuer Partikel, insbesondere während des arktischen Frühlings und Sommers. **Kellermann et al.** führten mit dem TROPOS-Fesselballonsystem BELUGA vertikale Profilierungen von ultrafeinen Partikeln in der Arktis durch und analysierten diese.

Die mobile Fernerkundungsanlage OCEANET von TROPOS wurde sowohl in der Arktis während MOSAiC als auch in der Antarktis auf der AWI-Neumayer-Station für mehr als ein Jahr eingesetzt. Anhand dieser Daten zeigen **Griesche et al.**, dass freie troposphärische Mischphasenwolken in der Arktis in der Regel nicht durch die Versorgung mit CCN (Wolkenkondensationskeimen) und INP begrenzt sind, während sich Wolken in der Antarktis unter aerosolbegrenzten Bedingungen bilden.

Letzteres könnte auch für kontinentale Mischphasenwolken gelten. Um dies zu untersuchen, führte TROPOS in Zusammenarbeit mit der ETH Zürich Silberiodid-Wolkenimpfungsexperimente durch und begleitete diese numerisch in einem Modell mit neuen Nukleationsparametrisierungen. **Schimmel et al.** präsentieren die Modellsimulationen und deren gute Übereinstimmung mit den Beobachtungen.

### *Charakterisierung von Aerosolen*

Aerosole variieren stark in Größe, Konzentration und Art, was ihre Auswirkungen auf Gesundheit und Klima bestimmt, wobei letzteres entweder direkt oder indirekt über die Wechselwirkung zwischen Aerosolen und Wolken erfolgt. Jüngste Entwicklungen bei TROPOS im Bereich der Modellierung und Beobachtung haben unsere Fähigkeiten, zwischen verschiedenen Aerosolarten zu unterscheiden und ihre entsprechenden Auswirkungen auf die Wolkenbildung zu bewerten, erheblich verbessert.

Da viele Aerosolprozesse einen starken regionalen Charakter haben, wie beispielsweise Wüstenstaub und Waldbrandrauch, entwickelten **Heinold et al.** eine auf einen begrenzten Bereich beschränkte Konfiguration des ICON-Erdsystemmodells, gekoppelt mit dem Aerosolmodul HAM-lite mit reduzierter Komplexität, um rechnerisch effiziente, konvektionsfähige Aerosolsimulationen zu ermöglichen. Die explizite Darstellung der Konvektion ermöglicht eine konsistente Kopplung von Aerosol, Wolken und Strahlung und wurde erfolgreich auf Wüstenstaub und große Waldbrände in Australien angewendet.

## Overview of the individual contributions / Übersicht der Einzelbeiträge

### *Air quality - from regional to homes*

Ground-level aerosols have a significant impact on the quality of the air we breathe and are influenced by human activity more than almost any other atmospheric component. Since its founding, TROPOS has set itself the major challenge of capturing and understanding the complex physical and chemical composition, spatiotemporal distribution and trends of aerosols in landscapes with varying levels of pollution.

The Melpitz Observatory forms the backbone of air quality research at TROPOS and now has decades of time series data, revealing the influence of weather conditions, annual cycles and multi-year trends. **Atabakhsh et al.** demonstrate this using the example of online mass spectroscopy of organic sources and find a significant decline in PM1 concentrations due to the decrease in local winter emissions of domestic fuels and their long-range transport from the east.

A characteristic type of aerosol produced by the incomplete combustion of biomass is black carbon (BC). Using physical aerosol measurements in Melpitz, **Yang et al.** were able to show how the properties of BC-containing particles changes as a result of photochemical processes and seasonally varying long-range transport. Residential heating in particular leads to larger core diameters and thicker coatings.

Seasonal variation and weather- and climate-related fluctuations also occur in organic aerosols from vegetation sources. Using a model study, **Wackermann et al.** were able to demonstrate how bark beetle infestation in spruce forests triggered by periods of drought leads to increased stress-related emissions of precursors for secondary organic aerosol mass, which also has an impact on air quality.

The extent to which air quality in certain regions is influenced by local emissions, ageing processes and long-range transport is the subject of more or less continuous field work in cooperation with regional environmental agencies. Specifically for the town of Radeburg, **Deabji et al.** investigated the influence of wood burning on air quality and were able to quantitatively correlate pollutant levels with local heating periods.

Naturally, the city of Leipzig has also been the subject of long-term air quality studies at TROPOS for several decades. Based on measurement campaigns between 1999 and 2024, **Engelhardt et al.** demonstrate significant reductions in fine particle concentrations from coal combustion and traffic exhaust emissions, over the last 25 years. In contrast, coarse particles, associated to non-exhaust emissions increased over time. In addition, secondary aerosol formation is now a major aerosol source in the region, while episodic contributions from long-range transport

Die größte Herausforderung bei der Fernerkundung von Staub besteht darin, die irregulär geformten Staubpartikel korrekt zu berücksichtigen. **Haarig et al.** berichten über die neue Leibniz-Nachwuchsgruppe „Optical LABORatory for Lidar Applications“ (OLALA), die erstmals eine Laborbasis für die Bestimmung der Lidar-Eigenschaften realer Staubpartikel in exakter Rückstreurichtung bietet, um Lidar-Erkundungs-Algorithmen zu verbessern.

Vielversprechende Anwendungsbereiche dieser Erkundungs-Algorithmen liegen im Staubgürtel der nördlichen Hemisphäre, der sich von Westafrika über Zentralasien bis nach China erstreckt. **Hofer et al.** präsentieren die erste Langzeitanalyse der permanent betriebenen Lidar-Station in Zentralasien, die von TROPOS in Zusammenarbeit mit lokalen Partnern in Duschambe, Tadschikistan, betrieben wird. Diese zeigt beispielsweise charakteristische saisonale Muster der Mineralstaubbelastung.

Eine weitere Aerosolart, die bei der Untersuchung des gekoppelten Biosphären-Atmosphären-Systems zunehmend Beachtung findet, sind biogene Partikel. Am Beispiel der Rußemissionen aus großen Waldbränden zeigen **Gast et al.**, wie diese mit Hilfe der Fluoreszenz-Lidar-Technologie hoch in der Stratosphäre und damit auch ihr globale Ferntransport nachgewiesen werden können.

### *Luftqualität – von der Region bis zum Eigenheim*

Bodennahes Aerosol hat einen erheblichen Einfluss auf die Qualität der Luft, die wir atmen, und wird stärker als fast alle anderen atmosphärischen Komponenten durch menschliche Aktivitäten beeinflusst. Seit seiner Gründung hat sich TROPOS der großen Herausforderung gestellt, die komplexe physikalische und chemische Zusammensetzung, die räumlich-zeitliche Verteilung und die Trends von Aerosolen in Landschaften mit unterschiedlichem Verschmutzungsgrad zu erfassen und zu verstehen.

Das Melpitz-Observatorium bildet das Rückgrat der Luftqualitätsforschung bei TROPOS und bietet mittlerweile dekadische Zeitreihendaten, die den Einfluss von Wetterbedingungen, Jahreszyklen und mehrjährigen Trends aufzeigen. **Atabakhsh et al.** demonstrieren dies am Beispiel der Online-Massenspektroskopie organischer Quellen und stellen einen signifikanten Rückgang der PM1-Konzentrationen fest, der auf die Abnahme der lokalen Winteremissionen von Haushaltsbrennstoffen und deren weiträumigen Transport aus dem Osten zurückzuführen ist.

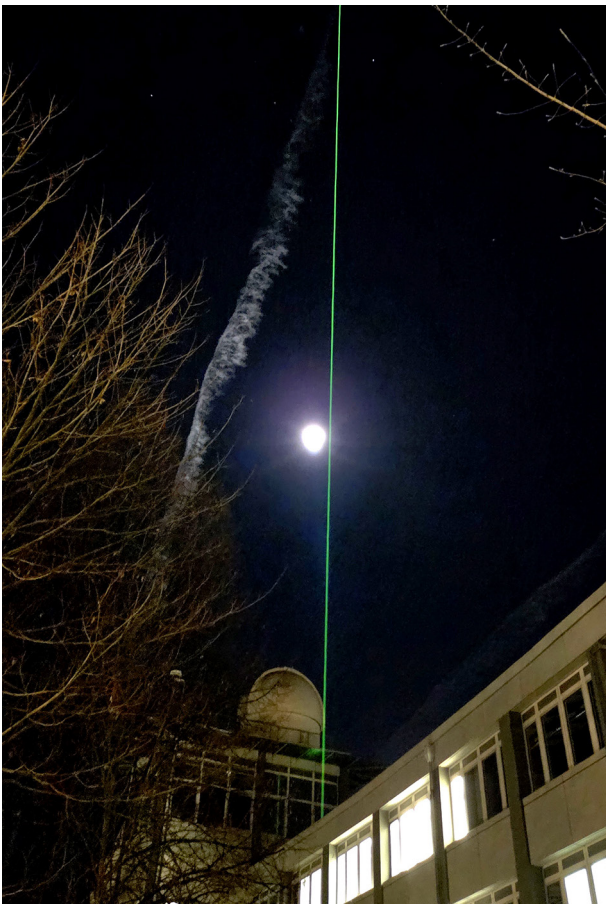
Ein charakteristischer Aerosoltyp, der bei der unvollständigen Verbrennung von Biomasse entsteht, ist Ruß (BC). Anhand physikalischer Aerosolmessungen in Melpitz konnten **Yang et al.** zeigen, wie sich die Eigenschaften von BC-haltigen Partikeln durch

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linked to war-related emissions from Ukraine were also identified.

The example of Leipzig was also used to investigate how pollutant concentrations behave in urban areas. To this end, a network of low-cost particle sensors was operated in Leipzig around an official air quality monitoring station, also with a view to investigate the added value of innovative sensor technology. **Schrödner et al.** combined observations and high-resolution urban transport modelling to create an overall picture of pollutant concentrations.

Another promising area of application for low-cost sensors is the monitoring of indoor air quality. Indoor air pollutants can reach dangerous concentrations, but are rarely detected due to the complexity of conventional measuring devices. **Cuesta-Mosquera et al.** developed a portable and user-friendly multi-sensor measuring device with public involvement, enabling them to capture the dynamics of indoor pollution.



*Fig. / Abb. 1: Fluorescence measurements taken by the MARTHA lidar help to learn more about the interactions between smoke and atmospheric processes and are part of the new Leibniz Science Campus BioSmoke. / Fluoreszenzmessungen des MARTHA-Lidars tragen dazu bei, mehr über die Wechselwirkungen von Rauch mit den Atmosphären-Prozessen zu erfahren und sind Teil des neuen Leibniz Science Campus BioSmoke. © Ariane Pohlentz, TROPOS*

photochemische Prozesse und saisonal variierenden Ferntransport verändern. Insbesondere die Heizung von Wohngebäuden führt zu größeren Kerndurchmessern und dickeren Beschichtungen der Rußpartikel.

Saisonale sowie wetter- und klimabedingte Schwankungen treten auch bei organischen Aerosolen aus pflanzlichen Quellen auf. Anhand einer Modellstudie konnten **Wackermann et al.** zeigen, wie der durch Trockenperioden ausgelöste Borkenkäferbefall in Fichtenwäldern zu erhöhten stressbedingten Emissionen von Vorläufern für sekundäre organische Aerosole führt, was sich ebenfalls auf die Luftqualität auswirkt.

Inwieweit die Luftqualität in bestimmten Regionen durch lokale Emissionen, Alterungsprozesse und den Ferntransport beeinflusst wird, ist Gegenstand mehr oder weniger kontinuierlicher Feldarbeiten in Zusammenarbeit mit regionalen Umweltbehörden. Speziell für die Stadt Radeburg untersuchten **Deabji et al.** den Einfluss der Holzverbrennung auf die Luftqualität und konnten die Schadstoffwerte quantitativ mit den lokalen Heizperioden korrelieren.

Natürlich ist auch die Stadt Leipzig seit mehreren Jahrzehnten Gegenstand langfristiger Luftqualitätsstudien am TROPOS. Auf der Grundlage von Messkampagnen zwischen 1999 und 2024 zeigen **Engelhardt et al.** eine signifikante Verringerung der Feinstaubkonzentrationen aus Kohleverbrennung und Verkehrsemissionen in den letzten 25 Jahren. Im Gegensatz dazu nahmen grobe Partikel, die mit Nicht-Abgasemissionen in Verbindung stehen, im Laufe der Zeit zu. Darüber hinaus ist die sekundäre Aerosolbildung mittlerweile eine wichtige Aerosolquelle in der Region, während episodische Beiträge aus dem Fernverkehr im Zusammenhang mit kriegsbedingten Emissionen aus der Ukraine ebenfalls identifiziert wurden.

Das Beispiel Leipzig wurde auch herangezogen, um zu untersuchen, wie sich Schadstoffkonzentrationen in städtischen Gebieten verhalten. Zu diesem Zweck wurde in Leipzig ein Netzwerk kostengünstiger Partikelsensoren rund um eine offizielle Luftqualitätsmessstation betrieben, auch um den Mehrwert innovativer Sensortechnologie zu untersuchen. **Schrödner et al.** kombinierten Beobachtungen und hochauflösende städtische Verkehrsmodelle, um ein Gesamtbild der Schadstoffkonzentrationen zu erstellen.

Ein weiterer vielversprechender Anwendungsbereich für kostengünstige Sensoren ist die Überwachung der Innenraumluftqualität. Schadstoffe in der Innenraumluft können gefährliche Konzentrationen erreichen, werden jedoch aufgrund der Komplexität herkömmlicher Messgeräte selten erkannt. **Cuesta-Mosquera et al.** entwickelten unter Einbeziehung der Öffentlichkeit ein tragbares und benutzerfreundliches Multisensor-Messgerät, mit dem sie die Dynamik der Innenraumverschmutzung erfassen konnten.

### Highlight Publications

#### **Improved cookstoves enhance household air quality and respiratory health in rural Rwanda**

Cuesta-Mosquera, A., Kothe, H., Madueno, L., Mubiru, A., Muhongerva, C., Müller, T., Rupp, J., van Pinxteren, D., van Pinxteren, M., Ogurtsova, K., Soppa, V., Wiese-Posselt, M., and Pöhlker, M., *Sci Rep* 15, 26065 (2025). <https://doi.org/10.1038/s41598-025-09863-6>

In an interdisciplinary study, the Leibniz Institute for Tropospheric Research (TROPOS) investigated household air pollution (HAP) and health impacts associated with traditional cooking and improved stoves (ICS) among rural Rwandan adults. HAP measurements (n=45) revealed extremely high concentrations during traditional cooking, while adopting ICS reduced aerosol exposure up to 70%. Health data (n=529) showed that ICS users experienced fewer symptoms and maintained better lung function over 3 years. The findings provide evidence of the context-specific impacts of residential biomass burning, key to developing targeted mitigation strategies tailored to regional conditions.

#### **Strong synergistic and antagonistic effects of quinones and metal ions in oxidative potential (OP) determination by ascorbic acid (AA) assays**

Eduardo José dos Santos Souza, Khanneh Wadinga Fomba, Manuela van Pinxteren, Nabil Deabji, Hartmut Herrmann (2024). *Journal of Hazardous Materials*, Volume 478, 5 October 2024, 135599 <https://doi.org/10.1016/j.jhazmat.2024.135599>

This study examines the role of quinones and trace metals, i.e., hazardous particulate matter in the atmosphere, in the development of oxidative stress in the human respiratory tract. A key challenge is determining the oxidation potential (OP) of redox-active aerosol components and their cumulative effect. Based on this study, an improved method was developed for estimating the oxidation potential of toxic aerosol components and the resulting health effects.

#### **Impact of sensible heating and water vapor emission on pyro-convective plume characteristics**

Müller, J., Senf, F., & Tegen, I. (2025). Impact of sensible heating and water vapor emission on pyro-convective plume characteristics. *Journal of Geophysical Research*:

### Highlight-Publikationen

#### **Verbesserte Kochherde tragen zur Verbesserung der Luftqualität in Haushalten und der Gesundheit der Atemwege in ländlichen Gebieten Ruandas bei**

Cuesta-Mosquera, A., Kothe, H., Madueno, L., Mubiru, A., Muhongerva, C., Müller, T., Rupp, J., van Pinxteren, D., van Pinxteren, M., Ogurtsova, K., Soppa, V., Wiese-Posselt, M., and Pöhlker, M., *Sci Rep* 15, 26065 (2025). <https://doi.org/10.1038/s41598-025-09863-6>

In einer interdisziplinären Studie untersuchte das Leibniz-Institut für Troposphärenforschung (TROPOS) die Luftverschmutzung in Haushalten (HAP) und die gesundheitlichen Auswirkungen, die mit traditionellem Kochen und verbesserten Öfen (ICS) bei Erwachsenen in ländlichen Gebieten Ruandas verbunden sind. HAP-Messungen (n=45) ergaben extrem hohe Konzentrationen beim traditionellen Kochen, während die Verwendung von ICS die Aerosolbelastung um bis zu 70 % reduzierte. Gesundheitsdaten (n=529) zeigten, dass ICS-Nutzer über einen Zeitraum von drei Jahren weniger Symptome aufwiesen und eine bessere Lungenfunktion beibehielten. Die Ergebnisse liefern Belege für die kontextspezifischen Auswirkungen der Verbrennung von Biomasse in Wohngebäuden, die für die Entwicklung gezielter, auf die regionalen Gegebenheiten zugeschnittener Minderungsstrategien von entscheidender Bedeutung sind.

#### **Starke synergistische und antagonistische Effekte von Chinonen und Metallionen bei der Bestimmung des Oxidationspotenzials (OP) durch Ascorbinsäure (AA)-Assays**

Eduardo José dos Santos Souza, Khanneh Wadinga Fomba, Manuela van Pinxteren, Nabil Deabji, Hartmut Herrmann (2024). *Journal of Hazardous Materials*, Volume 478, 5 October 2024, 135599 <https://doi.org/10.1016/j.jhazmat.2024.135599>

In dieser Studie wird die Rolle von Chinonen und Spurenmetallen, als gefährliche Partikelbestandteile in der Atmosphäre, bei der Entstehung von oxidativem Stress in den Atemwegen des Menschen beleuchtet. Eine zentrale Herausforderung ist die Bestimmung des Oxidationspotenzials (OP) redoxaktiver Aerosolbestandteile sowie ihrer kumulativen Wirkung. Auf Grundlage dieser Studie wird eine verbesserte Methode vorgeschlagen, um das Oxidationspotenzial toxischer Aerosolbestandteile und die dadurch verursachten Gesundheitsauswirkungen abzuschätzen.

## Highlight Publications / Highlight-Publikationen

Atmospheres, 130, e2025JD043552. <https://doi.org/10.1029/2025JD043552>

Intense wildfires can cause strong convection and thunderstorm-like formations, so-called Pyrocumulonimbus (pyroCb) clouds. These can loft smoke as high as the stratosphere, thereby affecting the climate in a manner similar to that of volcanic eruptions. This study shows that pyroCbs form abruptly when sensible heat flux from the fire exceeds  $\sim 50 \text{ kW m}^{-2}$ . The height of the plume mainly depends on the total heat released. Accurate estimates of heat and moisture released by fires is important for predicting pyroCb development.

### **Ground-based remote sensing of aerosol, clouds, dynamics and precipitation in Antarctica: First results from the 1-Year COALA Campaign at Neumayer Station III in 2023**

Radenz, M, Engelmann, R., Henning, S. Schmithüsen, H, Baars, H., Frey, M. M., Weller, R., Bühl, J., Jimenez, C., Roschke, J., Muser, L. O., Wullenweber, N., Zeppenfeld, S., Griesche, H., Wandinger, U. & Seifert, P. (2024) Bulletin of the American Meteorological Society, 105, E1438-E1457, <https://doi.org/10.1175/BAMS-D-22-0285.1>

Based on the deployment of the ACTRIS remote sensing observatory OCEANET-Atmosphere of TROPOS at the Neumayer III Antarctic station, the annual cycle of the vertical distribution of aerosol and cloud properties was recorded for the first time for East Antarctica. The article, published as the title study in the print edition of the Bulletin of the American Meteorological Society, highlights the potential of the data obtained for improving our understanding of polar aerosol and cloud processes. The outreach of the project is particularly evident in its inclusion in several national and international follow-up studies, including the leading role assigned to the OCEANET-Atmosphere platform in the upcoming Antarctica-InSync program.

### **Auswirkungen von sensibler Wärme und Wasserdampfemission auf die Eigenschaften pyrokonvektiver Rauchfahnen**

Müller, J., Senf, F., & Tegen, I. (2025). Journal of Geophysical Research: Atmospheres, 130, e2025JD043552. <https://doi.org/10.1029/2025JD043552>

Intensive Waldbrände können starke Konvektion und gewitterähnliche Formationen verursachen, sogenannte Pyrocumulonimbus-Wolken (PyroCb). Diese können Rauch bis in die Stratosphäre aufsteigen lassen und so das Klima ähnlich wie Vulkanausbrüche beeinflussen. Diese Studie zeigt, dass sich PyroCbs abrupt bilden, wenn der sensible Wärmefluss des Feuers  $\sim 50 \text{ kW m}^{-2}$  überschreitet. Die Höhe der Rauchwolke hängt hauptsächlich von der insgesamt freigesetzten Wärme ab. Genaue Schätzungen der durch Brände freigesetzten Wärme und Feuchtigkeit sind wichtig für die Vorhersage der PyroCb-Entwicklung.

### **Bodenbasierte Fernerkundung von Aerosolen, Wolken, Dynamik und Niederschlag in der Antarktis: Erste Ergebnisse der einjährigen COALA-Kampagne an der Neumayer-Station III im Jahr 2023**

Radenz, M, Engelmann, R., Henning, S. Schmithüsen, H, Baars, H., Frey, M. M., Weller, R., Bühl, J., Jimenez, C., Roschke, J., Muser, L. O., Wullenweber, N., Zeppenfeld, S., Griesche, H., Wandinger, U. & Seifert, P. Bulletin of the American Meteorological Society, 105, E1438-E1457, <https://doi.org/10.1175/BAMS-D-22-0285.1>

Mit dem Einsatz des ACTRIS Fernerkundungsobservatoriums OCEANET-Atmosphäre des TROPOS an der Antarktisstation Neumayer III wurden erstmalig für die gesamte Ostantarktis der Jahresgang der vertikalen Verteilung von Aerosol und Wolkeneigenschaften erfasst. In dem als Titelstudie in der Druckausgabe des Bulletin of the American Meteorological Society veröffentlichtem Artikel wird das Potenzial der gewonnenen Daten für die Verbesserung des Verständnisses polarer Aerosol- und Wolkenprozesse aufgezeigt. Die Reichweite des Projekts wird insbesondere durch dessen Einbeziehung in mehrere nationale und internationale Folgestudien deutlich, eingeschlossen der eingenommenen führenden Rolle der OCEANET-Atmosphäre-Plattform im bevorstehenden Antarctica-InSync-Programm.

## Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick

### Transfer in science and society – overview

#### Knowledge transfer and external impact

##### TROPOS research for specialist audiences.

Due to the institute's focus on application-oriented basic research, the scientific results are mainly published in specialist publications and conference papers (see list, p. 151).

The following **scientific conferences** in which TROPOS participated stand out during the reporting period:

The **SOLAS Open Science Conference 2024** took place from 10 to 14 November 2024 in Goa (India) – with five TROPOS researchers presenting on the topic of microplastics and their impact on the ocean and atmosphere. Manuela van Pinxteren gave a keynote speech and Ankush Kaushik received a poster award for his innovative contributions to microplastics research.

SOLAS (Surface Ocean – Lower Atmosphere Study) is an international research initiative that aims to understand the most important biogeochemical and physical interactions and feedbacks between the ocean and the atmosphere. The SOLAS scientific community comprises over 1,200 researchers from many disciplines, including oceanography, ecology, biogeochemistry, physics, chemistry and atmospheric sciences. TROPOS is involved in this initiative because research on the atmosphere-ocean interface fits perfectly with the profile of the international initiative.

The **ACTRIS Science Conference 2024** was held in Rennes, France, from 13 to 16 May 2024. The international conference brought together researchers and engineers from the fields of air quality, sustainable development and health. In addition to the composition and processes in the atmosphere, the five topics included extreme weather events, innovative observation methods and health in urban areas. Felix Fritsch won the poster prize.

The Leibniz project **DUSTRISK** came to an end in May 2024 in Praia (Cabo Verde) with a workshop and lectures for the public. TROPOS was represented by Khandeh Wadinga Fomba, Eduardo Souza and Dietrich Althausen, among others. The project was funded as part of the Leibniz competition in the "Cooperative Excellence" funding programme. A broad public was also reached through awareness campaigns at schools and universities in Cabo Verde and media reports. Among others, the national television station RTC reported on the final workshop.

Scientific collaboration on the new **EarthCARE** Earth observation satellite from ESA and JAXA led

### Transfer in Wissenschaft und Gesellschaft – Überblick

#### Wissenstransfer und Außenwirkung

##### TROPOS-Forschung für Fachpublikum.

Aufgrund der Ausrichtung des Institutes auf anwendungsorientierte Grundlagenforschung erfolgt die Verwertung der wissenschaftlichen Ergebnisse hauptsächlich in Fachpublikationen und Konferenzbeiträgen (siehe Liste, S. 151).

Aus den **wissenschaftlichen Tagungen**, an denen TROPOS beteiligt war, stechen im Berichtszeitraum folgende heraus:

Die **SOLAS Open Science Conference 2024** fand vom 10. bis 14.11.24 in Goa (Indien) statt - u.a. mit 5 Forschenden des TROPOS mit dem Thema Mikroplastik und dessen Auswirkungen auf Ozean und Atmosphäre. Manuela van Pinxteren hielt dabei eine Key-Note und Ankush Kaushik erhielt einen Posterpreis für seine innovativen Beiträge zur Mikroplastikforschung.

SOLAS („Surface Ocean – Lower Atmosphere Study“) ist eine internationale Forschungsinitiative, deren Ziel es ist, die wichtigsten biogeochemisch-physikalischen Wechselwirkungen und Rückkopplungen zwischen Ozean und Atmosphäre zu verstehen. Die wissenschaftliche Gemeinschaft von SOLAS setzt sich aus über 1200 Forschenden vieler Disziplinen zusammen, darunter Ozeanographie, Ökologie, Biogeochemie, Physik, Chemie und Atmosphärenwissenschaften. TROPOS engagiert sich hier, weil die Forschung zur Schnittstelle Atmosphäre-Ozean genau ins Profil der internationalen Initiative passt.

Die **ACTRIS Science Conference 2024** wurde vom 13. bis 16.05.24 in Rennes, Frankreich, ausgetragen. Die internationale Konferenz brachte Forschende und Ingenieur:innen aus den Bereichen Luftqualität, nachhaltige Entwicklung und Gesundheit zusammen. Neben der Zusammensetzung und den Prozessen in der Atmosphäre gehörten extreme Wetterereignisse, innovative Beobachtungsmethoden und die Gesundheit in städtischen Gebieten zu den fünf Themen. Felix Fritsch gewann den Posterpreis.

Mit einem Workshop und Vorträgen für die Öffentlichkeit ging im Mai 2024 in Praia (Cabo Verde) das Leibniz-Projekt **DUSTRISK** zu Ende. TROPOS war u.a. durch Khandeh Wadinga Fomba, Eduardo Souza und Dietrich Althausen vertreten. Das Projekt wurde im Rahmen des Leibniz-Wettbewerbs im Förderprogramm „Kooperative Exzellenz“ gefördert. Über Sensibilisierungskampagnen an Schulen und Universitäten in Cabo Verde sowie Medienberichte

## Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick



Fig. / Abb. 1: 43<sup>rd</sup> EarthCARE joint meeting of European and Japanese scientists (JMAG) in Leiden (Netherlands). / 43. EarthCARE-Treffen Europäischer und Japanischer Forschender (JMAG – Joint Mission Advisory Group) in Leiden (Niederlande). © ESA / JAXA

to a series of meetings of this large international community: one important meeting was the 43rd Joint Meeting of European and Japanese Scientists (JMAG) on 24-26 September 2024. Ulla Wandinger (RSD) attended the three-day joint EarthCARE meeting of European and Japanese researchers (JMAG – Joint Mission Advisory Group) in Leiden (Netherlands). TROPOS also played a key role in organising the first ESA-JAXA EarthCARE In-Orbit Validation Workshop (online). The international community met at ESA-ESRIN in Frascati, Italy, on 17-20 March 2025 for the second ESA-JAXA EarthCARE In-Orbit Validation Workshop – also with strong participation from TROPOS. On 1-5 December 2025, the EarthCARE Science and Validation Workshop 2025 took place in Tokyo, Japan, where TROPOS was well represented and presented its latest results. In addition to these conference-style workshops, several meetings of the EarthCARE Quality Working Group (QWG) (the successor to JMAG), of which Ulla Wandinger is a member, took place in Italy (21 March 2025 in Frascati) and Japan (9–11 September 2025 in Tokyo). Regular meetings of EarthCARE's Data Innovation and Science Cluster (DISC), to which several TROPOS scientists belong, were held regularly in Europe.

From 17 to 19 March 2025, more than 350 researchers gathered at Leipzig University's Jahnallee campus for the 2025 **Bunsen Conference**. The traditional conference of the German Bunsen Society (DBG) was dedicated specifically to the chemistry of climate and atmosphere in 2025. Leipzig is home to many research groups working on this topic, from chemistry and meteorology to the geosciences. The conference was organised by Hartmut Herrmann (TROPOS and Leipzig University) and his team.

wurde zudem eine breite Öffentlichkeit erreicht. So berichtete u.a. das nationale Fernsehen RTC vom Abschlussworkshop.

Die wissenschaftliche Mitarbeit am neuen Erdbereobachtungssatelliten **EarthCARE** von ESA und JAXA sorgte für eine Reihe von Treffen dieser großen internationalen Community: Ein wichtiges Meeting war dabei das 43rd Joint Meeting of European and Japanese Scientists (JMAG) am 24.-26.09.24. Auf dem dreitägigen gemeinsamen EarthCARE-Treffen Europäischer und Japanischer Forschender (JMAG - Joint Mission Advisory Group) in Leiden (Niederlande) war Ulla Wandinger (RSD) dabei. TROPOS war außerdem maßgeblich an der Ausrichtung des ersten ESA-JAXA EarthCARE In-Orbit Validation Workshops (online) beteiligt. Die internationale Community traf sich am 17.-20.03.25 am ESA-ESRIN in Frascati, Italien, zum zweiten ESA-JAXA EarthCARE In-Orbit Validation Workshop – ebenfalls mit starker TROPOS-Beteiligung. Am 01.-05.12.25 fand der EarthCARE Science and Validation Workshop 2025 in Tokio, Japan statt, auf dem TROPOS maßgeblich vertreten war und neueste Ergebnisse präsentierte. Neben diesen konferenzartigen Workshops, fanden in Italien (21.03.25 in Frascati) und Japan (9.-11.09.25 in Tokio) mehrere Treffen der Quality Working Group (QWG) von EarthCARE (dem Nachfolger des JMAG) statt, welcher Ulla Wandinger angehört. Reguläre Treffen des Data Innovation and Science Clusters (DISC) von EarthCARE, dem mehrere TROPOS Wissenschaftler angehören, wurden regelmäßig in Europa durchgeführt.

Vom 17. bis 19.03.25 trafen sich über 350 Forschende auf dem Campus Jahnallee der Universität Leipzig zur **Bunsen-Tagung** 2025. Die traditionsreiche Konferenz der Deutschen Bunsen-Gesellschaft (DBG) widmete sich 2025 speziell der Chemie von Klima und Atmosphäre. Leipzig beherbergt viele Forschungsgruppen, die sich mit diesem Thema beschäftigen von der Chemie über die Meteorologie bis zu den Geowissenschaften. Organisiert wurde sie von Hartmut Herrmann (TROPOS und Universität Leipzig) und seinem Team.

### Ausgewählte Themen und Aktivitäten für Politik und Gesellschaft

Die Forschungsergebnisse des TROPOS dienen auch als Beitrag zur **Politikberatung** im Umweltbereich. So werden u.a. für das Land Sachsen oder das Umweltbundesamt (UBA) praxisrelevante Untersuchungen zum Verhalten und zur künftigen Entwicklung von Schadstoffen in der Atmosphäre durchgeführt. Außerdem werden im Rahmen von Auftragsprojekten für das UBA und das Sächsische

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### Selected topics and activities for politics and society

TROPOS' research results also contribute to **policy advice** in the environmental sector. For example, practical studies on the behaviour and future development of pollutants in the atmosphere are carried out for the state of Saxony and the Federal Environment Agency (UBA), among others. In addition, as part of contract research projects for the UBA and the Saxon State Office for Environment and Geology (LfULG), measurement data on the concentrations of fine and ultrafine aerosol particles and on the chemical composition of particles in the atmosphere are collected over longer periods of time, scientifically evaluated and made available for further use.

Examples of **transfer projects** in 2024/2025 include: The Leibniz-SAW project DUSTRISK ("A risk index for health effects of mineral dust and associated microbes"), which investigated the harmful aspects of mineral dusts in combination with adhering microbes from 2020 to 2024. To this end, field measurements, laboratory tests and modelling studies were carried out in collaboration with partners from the Leibniz Institutes DSMZ, FZB and IUL, as well as from Cabo Verde, including hospitals, universities and public health institutes. The aim was to conduct comprehensive investigations into the health risks posed by exposure to mineral dust and its microbial components. These health risks are a problem that affects not only the archipelago of West Africa, but many regions worldwide that suffer from desertification. Close cooperation between different disciplines and countries promoted knowledge transfer and contributed to methodological innovations. DUSTRISK has thus made a significant contribution to understanding dust exposure and created a reliable basis for future prevention approaches.

While people in arid regions of the world fear mainly visible, coarse mineral dust, in Germany the concern is more about invisible fine dust: people living near airports in particular are now worried not only about the effects of noise emissions, but also about fine dust from aircraft engines. At Germany's largest airport in Frankfurt/Main, the discussion surrounding emissions and the effects of ultrafine particles (UFP), i.e. particles with a diameter of less than 100 nm, has also intensified. The Airport and Region Forum (FFR) organises dialogue between the region and the aviation industry. This includes studies on air pollution caused by UFP and its health effects in the Rhine-Main region. In 2023, a UFP pollution study ("SOURCE FFR") was launched, which is being carried out by a consortium led by TROPOS. Among other things, the pollution study aims to provide

Landesamt für Umwelt und Geologie (LfULG) über längere Zeiträume Messdaten zu den Konzentrationen feiner und ultrafeiner Aerosolpartikel sowie zur chemischen Partikelzusammensetzung in der Atmosphäre erhoben, wissenschaftlich ausgewertet und zur weiteren Nutzung zur Verfügung gestellt.

Beispiele für **Transfer-Projekte** in den Jahren 2024/2025 sind unter anderem: Das Leibniz-SAW-Projekt DUSTRISK („A risk index for health effects of mineral dust and associated Microbes“), das von 2020 bis 2024 schädliche Aspekte von Mineralstäuben in Kombination mit anhaftenden Mikroben untersucht hat. Dazu wurden Feldmessungen, Laboruntersuchungen sowie Modellierungsstudien in Zusammenarbeit mit Partnern aus den Leibniz-Instituten DSMZ, FZB und IUL sowie aus Cabo Verde durchgeführt, darunter mit Krankenhäusern, Universitäten und öffentlichen Gesundheitsinstituten. Das Ziel war, umfassende Untersuchungen der Gesundheitsrisiken durchzuführen, die durch die Exposition gegenüber mineralischem Staub und seinen mikrobiellen Bestandteilen entstehen. Diese Gesundheitsrisiken sind ein Problem, das nicht allein die Inselgruppe vor Westafrika betrifft, sondern viele Regionen weltweit, die unter Desertifikation und Wüstenausbreitung leiden. Die enge Zusammenarbeit verschiedener Disziplinen und Länder förderte den Wissenstransfer und trug zu methodischen Innovationen bei. DUSTRISK hat damit maßgeblich zum Verständnis von Staubexposition beigetragen und eine verlässliche Basis für zukünftige Präventionsansätze geschaffen.

Während sich in ariden Regionen der Erde Menschen vor allem vor sichtbaren, groben Mineralstaub fürchten, geht es in Deutschland eher um unsichtbarer Feinstaub: Besonders Menschen im Umfeld von Flughäfen sorgen sich inzwischen nicht nur um die Auswirkungen der Lärmemissionen, sondern ebenfalls um Feinstaub aus Flugzeugtriebwerken. Auch am größten deutschen Flughafen in Frankfurt/Main hat sich die Diskussion rund um die



Fig. / Abb. 2: Bunsen Conference 2025 in Leipzig. / Bunsen-Tagung 2025 in Leipzig. © Tilo Arnhold, TROPOS

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information on the sources of UFPs in the area, their relevance and how UFP emissions are distributed or spread in the area. This will then be used to derive possible mitigation measures. Every step is being closely monitored by citizens' initiatives and a critical public, who expect solid and reliable results. The transparency and depth with which the UFP study is being conducted is unprecedented in Germany and will set new standards. The UFP exposure study "SOURCE FFR" therefore provides important data in the area of conflict between human health and economic growth, which is the subject of a broad-based social debate – from local citizens' initiatives to the state government in Hesse. The exposure study is expected to be completed in 2026.

Another UFP project with strong TROPOS involvement ran until summer 2025 in Berlin. Since 2020, the ULTRAFLEB project of the Federal Environment Agency has been investigating the influence of the new BER airport on the temporal and spatial distribution of ultrafine particles smaller than 100 nm in the greater Berlin area. TROPOS focused on measuring ultrafine particles (UFP) in Blankenfelde-Mahlow (5 km west of the BER terminal) and mobile measurements by trailer (together with TU Berlin). As the measurements were taken before flight operations began at BER, they provide a good insight into the changed pollution situation and supply important data for the Berlin Brandenburg Air Study (BEAR), a study launched in 2020 by Charité – Universitätsmedizin Berlin and Düsseldorf University Hospital on the health effects on children. The ULTRAFLEB final meeting took place on 14 May 2025 in Berlin.

The proven cooperation between LfULG and TROPOS continued in 2024/25 with a series of research projects on aspects of air quality. These include, for example, the SAXOZONE project (1



Fig. / Abb. 3: Public dialogue on ultrafine particulate matter (UFP) and BER Airport at Berlin Science Week 2025. / Bürgerdialog zu Ultrafeinstaub (UFP) und Flughafen BER zur Berlin Science Week 2025. © Tilo Arnhold, TROPOS

Emissionen und Auswirkungen ultrafeiner Partikel (UFP), also Partikel im Größenbereich < 100 nm Durchmesser, intensiviert. Das Forum Flughafen und Region (FFR) organisiert den Dialog zwischen der Region und der Luftverkehrswirtschaft. Dazu gehören Untersuchungen zur Belastung der Luft durch UFP und deren gesundheitliche Wirkung in der Rhein-Main-Region. 2023 ist dazu eine UFP-Belastungsstudie („SOURCE FFR“) gestartet, die von einem Konsortium unter Federführung des TROPOS durchgeführt wird. Die Belastungsstudie soll unter anderem Auskunft darüber geben, welche Quellen für UFP es dort gibt, welche Relevanz diese haben und wie sich die UFP-Emissionen im Raum verteilen bzw. ausbreiten. Daraus lassen sich dann möglichen Minderungsmaßnahmen ableiten. Jeder Schritt wird von den Bürgerinitiativen und einer kritischen Öffentlichkeit aufmerksam verfolgt, die solide und belastbare Ergebnisse erwartet. Die Transparenz und Tiefe, mit der die UFP-Studie durchgeführt wird, ist beispiellos in Deutschland und wird Maßstäbe setzen. Die UFP-Belastungsstudie „SOURCE FFR“ liefert daher wichtige Daten im Spannungsfeld zwischen menschlicher Gesundheit und wirtschaftlichen Wachstum, zu dem eine breit angelegte gesellschaftliche Diskussion läuft – von lokalen Bürgerinitiativen bis hin zur Landesregierung in Hessen. Mit dem Abschluss der Belastungsstudie wird für 2026 gerechnet.

Ein weiteres UFP-Projekt mit starker TROPOS-Beteiligung lief bis Sommer 2025 in Berlin. Im ULTRAFLEB-Projekt des Umweltbundesamtes wurde seit 2020 der Einfluss des neuen Großflughafens BER auf zeitliche und räumliche Verteilungen von Ultrafeinstaub kleiner 100nm im Großraum Berlin untersucht. TROPOS konzentrierte sich dabei auf die Messung von Ultrafeinpartikeln (UFP) in Blankenfelde-Mahlow (5 km westlich des BER-Terminals) und mobile Messungen per Trailer (zusammen mit TU Berlin). Da die Messungen bereits vor Beginn des Flugbetriebs am BER aufgenommen wurden, bieten sie einen guten Einblick in die veränderte Belastungssituation und liefern wichtige Daten für die Berlin Brandenburg Air Study (BEAR), eine im Jahr 2020 begonnene Studie der Charité – Universitätsmedizin Berlin und des Universitätsklinikums Düsseldorf, zu den gesundheitlichen Auswirkungen auf Kinder. Das ULTRAFLEB-Abschlussmeeting fand am 14. Mai 2025 in Berlin statt.

Die bewährte Kooperation von LfULG und TROPOS wurde auch 2024/25 mit einer Reihe von Forschungsprojekten zu Aspekten der Luftqualität fortgesetzt. Dazu zählen beispielsweise das SAXOZONE-Projekt (01.10.21 - 30.06.24), das

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October 2021 to 30 June 2024), which evaluated ozone measurements from 1997 to 2020 in order to investigate trends, modelling and mitigation approaches to reduce ground-level ozone pollution. Given its importance for human health, vegetation and the climate, trends in ground-level ozone concentrations ( $O_3$ ) were systematically analysed using long-term data from 16 measuring stations. The results show that, despite a reduction in nitrogen oxide concentrations at all locations, ozone pollution in Saxony has actually increased over the last ten years, especially in densely populated urban areas. In their evaluation, the team of authors led by Dominik van Pinxteren therefore discusses the complex relationships between trends in precursor gases and ground-level ozone. Traditionally, particles have been the focus of cooperation, as has been the case in several projects over the past two years: from 2023 to 2025, TROPOS investigated the effects of the increased use of small combustion plants with solid fuels on air quality in Saxony. From 2023 to 2025, the third grain size-differentiated chemical-physical aerosol characterisation (“Impaktor II”) took place in Leipzig, providing detailed insight into the composition of particulate matter and allowing conclusions to be drawn about trends through comparisons with campaigns in 1999-2000 and 2013-2015. In recent years, TROPOS has investigated the effects of wood heating on local air quality in Seiffen (Erzgebirge in southern Saxony) and Melpitz near Torgau (northern Saxony lowlands), among other places. To round off the picture and capture the current situation in a very dynamic development in private heating, a third major measurement campaign on wood heating in Saxony was launched in autumn. This time, the focus is on Radeburg, a small town near Dresden. TROPOS will be conducting measurements there for two winters. The LfULG project was presented to the public on 1 October 2024 in Radeburg Town Hall by experts from LfULG & TROPOS.

In addition to policy advice, environmental education and, in particular, efforts to combat the impending shortage of skilled workers in the natural sciences and technology (STEM) play an important role. The BMFTR project EngageMINT aims to make environmental research accessible to young people. As part of the project, the participants are developing a digital transfer tool that communicates the results and processes of current research at TROPOS on environmental and climate issues. This tool is aimed at environmentally conscious young people and aims to promote interest and skills in STEM subjects, taking into account their interest profiles and using appropriate feedback systems. Partners are Leibniz



Fig. / Abb. 4: Discussion on air quality in Saxony with Prof. Hartmut Herrmann at the LfULG Status Colloquium on Air & Climate on 30 September 2025. / Diskussion zur Luftqualität in Sachsen mit Prof. Hartmut Herrmann beim LfULG-Statuskolloquium Luft & Klima am 30.09.25. © Tilo Arnholt, TROPOS

Ozonmessungen von 1997 bis 2020 ausgewertet hat, um Trends, Modellierung and Minderungsansätze untersucht hat, um die Belastung mit bodennahem Ozon zu reduzieren. Angesichts seiner Bedeutung für die menschliche Gesundheit, die Vegetation und das Klima wurden die Trends der bodennahen Ozonkonzentrationen ( $O_3$ ) anhand der Langzeitdaten von 16 Messstationen systematisch analysiert. Die Ergebnisse zeigen, dass trotz einer Verringerung der Stickoxidkonzentrationen an allen Standorten die Ozonbelastung in Sachsen in den letzten zehn Jahren tatsächlich zugenommen hat, insbesondere in dicht besiedelten städtischen Gebieten. Das Autorenteam um Dominik van Pinxteren diskutiert in ihrer Auswertung daher die komplexen Zusammenhänge zwischen Trends bei den Vorläufergasen und dem bodennahen Ozon. Traditionell stehen Partikel im Mittelpunkt der Zusammenarbeit, so auch in diesen beiden Jahren bei mehreren Projekten: 2023 bis 2025 untersuchte TROPOS die Auswirkungen der verstärkten Nutzung von Kleinfeuerungsanlagen mit Festbrennstoffen auf die Luftqualität in Sachsen. 2023 bis 2025 fanden mit der dritten korngrößendifferenzierten chemisch-physikalische Aerosolcharakterisierung („Impaktor III“) Filtermessungen in Leipzig statt, die einen detaillierten Einblick in die Zusammensetzung des Feinstaubes geben und durch Vergleiche mit Kampagnen 1999-2000 und 2013-2015 auch Aussagen zu Trends erlauben. Die Auswirkungen von Holzheizung auf die lokale Luftqualität hat TROPOS in den vergangenen Jahren u.a. in Seiffen (Erzgebirge im Süden Sachsen) und Melpitz bei Torgau (Nordsächsisches Tiefland) untersucht. Um das Bild abzurunden und die aktuelle Situation in einer sehr dynamischen Entwicklung bei privaten Heizungen zu erfassen, startete im Herbst eine dritte große Messkampagne zu Holzheizungen in Sachsen. Dieses Mal steht mit Radeburg bei Dresden

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Fig. / Abb. 5: TV documentary 'Expedition Amazonas', in which the ZDF team travelled along the Amazon for several days with Prof. Mira Pöhlker to show the effects of climate change on the occasion of the UN Climate Change Conference COP25 in Belém. / TV-Dokumentation „Expedition Amazonas“, bei der das ZDF-Team zusammen mit Prof. Mira Pöhlker einige Tage den Amazonas bereiste, um die Auswirkungen des Klimawandels anlässlich der UN-Klimakonferenz COP25 in Belém zu zeigen. ([ZDF, 10.11.25](#)). © Ralf Gemmecke, ZDF

University Hannover (LUH) and the Leibniz Institute for Science and Mathematics Education (IPN).

### TROPOS research for the general public.

TROPOS engages in dialogue with the public – including via print media, radio and television. In 2024/25, 28 press releases were issued. This resulted in over 110 media publications in 2024 (as far as is known). In 2025, there were 115 publications (as far as is known).

Topics to which TROPOS researchers were able to contribute in the media included polar research (e.g. through Martin Radenz's Antarctic wintering and the HALO South campaign), clouds, dust (Sahara & Aral Sea), forest fires and, of course, air quality (ultrafine dust at airports, wood heating). Two movies stood out in particular: In "Checker Tobi and the Journey to the Flying Rivers", Mira Pöhlker played herself as a researcher at the ATTO measuring tower in the Brazilian Amazon region ([link to the trailer](#)). "Wind - Measuring the Great Air Ocean" shows

eine Kleinstadt im Fokus. TROPOS misst dort zwei Winter lang. Das LfULG-Projekt wurde am 01.10.2024 im Rathaus von Radeburg durch Expert:innen von LfULG & TROPOS der Bevölkerung vorgestellt.

Neben der Politikberatung spielt auch die Umweltbildung und besonders die Arbeit gegen den drohenden Fachkräftebedarf im naturwissenschaftlich-technischen Bereich (MINT) eine wichtige Rolle. Das BMFTR-Projekt EngageMINT soll dazu Umweltforschung für Jugendliche greifbar machen. Im Rahmen des Projekts entwickeln die Beteiligten ein digitales Transferinstrument, das Ergebnisse und Prozesse der aktuellen Forschung am TROPOS zu Umwelt- und Klimathemen vermittelt. Gerichtet ist dieses Instrument an umweltbewusste Jugendliche und hat zum Ziel, unter Berücksichtigung ihrer Interessensprofile und unter Einsatz geeigneter Feedback-Systeme, Interesse an und Kompetenzen in den MINT-Fächern zu fördern. Partner sind die Leibniz Universität Hannover (LUH) sowie das Leibniz-Institut für Pädagogik der Naturwissenschaften und Mathematik (IPN).

### TROPOS-Forschung für die breite Öffentlichkeit.

TROPOS steht im Dialog mit der Öffentlichkeit – u.a. auch über Printmedien sowie Hör- und Fernsehfunk. 2024/25 wurden 28 Pressemitteilungen herausgegeben. Daraus resultierten im Jahr 2024 über 110 Medienveröffentlichungen (soweit bekannt). Im Jahr 2025 waren es 115 Veröffentlichungen (soweit bekannt).

Themen zu denen TROPOS-Forschende medial beitragen konnte waren Polarforschung (z.B. durch die Antarktis-Überwinterung von Martin Radenz und die HALO-South-Kampagne), Wolken, Staub (Sahara & Aralsee), Waldbrände und natürlich Luftqualität (Ultrafeinstaub an Flughäfen, Holzheizungen). Besonders heraus ragten dabei zwei Kinofilme: In „Checker Tobi und die Reise zu den fliegenden Flüssen“ spielte Mira Pöhlker sich selbst als Forscherin am ATTO-Messturm im brasilianischen Amazonasgebiet (Trailer: [Link zum Trailer](#)). „Wind - Die Vermessung des großen Luftozeans“ zeigt u.a. Elisa Akansu bei ihrer Arbeit in der Arktis im Rahmen von (AC)<sup>3</sup>. Aber auch mehrere aufwendig produzierte TV-Dokumentationen mit Mira Pöhlker zum Thema Wolken: „Können wir Wolken steuern?“ (42 auf arte, 17.02.24), „Rätselhafte Phänomene – Springfluten und Polsprünge“ (Terra X im ZDF, 28.04.24, [Link zum Video](#)), „Risiko Extremwetter: Gewitter, Hagel und Starkregen“ (arte, 18.09.24, [Link zum Video](#)), „Die Rätsel der Wolken“

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Elisa Akansu at work in the Arctic as part of (AC)<sup>3</sup>. There were also several elaborately produced TV documentaries with Mira Pöhlker on the subject of clouds: “Können wir Wolken steuern?” (Can we control clouds?) (42 on arte, 17 February 2024), “Rätselhafte Phänomene – Springfluten und Polsprünge” (Mysterious phenomena – Spring tides and pole shifts) (Terra X on ZDF, 28 April 2024, [link to the video](#)), “The risk of extreme weather: thunderstorms, hail and heavy rain” (arte, 18 September 2024, [link to the video](#)), “The mysteries of clouds” (arte, 31 May 2025, [link to the trailer](#)) and Holger Baars and Sebastian Bley on Aeolus in “The wind – engine of climate change” (arte, 22 September 2024, [link to the video](#)). The high quality of these arte documentaries is demonstrated, among other things, by the fact that “The Mysteries of Clouds” was nominated in the “Best Science Film” category at the Green Screen Festival 2025 in Eckernförde, Europe’s largest nature film festival, and at the SILBERSALZ Science & Media Festival 2025 in Halle (Saale). Sebastian Lindemann’s documentary explores the secrets of clouds and their role in shaping the Earth’s climate – featuring Mira Pöhlker, Dennis Niedermeier and Peter Mettke from TROPOS, among others – with pictures from the HALO mission CAFE-Pacific in Australia and the TROPOS laboratories in Leipzig.

A particular highlight was the TV documentary “Expedition Amazonas”, in which the ZDF team travelled along the Amazon for several days with Mira Pöhlker to show the effects of climate change on the occasion of the UN Climate Change Conference COP25 in Belém. The film was broadcasted on 10 November 2025 as a WISO special during prime time and reached around 2 million viewers ([link to the video](#)). The programme “ZDF Magazin Royale”, which Jan Böhmermann devoted to the topic of particulate matter in a satirical manner on 6 September 2024 ([link to the video](#)), also reached an audience of millions and quoted a TROPOS study from 2018 from Bolivia (“Soot from traffic in megacities contributes to global warming”).

In 2024/25, a total of 25 television reports on a wide variety of topics were produced – from the MDR regional magazine Sachsen Spiegel, which reported on an emergency course for TROPOS researchers working in the wilderness, to Australian ABC News, which interviewed Mira Pöhlker about the HALO campaign CAFE-PACIFIC in Queensland.

Radio science programmes once again covered a wide range of topics in the reporting period: from a TROPOS researcher’s winter in Antarctica (MDR-Sachsen), urban greenery and air quality (DLF), Saharan dust and diseases (BR2 & DLF Nova)

(arte, 31.5.25, [Link zum Trailer](#)), sowie Holger Baars und Sebastian Bley zu Aeolus in „Der Wind - Motor des Klimawandels“ (arte, 22.09.24, [Link zum Video](#)). Die hohe Qualität dieser arte-Dokumentationen zeigt sich u.a. dadurch, dass „Die Rätsel der Wolken“ beim Green Screen Festival 2025 in Eckernförde, dem größten Naturfilmfestival Europas, und beim SILBERSALZ Science & Media Festival 2025 in Halle (Saale) jeweils in der Kategorie „Bester Wissenschaftsfilm“ nominiert war. Die Dokumentation von Sebastian Lindemann erkundet die Geheimnisse der Wolken und ihre Rolle bei der Formung des Erdklimas – u.a. mit Mira Pöhlker, Dennis Niedermeier und Peter Mettke vom TROPOS) sowie mit Aufnahmen von der HALO-Mission CAFE-Pacific in Australien und den TROPOS-Laboren in Leipzig.

Ein besonderes Highlight war die TV-Dokumentation „Expedition Amazonas“, bei der das ZDF-Team zusammen mit Mira Pöhlker einige Tage den Amazonas bereiste, um die Auswirkungen des Klimawandels anlässlich der UN-Klimakonferenz COP25 in Belém zu zeigen. Der Film wurde am 10.11.25 als WISO-Spezial zur besten Sendezeit ausgestrahlt und erreichte rund 2 Millionen Zuschauerinnen und Zuschauer ([Link zum Video](#)). Ebenfalls ein Millionenpublikum erreichte die Sendung „ZDF Magazin Royale“, die Jan Böhmermann am 6.9.24 satirisch dem Thema Feinstaub widmete ([Link zum Video](#)) und darin auch eine TROPOS-Studie von 2018 aus Bolivien zitierte („Ruß aus dem Verkehr der Megacities trägt zur Klimaerwärmung bei“).

2024/25 sind insgesamt 25 Fernsehbeiträge zu verschiedensten Themen entstanden - vom MDR-Regionalmagazin Sachsen Spiegel, das über einen Notfallkurs für Einsätze von TROPOS-Forschende in



Fig. / Abb. 6: Science cinema for children on 13 April 2024 in Leipzig with ‘Checker Tobi and the Journey to the Flying Rivers’ and Prof. Mira Pöhlker. / Wissenschaftskino für Kinder am 13.04.24 in Leipzig mit „Checker Tobi und die Reise zu den fliegenden Flüssen“ und Prof. Mira Pöhlker. © Tilo Arnhold, TROPOS

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to the new cloud observatory in the Thuringian Forest (MDR-Thüringen).

Traditional print media continued to decline in importance, but still play a role in shaping public opinion and remain important for anchoring the region. So when the Sächsische Zeitung writes about a Leipzig researcher's Antarctic wintering, Leipzig's contribution to the new EarthCARE environmental satellite, or the results of Saxon participants in a Polarstern expedition, it underscores the importance of research in the Free State. While the circulation of the printed newspaper is declining, its online editions reach a wide audience – especially in reputable English-language media: an online report by the British Guardian on the results of the TROPOS study on wood heating made Melpitz internationally better known and led to several follow-up reports in German online media. TROPOS research results on forest fires in Canada, the silting up of the Aral Sea and Saharan dust, among other topics, also received international attention.

Podcasts and YouTube videos have now established themselves as new, additional media, in which TROPOS was present in 2024/25 with cloud and polar research, among other things.

The website [www.tropos.de](http://www.tropos.de) is aimed at both researchers and the general public, especially in the "News" section. The "Discover" section therefore aims to explain research in an easily understandable way. The "Events" section provides background information and visual impressions of various public events. The "Campaign Reports" section picked up speed again after the pandemic-related decline from 2023/24 onwards. Here, researchers reported on cloud measurements at the German Neumayer III research



Fig. / Abb. 7: The BMFTR project EngageMINT makes environmental research accessible to young people and provides insight into air measurements at TROPOS. / Das BMFTR-Projekt EngageMINT macht Umweltforschung für Jugendliche greifbar und gibt am TROPOS dazu Einblick in Luftmessungen. © Tilo Arnhold, TROPOS

der Wildnis berichtete, bis hin zum Australischen ABC News, das Mira Pöhlker zur HALO-Kampagne CAFE-PACIFIC in Queensland interviewte.

Die Wissenschaftsformate des Hörfunks deckten auch im Berichtsraum wieder eine große Bandbreite an Themen ab: Von der Antarktis-Überwinterung eines TROPOS-Forschers (MDR-Sachsen), Städtischem Grün und Luftqualität (DLF), Saharastaub und Krankheiten (BR2 & DLF Nova) bis hin zum neuen Wolkenobservatorium im Thüringer Wald (MDR-Thüringen).

Klassische Printmedien haben weiter an Bedeutung verloren, sind aber immer noch Teil der öffentlichen Meinungsbildung und spielen für die Verankerung in der Region nach wie vor eine Rolle. Wenn die Sächsische Zeitung also über die Antarktis-Überwinterung eines Leipziger Forschers, den Leipziger Beitrag zum neuen Umweltsatelliten EarthCARE oder Ergebnisse von Sächsischen Teilnehmenden einer Polarstern-Expedition schreibt, dann unterstreicht das den Stellenwert der Forschung im Freistaat. Während die Auflage der gedruckten Zeitung zurückgeht, erreichen deren Online-Ausgaben ein weites Publikum – besonders bei angesehenen englischsprachigen Medien: Ein Online-Bericht des britischen Guardians über Ergebnisse der TROPOS-Studie zu Holzheizungen machte Melpitz international bekannter und sorgte für mehre Folgeberichten in deutschen Online-Medien. International wahrgenommen wurden TROPOS-Forschungsergebnisse auch u.a. zu den Waldbränden in Kanada, zur Verlandung des Aralsees und zum Saharastaub.

Als neue, zusätzliche Medien haben sich inzwischen Podcasts und Youtube-Videos etabliert, in denen TROPOS 2024/25 u.a. mit Wolken- und Polarforschung präsent war.

Das Internetangebot [www.tropos.de](http://www.tropos.de) richtet sich neben Forschenden zugleich an die breite Öffentlichkeit – vor allem im Bereich „Aktuelles“: Die Rubrik „Entdecken“ hat daher zum Ziel, die Forschung leicht verständlich zu erläutern. Die Rubrik „Veranstaltungen“ liefert Hintergrundinfos und optische Eindrücke von diversen Publikumsveranstaltungen. Die Rubrik „Kampagnenberichte“ nahm nach dem Pandemie-bedingten Rückgang ab 2023/24 wieder an Fahrt auf. Hier berichteten Forschende u.a. von den Wolkenmessungen an der deutsche Forschungsstation Neumayer III in der Antarktis (COALA 2022 - 2024) und einer Expedition des Forschungsschiffes Sonne im Indischen Ozean (SO305 BIOCAT-IIOE2). Um die vielfältigen Kampagnenberichte und Forschungsprojekte besser auffindbar zu machen, wurden die Kampagnenberichte 2024 in einen Science-Blog überführt, in dem die Forschenden sowohl über ihre Messkampagnen als auch über

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station in Antarctica (COALA 2022–2024) and an expedition by the research vessel Sonne in the Indian Ocean (SO305 BIOCAT-IIOE2), among other things. To make the diverse campaign reports and research projects easier to find, the 2024 campaign reports were transferred to a science blog, where researchers can easily share information about their measurement campaigns and news from various stations or projects. Keywords now make it possible to see what else has been published on a topic in the blog with just one click.

**Social media:** In January 2025, more than 60 German-speaking colleges, universities and other research institutions joined forces to send a message and suspended their activities on the social media platform X (formerly Twitter) in protest. The Leibniz Association's office also suspended its activity on X because it promoted the spread of disinformation and hostility towards people and democracy to an alarming degree. TROPOS has also frozen its activity on X and now posts on other platforms: Bluesky, Mastodon, LinkedIn and Instagram. The world of social media platforms has changed and diversified very dynamically in 2024/2025. While TROPOS once had over 1,000 followers on X in both German and English, after about a year it now has just under 200 on Bluesky, just under 100 on Mastodon, over 100 on LinkedIn and just under 100 on Instagram.

### Events

A total of 44 public events were held in 2024/2025. The formats were diverse. Well-known formats such as group visits and lectures were of course included, but a series of appearances at popular science events are now also part of the repertoire. TROPOS researchers are now regular guests at the Leibniz format "Book a Scientist" – for example, in 2025 with Andrea Cuesta-Mosquera on "Indoor air pollution" and Roland Schrödner on "Air quality over time". However, unusual formats such as the science show "Circus of Science" in Leipzig or the "Ice & Sky Explorer's Day" in Christchurch, New Zealand, were also used for appearances. Among the popular science events, the following stood out in particular:

The first Saxon science festival, SPIN2030, attracted around 8,000 guests on 8–9 March 2024. The concept of integrating current research into the permanent exhibitions and interactive worlds of the Dresden Technical Collections for two days was a complete success. More than 50 scientific institutions, including all universities and non-university research institutions in Saxony, brought the broad and diverse range of research in the Free State to life and amazed



*Fig. / Abb. 8: The first Saxon science festival SPIN2030 attracted around 8,000 guests to the Technical Collections Dresden on 8–9 March 2024. TROPOS was there with a stand and events. / Das erste sächsische Wissenschaftsfestival SPIN2030 lockte am 8.-9.03.24 rund 8.000 Gäste in die Technischen Sammlungen Dresden. TROPOS war mit Stand und Veranstaltungen dabei. © Tilo Arnhold, TROPOS*

Neuigkeiten von diversen Stationen oder Projekten leicht verständlich erzählen. Die Verschlagwortung ermöglicht es jetzt, mit einem Klick zu sehen, was zu einem Thema noch im Blog erschienen ist.

**Social Media:** Im Januar 2025 haben mehr als 60 deutschsprachige Hochschulen, Universitäten und weitere Forschungsinstitutionen haben sich zusammengeschlossen, um ein Zeichen zu setzen und ihre Aktivitäten auf der Social-Media-Plattform X (ehemals Twitter) aus Protest eingestellt. Die Geschäftsstelle der Leibniz-Gemeinschaft hat ihre Aktivität auf X ebenfalls eingestellt, weil diese die Verbreitung von Desinformation und Menschen- und Demokratiefreundlichkeit in einem erschreckenden Maß begünstigt. Auch TROPOS hat seine Aktivität auf X eingefroren und postet inzwischen über andere Plattformen: Bluesky, Mastodon, LinkedIn und Instagram. Die Welt der Social-Media-Plattformen hat sich 2024/2025 sehr dynamisch verändert und diversifiziert. Während TROPOS einst bei X auf Deutsch und Englisch jeweils über 1000 Follower hatte, sind es nach rund einem Jahr bei Bluesky knapp 200, bei Mastodon knapp 100, bei LinkedIn über 100 und bei Instagram knapp 100 Follower.

### Veranstaltungen

2024/2025 konnten insgesamt 44 öffentliche Veranstaltungen realisiert werden. Die Formate waren dabei vielfältig. Bekannte Formate wie Gruppenbesuche und Vorträge fehlten natürlich nicht, aber auch eine Reihe von Auftritten bei populärwissenschaftlichen Veranstaltungen gehören mittlerweile zum Repertoire. Beim Leibniz-Format „Book a Scientist“ sind TROPOS-Forschende inzwischen regelmäßig zu Gast – so 2025 mit Andrea Cuesta-Mosquera zu

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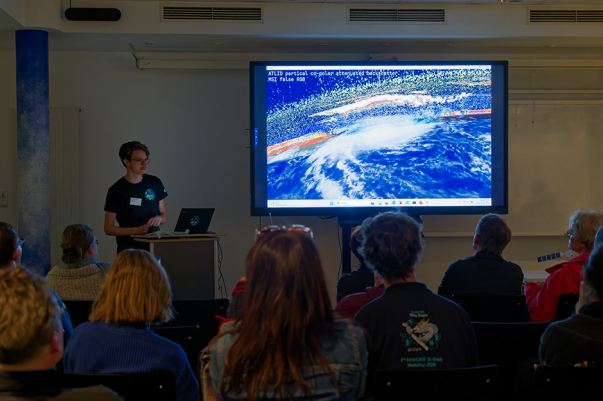


Fig. / Abb. 9: At Space Day on 28 March 2025, TROPOS researchers demonstrated how knowledge from Leipzig contributes to the successes of space travel. / Beim „Tag der Raumfahrt“ am 28.03.25 zeigten TROPOS-Forschende, wie Wissen aus Leipzig zu den Erfolgen der Raumfahrt beiträgt. © Tilo Arnhold, TROPOS

children and adults alike. Scientists answered all questions and also imparted knowledge in entertaining formats, such as the Science Slam or “Meet a Scientist”. TROPOS was there with a stand, a Science Slam and two film discussions.

“Earth-shattering films on burning issues of our time” is the motto of Saxony’s School Cinema Weeks, which also showed “Checker Tobi and the Journey to the Flying Rivers” in March 2024. Over 100 screenings in various cinemas throughout Saxony were on the programme. Cloud researcher Prof. Mira Pöhlker, who shows Tobi the ATTO tower in the Amazon in the film, held three film discussions in Leipzig. The cloud researcher also delighted her young fans at the Ülzen Children’s Cinema and the Science Cinema for Children in Leipzig.

In 2025, Space Day was organised for the first time as a day of action by the German Federal Government and the German Space Agency at the DLR. TROPOS used the occasion on 28 March 2025 to show how Leipzig researchers are contributing to the successes of space travel. Under the motto “Observing the weather from space with Leipzig knowledge”, information was provided on EarthCARE, remote sensing from the ground and a radiosonde ascent.

Another new development in 2025 was that TROPOS took part in Berlin Science Week for the first time. The tenth edition took place under the motto “Beyond Now” and transformed the city into a vibrant festival of scientific ideas, explorations and experiments. The event “Air quality and ultrafine particles – what does this have to do with BER Airport?” where experts from UBA, Charité and TROPOS presented the results of ULTRAFLEB and the BEAR study on 6 November 2025 in the Charité auditorium

„Indoor air pollution“ und Roland Schrödner zu „Luftqualität im Wandel der Zeit“. Aber auch außergewöhnliche Formate wie die Wissenschaftsshow „Circus of Science“ in Leipzig oder der „Ice & Sky Explorer’s Day“ in Christchurch, Neuseeland, wurden für Auftritte genutzt. Unter den populärwissenschaftlichen Veranstaltungen stachen besonders heraus:

Das erste sächsische Wissenschaftsfestival SPIN2030 hat am 8./9. März 2024 rund 8.000 Gäste in seinen Bann gezogen. Das Konzept, aktuelle Forschung für zwei Tage in die Dauerausstellungen und Erlebniswelten der Technischen Sammlungen Dresden zu integrieren, war ein voller Erfolg. Mehr als 50 Wissenschaftseinrichtungen, darunter alle Hochschulen sowie außeruniversitäre Forschungseinrichtungen aus Sachsen machten die breit aufgestellte und vielfältige Forschung im Freistaat erlebbar und brachten Kinder und Erwachsene gleichermaßen zum Staunen. Wissenschaftlerinnen und Wissenschaftler stellten sich allen Fragen und vermittelten mit unterhaltsamen Formaten auch Wissen, etwa beim Science Slam oder bei „Meet a Scientist“. TROPOS war mit einem Stand, einem Science Slam und zwei Filmgesprächen dabei.

„Weltbewegende Filme zu brennenden Fragen ihrer Zeit“ ist das Motto der Schulkinowochen Sachsen, die im März 2024 auch „Checker Tobi und die Reise zu den fliegenden Flüssen“ zeigten. Über 100 Vorstellungen in diversen Kinos in ganz Sachsen standen dabei auf dem Programm. Mit Wolkenforscherin Prof. Mira Pöhlker, die im Film Tobi den ATTO-Turm im Amazonas zeigt, gab es drei Filmgespräche in Leipzig. Außerdem begeisterte die Wolkenforscherin ihre kleinen Fans bei Kinderkino Ülzen und beim Wissenschaftskino für Kinder in Leipzig.

2025 wurde der „Tag der Raumfahrt“ erstmals als Aktionstag der Bundesregierung und der Deutschen Raumfahrt Agentur im DLR organisiert. TROPOS nutzte den Anlass, um am 28.03.25 zu zeigen, wie Leipziger Forschende zu den Erfolgen der Raumfahrt beitragen. Unter dem Motto „Mit Leipziger Wissen das Wetter aus dem All beobachten“ es gab Informationen zu EarthCARE, zu Fernerkundung vom Boden aus und einen Radiosondenaufstieg.

Neu war 2025 auch, dass TROPOS zum ersten Mal an der „Berlin Science Week“ teilnahm. Die zehnte Ausgabe fand unter dem Motto „Beyond Now“ statt und verwandelte die Stadt in ein pulsierendes Festival wissenschaftlicher Ideen, Erkundungen und Experimente. Dazu trug auch die Veranstaltung „Luftqualität und ultrafeine Partikel – was hat das mit dem Flughafen BER zu tun?“ bei, wo Expertinnen und Experten von UBA, Charité und TROPOS am 06.11.25 im Auditorium der Charité im Charité-Cross-Over (CCO) in Berlin Ergebnisse von ULTRAFLEB

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at Charité-Cross-Over (CCO) in Berlin and answered detailed questions about ultrafine dust.

The dialogue with citizens also included two local information events in Melpitz near Torgau and Radeburg near Dresden, where TROPOS researchers provided information about measurements and results from their research projects on the effects of wood-burning heating systems on local air quality.

In 2024, Heike Wex was the first TROPOS researcher to appear at the Extreme Weather Congress in Hamburg, where she discussed the topic “Should every individual save the climate? Society between drive and depression” on 25 September 2024.

The “Leibniz in the Bundestag” format plays an important role in **policy advice**, with TROPOS regularly participating with topics such as air quality and other politically relevant issues. Other events with political relevance during the reporting period include the following:

The consultation on the German Strategy for Adaptation to Climate Change 2024. With the Federal Climate Adaptation Act (KAnG) coming into force in July 2024, the German government was obliged to develop and implement a new, preventive climate adaptation strategy with measurable targets. As part of the association hearing held by the Federal Ministry for the Environment (BMUV) in October, the DKK was invited to participate in the online consultation on the draft German Strategy for Adaptation to Climate Change (DAS 2024). Roland Schrödner from TROPOS took this opportunity to contribute specific suggestions for improvement. The modeller also spoke on 4 September 2024 on the topic of “Monitoring air and water – making sustainable decisions” at the Ministerial Congress in Berlin, which was attended by 350 participants from more than 140 authorities/institutions in 2024. For 30 years, the Ministerial Congress has been the exclusive platform for an intensive exchange of experiences on the modernisation of federal, state and local government.

Africa-Europe cooperation: The initiative “Cooperation Lounge Africa-Europe: Science Meets Politics” met on 10-11 December 2024 at the Representation of the Free State of Bavaria in Brussels to strengthen dialogue between science and politics and improve research and innovation cooperation between Africa and Europe. TROPOS was represented by Andrea Cuesta-Mosquera.

Embassy visits: On 11 February 2025, the German Ambassador to Portugal and Cabo Verde, Julia Monar, visited the FS-Meteor at the end of the M207 expedition in Mindelo, together with the Minister of Science of Cabo Verde. Annett Skupin and Ronny

und der BEAR-Studie vorstellten und ausführlich Fragen rund um Ultrafeinstaub beantworteten.

Zum Dialog mit Bürgerinnen und Bürgern zählten auch zwei lokale Informationsveranstaltungen in Melpitz bei Torgau und Radeburg bei Dresden, in denen TROPOS-Forschende über Messungen und Ergebnisse ihrer Forschungsprojekte zu den Auswirkungen von Holzheizungen auf die Luftqualität vor Ort informierten.

Mit Heike Wex trat 2024 erstmalig eine TROPOS-Forschende auf dem Extremwetterkongress in Hamburg auf und diskutierte dort am 25.09.24 zum Thema „Soll jeder Einzelne das Klima retten? Gesellschaft zwischen Tatendrang und Depression.“

Bei der **Politikberatung** spielt das Format „Leibniz im Bundestag“ eine wichtige Rolle, an dem sich TROPOS regelmäßig mit Themenangeboten z.B. zu Luftqualität und anderen politisch relevanten Themen beteiligt. Als weitere Veranstaltungen mit politischem Bezug sind für den Berichtszeitraum folgende hervorzuheben:

Die Konsultation zur Deutschen Anpassungsstrategie an den Klimawandel 2024. Mit dem im Juli 2024 in Kraft getretenen Bundes-Klimaanpassungsgesetz (KAnG) wurde die Bundesregierung verpflichtet, eine neue, vorsorgende Klimaanpassungsstrategie mit messbaren Zielen zu entwickeln und umzusetzen. Das DKK wurde im Rahmen der Verbändeanhörung vom Bundesumweltministerium (BMUV) im Oktober eingeladen, sich an der Online-Konsultation zum Entwurf der Deutschen Anpassungsstrategie an den Klimawandel (DAS 2024) zu beteiligen. Von TROPOS nutzte diese Chance Roland Schrödner, um konkrete Verbesserungsvorschläge einzubringen. Der Modeller diskutierte auch am 04.09.24 zum Thema „Luft und Wasser monitoren – Nachhaltige Entscheidungen treffen“ auf dem Ministerialkongress in Berlin, an dem sich 2024 350 Teilnehmende aus mehr als 140



Fig. / Abb. 10: Long Night of Science at TROPOS on 20 June 2025. / Lange Nacht der Wissenschaften am TROPOS am 20.06.25. © Tilo Arnhold, TROPOS

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Engelmann presented the Oceanet-ACTRIS station and its sister station at the OSCM. Karamba Diaby, SPD Member of the Bundestag from Halle (Saale), visited the Ocean Science Centre Mindelo (OSCM) and the Cabo Verde Atmospheric Observatory (CVAO) on 4 February 2024 to learn about marine and atmospheric research. He was accompanied by Ludwig Blaurock, Deputy Head of Mission at the Embassy of the Federal Republic of Germany in Portugal. Diaby was a full member of the Bundestag's Committee on Economic Cooperation and Development and the Foreign Affairs Committee. He also chaired the West Africa Parliamentary Group. The Antarctic Season Opening on 10 October 2025 highlighted the role of Christchurch, New Zealand, as a global hub for polar science. German Ambassador Nicole Menzenbach visited the HALO research aircraft and spoke with researchers about the HALO-South mission.

### Equal opportunities and promoting young talent

Equality is implemented as a guiding principle at TROPOS. The institute thus meets the equality standards of the Leibniz Association. An essential



Fig. / Abb. 11: Conference 'Indoor Air 2024 – Measurement, Assessment and Healthy Living' on 6–8 May 2024 at the UBA in Dessau-Roßlau with the TROPOS Indoor Air Team. / Tagung „Innenraumlufte 2024 – Messen, Bewerten und Gesundes Wohnen“ am 06.-08.05.24 am UBA in Dessau-Roßlau mit dem TROPOS-Indoor-Luft-Team. © UBA

Behörden/Einrichtungen beteiligten. Der Ministerialkongress ist seit 30 Jahren die exklusive Plattform für einen intensiven Erfahrungsaustausch zur Modernisierung der Bundes-, Landes- und Kommunalverwaltung.

Kooperation Afrika-Europa: Die Initiative „Cooperation Lounge Africa-Europe: Science Meets Politics“ traf sich am 10./11.12.24 in der Vertretung des Freistaats Bayern in Brüssel, um den Dialog zwischen Wissenschaft und Politik zu stärken und die Forschungs- und Innovationszusammenarbeit zwischen Afrika und Europa zu verbessern. TROPOS war durch Andrea Cuesta-Mosquera vertreten.

Botschaftsbesuche: Die deutsche Botschafterin für Portugal und Cabo Verde, Julia Monar, besuchte am 11.02.25 zusammen mit dem Wissenschaftsminister von Cabo Verde die FS-Meteor am Ende der Expedition M207 in Mindelo. Annett Skupin und Ronny Engelmann präsentierten dabei die Oceanet-ACTRIS-Station und die Schwesterstation am OSCM. Karamba Diaby, SPD-Bundestagsabgeordneter aus Halle (Saale) besuchte am 04.02.24 das Ocean Science Centre Mindelo (OSCM) und das Cabo-Verde-Atmosphären-Observatorium (CVAO), um sich über Meeres- und Atmosphärenforschung zu informieren. Begleitet wurde er von Ludwig Blaurock, dem stellvertretenden Botschaftsleiter der Botschaft der Bundesrepublik Deutschland in Portugal. Diaby war ordentliches Mitglied im Ausschuss für wirtschaftliche Zusammenarbeit und Entwicklung und im Auswärtigen Ausschuss des Bundestages. Zudem hatte er den Vorsitz der Parlamentariergruppe Westafrika inne. Die „Antarctic Season Opening“ am 10.10.25 betonte die Rolle von Christchurch, Neuseeland, als globale Drehscheibe für die Polarwissenschaft. Dabei besuchte die deutsche Botschafterin Nicole Menzenbach das Forschungsflugzeug HALO und sprach mit den Forschenden über die Mission HALO-South.

### Chancengleichheit und Nachwuchsförderung

Gleichstellung ist am TROPOS als Leitprinzip implementiert. Das Institut erfüllt damit die Gleichstellungsstandards der Leibniz-Gemeinschaft. Ein wesentliches Instrument dabei ist der Gleichstellungsplan, dessen Umsetzung die Chancengleichheit für Menschen aller Geschlechter am TROPOS fördern und nachhaltig sichern soll. Er enthält schwerpunktmäßig Maßnahmen zur absolut diskriminierungsfreien Zusammenarbeit am Institut vom Einstellungsverfahren bis zur weiteren Erhöhung des Anteils von Frauen im Post-Doc-Bereich, in Festanstellungen, wissenschaftlichen Führungspositionen und Gremien. Der im August 2022 aufgestellte Plan gilt für vier Jahre und ist Teil des am TROPOS

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instrument in this regard is the equality plan, the implementation of which is intended to promote and sustainably ensure equal opportunities for people of all genders at TROPOS. It focuses on measures for absolutely non-discriminatory cooperation at the institute, from the recruitment process to further increasing the proportion of women in post-doctoral positions, permanent positions, scientific leadership positions and committees. The plan, which was drawn up in August 2022, is valid for four years and is part of the newly implemented personnel development plan at TROPOS. TROPOS's targets for increasing the proportion of women are based on the Leibniz Association's cascade model, whereby a step-by-step model adapted to the current institute-specific job situation has been defined.

To promote the scientific careers of women, the "Shape Your Future" mentoring programme was developed, a tandem programme of young female scientists at TROPOS with scientific mentors who support them in their scientific and personal growth for one year. It was launched in January 2024 for eight mentoring tandems. The regular Equality Café offers a platform for exchange, for example on applying for third-party funding and balancing work and career.

On 10 December 2020, the *berufundfamilie* audit certificate was confirmed after a successful dialogue process. This means that the certificate, which is regarded as a seal of quality for a strategically designed family- and life-phase-conscious personnel policy, is now permanent. On 18 June 2024, TROPOS was awarded the "berufundfamilie" audit for the fifth time.

### Promoting young talent

TROPOS actively promotes young scientists in bachelor's and master's programmes, during doctoral projects and beyond. The institute is closely involved in the development and implementation of the new bachelor's and master's programmes at the University of Leipzig and is responsible for 12 modules.

Highly qualified employees participate in teaching at Leipzig University as joint appointments. In addition to meteorology students, TROPOS also trains chemistry and physics students (see list, p. 181).

The institute offers young scientists individually tailored doctoral programmes accompanied by a support team as part of its structured doctoral training. TROPOS staff teach courses at universities, international summer schools, training courses and networks (see list, p. 178).

The Leibniz Graduate School on "Clouds, Aerosols and Radiation", founded in July 2012, has put doctoral training at TROPOS on a solid footing



Fig. / Abb. 12: On 10 December 2023, the audit certificate for work and family was confirmed after successfully completing the dialogue process. / Zum 10.12.2023 wurde das Zertifikat zum Audit berufundfamilie nach erfolgreichem Dialogverfahren bestätigt. © Jens Schicke, berufundfamilie Service

neu implementierten Personalentwicklungsplanes. TROPOS orientiert sich in den Zielvorgaben für die Erhöhung des Frauenanteils am Kaskadenmodell der Leibniz-Gemeinschaft, wobei ein an die momentane institutsspezifische Stellensituation angepasstes Stufenmodell definiert wurde.

Zur Förderung der wissenschaftlichen Karrieren von Frauen wurde das „Shape Your Future“-Mentoring-Programm entwickelt, ein Tandem Programm von jungen Wissenschaftlerinnen am TROPOS mit wissenschaftlichen Mentor\*innen, die sie für ein Jahr in ihrem wissenschaftlichen und persönlichen Wachstum fördern. Es wurde im Januar 2024 für 8 Mentoring-Tandems gestartet. Das regelmäßig stattfindende Equality-Café bietet eine Austauschplattform, zum Beispiel zur Beantragung von Drittmitteln und der Vereinbarkeit von Beruf und Karriere.

Zum 10.12.2020 wurde das Zertifikat zum Audit berufundfamilie nach erfolgreichem Dialogverfahren bestätigt. Damit erhält das Zertifikat, das als Qualitätssiegel für eine strategisch angelegte familien- und lebensphasenbewusste Personalpolitik gilt, seinen dauerhaften Charakter. TROPOS ist am 18. Juni 2024 zum fünften Mal mit dem Audit „berufundfamilie“ ausgezeichnet worden.

### Nachwuchsförderung

TROPOS fördert aktiv den wissenschaftlichen Nachwuchs in der Bachelor- und Masterausbildung, während der Promotionsvorhaben und darüber hinaus. Das Institut ist eng in die Entwicklung und in die Durchführung der neuen Bachelor- und Masterstudiengänge an der Universität Leipzig eingebunden und ist für 12 Module verantwortlich.

Hochqualifizierte Mitarbeiterinnen und Mitarbeiter beteiligen sich als gemeinsame Berufungen an der

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Fig. / Abb. 13: Prof. Hartmut Herrmann was honoured by the American Chemical Society (ACS) at the ACS Fall Meeting 2024 in Denver, Colorado, with a symposium and was presented with the Honor Award for Scientific Excellence. / Prof. Hartmut Herrmann wurde von der American Chemical Society (ACS) auf dem Herbsttreffen 2024 der ACS in Denver, Colorado, mit einem Symposium geehrt und dem Ehrenpreis für wissenschaftliche Exzellenz ausgezeichnet. © ACS

together with the University of Leipzig and pools joint expertise in the interlinked areas of “aerosols, clouds and radiation.” It is currently located at the Graduate Academy Leipzig (GA) with 50 members.

Promoting young talent contributes to the successful scientific functioning of the institute and secures its future. The institute has also drawn up a personnel development plan for this purpose. This plan provides a framework in which specific measures and agreements are integrated and appropriately labelled (strategic instruments, personnel planning in line with research strategy, measures and objectives for selecting and training personnel, health management, dual careers and teaming, as well as support during transitions).

### Shaping the future

TROPOS supports young people on their path to studying natural sciences by highlighting career prospects in the field of atmospheric research. School pupils learn about research work in a playful way and engage in conversation with researchers from the STEM field. As part of the STEM initiative, which aims to inspire young people to pursue careers in mathematics, computer science, natural sciences and technology, TROPOS also participates in Girls' Day, the Future Day. In 2024 and 2025, interested girls were able to find out about research work and training opportunities on this day. Four internships for school pupils and five study-related internships were realised in 2024/25.

TROPOS will continue to finance at least one apprenticeship position from its budget in the coming years.

Lehre der Universität Leipzig. Neben Studierenden der Meteorologie werden am TROPOS auch Chemie- und Physikstudierende ausgebildet (siehe Liste, S. 181).

Das Institut bietet jungen Wissenschaftlerinnen und Wissenschaftlern individuell abgestimmte und von einem Betreuungsteam begleitete Realisierung ihrer Promotionen im Rahmen der strukturierten Promovendenausbildung. Mitarbeitende des TROPOS halten Kurse an Universitäten, bei internationalen Sommerschulen, Ausbildungskursen und -netzwerken (siehe Liste, S. 178).

Die im Juli 2012 gegründete Leibniz-Graduiertenschule zu „Wolken, Aerosolen und Strahlung“ hat die Promovendenausbildung am TROPOS gemeinsam mit der Universität Leipzig auf eine solide Grundlage gestellt und bündelt die gemeinsame Expertise in den gekoppelten Bereichen „Aerosole-Wolken-Strahlung“. Sie ist mit aktuell 50 Mitgliedern in der „Graduate Academy Leipzig“ (GA) verortet.

Nachwuchsförderung trägt zu einer erfolgreichen wissenschaftlichen Funktion des Instituts und deren Sicherung für die Zukunft bei. Das Institut hat auch hierfür einen Personalentwicklungsplan erstellt. Dieser stellt einen Rahmen dar, in den konkrete Maßnahmen und Vereinbarungen eingebunden und entsprechend gekennzeichnet sind (strategische Instrumente, Personalplanung nach Forschungsstrategie, Maßnahmen und Ziele zur Auswahl und Einarbeitung von Personal, Gesundheitsmanagement, Dual Career und Teaming sowie Begleitung von Übergängen).

### Zukunft schaffen

TROPOS unterstützt den Weg zum naturwissenschaftlichen Studium, indem berufliche Perspektiven im Bereich der Atmosphärenforschung aufgezeigt werden. Schülerinnen und Schüler lernen die Forschungsarbeit auf spielerische Art kennen und kommen mit Forschenden aus dem MINT-Bereich ins Gespräch. Im Rahmen der MINT-Initiative, die zum Ziel hat, Jugendliche für einen Beruf in den Fächern Mathematik, Informatik, Naturwissenschaften und Technik zu begeistern, beteiligt sich TROPOS auch am Girls' Day, dem Zukunftstag. 2024 und 2025 konnten sich an diesem Tag interessierte Schülerinnen über die Forschungsarbeit und Ausbildungsmöglichkeiten informieren. Vier Praktika für Schüler:innen und fünf studienbegleitende Praktika konnten 2024/25 realisiert werden.

TROPOS wird auch in den nächsten Jahren mindestens einen Lehrlingsausbildungsplatz aus Haushaltsmitteln finanzieren.

# Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick

## Significant collaborations and networking in research

Numerous established networks within the Leibniz Association, with universities, with Max Planck Institutes, with institutes of the Helmholtz Association and at international level demonstrate the current status of TROPOS networking in interdisciplinary aerosol and cloud research. TROPOS is similarly networked at European and global level and is actively developing research programmes here (see list, p. 200).

Technological developments at TROPOS lead to international standards in the experimental direct and indirect detection of aerosols and hydrometeors from the ground to the high atmosphere as well as in the modelling of the complex multiphase system.

Cooperation opportunities within the Leibniz Association and beyond are being expanded as part of the Leibniz Association's competition fund. The Institute is linked to numerous international organisations through cooperation agreements (see list, p. 200). Notably, the Leibniz Science Campus BioSmoke deepened regional cooperations of TROPOS with DBFZ, UFZ, and the University of Leipzig.

TROPOS continues to participate in the research network Integrated Earth System Research (IESF), which aims to gain action-relevant knowledge for society about people in the Earth system. In particular, the ecological carrying capacity of the Earth system is to be determined and sustainable development paths derived from this.

TROPOS continues to be involved in the Leibniz research networks "CrisEn" (Environmental Crisis - Crisis Environments), Earth and Societies, and Mathematical Modelling and Simulation (MMS), as well as in Leibniz Labs Pandemic Preparedness and Systemic Sustainability (SYSTAIN).

TROPOS plays a leading role in the European research infrastructure ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure) and coordinates the German contribution to ACTRIS, called ACTRIS-D, as part of the National Roadmap of the Federal Ministry of Research, Technology and Space. More than 120 institutions in over 20 countries are already involved at European level. In June 2025, the first phase of ACTRIS-D was successfully evaluated securing the funding for the second phase for the next 3 years. The ACTRIS facilities form the world's largest multi-site infrastructure for atmospheric research, providing its users with free access to high quality data, instruments, expertise, training opportunities and other services. A highlight of this is the renewal of the Cabo Verde Atmospheric Observatory (CVAO) which is operated by a consortium of the Cape Verdean Institute of Meteorology and Geophysics

## Bedeutende Kooperationen und Vernetzung in der Forschung

Zahlreiche etablierte Netzwerke innerhalb der Leibniz-Gemeinschaft, mit Universitäten, mit Max-Planck-Instituten, mit Instituten der Helmholtz-Gemeinschaft und auf internationaler Ebene zeigen den aktuellen Stand der Vernetzung von TROPOS in der interdisziplinären Aerosol- und Wolkenforschung. Ähnlich ist TROPOS auf der europäischen und weltweiten Ebene vernetzt und entwickelt hier aktiv Forschungsprogramme (siehe Liste, S. 200).

Technologische Entwicklungen am TROPOS führen zu internationalen Standards in der experimentellen direkten und indirekten Erfassung von Aerosolen und Hydrometeoren vom Boden bis zur hohen Atmosphäre sowie in der Modellierung des komplexen Multiphasensystems.

Im Rahmen des Wettbewerbsfonds der Leibniz-Gemeinschaft werden die Kooperationsmöglichkeiten innerhalb der Leibniz-Gemeinschaft und darüber hinaus ausgebaut. Durch Kooperationsvereinbarungen ist das Institut mit zahlreichen internationalen Einrichtungen verbunden (siehe Liste, S. 200).

TROPOS beteiligt sich weiterhin am Forschungsnetzwerk Integrierte Erdsystemforschung (IESF), das für die Gesellschaft handlungsrelevante Erkenntnisse über die Menschen im Erdsystem gewinnen will. Vor allem die ökologischen Tragfähigkeiten des Erdsystems sollen bestimmt und daraus nachhaltige Entwicklungspfade abgeleitet werden.

TROPOS ist weiterhin an den Leibniz-Forschungsnetzwerken „CrisEn“ (Environmental Crisis - Crisis Environments), „Earth and Society“ und „Mathematische Modellierung und Simulation“ (MMS) sowie an den Leibniz-Labs „Pandemic Preparedness“ und „Systemic Sustainability“ (SYSTAIN) beteiligt.



Fig. / Abb. 14: Kick-off meeting for phase 3 of the DFG Transregio (AC)<sup>3</sup> in Braunlage on 28/29 May 2024. / Kick-off-Treffen zu Phase 3 des DFG-Transregios (AC)<sup>3</sup> in Braunlage am 28./29.05.24. © Tilo Arnhold, TROPOS

## Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick

(INMG), the Leibniz Institute for Tropospheric Research (TROPOS) in Leipzig, the Max Planck Institute for Biogeochemistry in Jena (MPI-BGC) and the University of York in the UK. Cooperations in the Cabo Verde islands are further expanded with the collocation of TROPOS ground-based remote sensing equipment at GEOMAR's Ocean Science Centre Mindelo (OSCM).

TROPOS is also still involved in the European and national roadmap project IAGOS (In-service Aircraft for a Global Observing System) and, together with its national partners, has successfully completed the set-up phase and commenced operations in December 2022.

TROPOS plays a central role in the development and use of satellite-based earth observation and is involved in the international consortia of the first wind lidar AEOLUS of the European Space Agency ESA and the Earth Explorer satellite EarthCARE which now has an expected lifetime of 10 years. After contributing significantly to the great success of the AEOLUS mission, TROPOS now leads the development of algorithms for two of the four instruments onboard the satellite: the Atmospheric Lidar (ATLID) and the Multi-Spectral Imager (MSI), and coordinates the validation activities for EarthCARE.

In the competition for a cluster of excellence, both projects from Leipzig University reached the final round: the Breathing Nature initiative defended its full application on 5 December 2024. Science Minister Sebastian Gemkow was also present in Bonn and pledged the Free State's full support for the projects.



Fig. / Abb. 15: Dr. Karamba Diaby, SPD Member of the German Parliament from Halle (Saale), visited the Cabo Verde Atmospheric Observatory (CVAO) on 4 February 2024. / Karamba Diaby, SPD-Bundestagsabgeordneter aus Halle (Saale), besuchte am 04.02.24 das Cabo-Verde-Atmosphären-Observatorium (CVAO). © Edson Silva Delgado, GEOMAR

TROPOS spielt eine führende Rolle in der europäischen Forschungsinfrastruktur ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure) und koordiniert den deutschen Beitrag zu ACTRIS, genannt ACTRIS-D, als Teil der Nationalen Roadmap des Bundesministeriums für Forschung, Technologie und Raumfahrt. Auf europäischer Ebene sind bereits mehr als 120 Institutionen in über 20 Ländern beteiligt. Im Juni 2025 wurde die erste Phase von ACTRIS-D erfolgreich evaluiert, wodurch die Finanzierung für die zweite Phase für die nächsten drei Jahre gesichert wurde. Die ACTRIS-Einrichtungen bilden die weltweit größte standortübergreifende Infrastruktur für Atmosphärenforschung und bieten ihren Nutzern freien Zugang zu hochwertigen Daten, Instrumenten, Fachwissen, Schulungsmöglichkeiten und anderen Dienstleistungen. Ein Highlight ist die Erneuerung des Cabo Verde Atmospheric Observatory (CVAO), das von einem Konsortium aus dem Kapverdischen Institut für Meteorologie und Geophysik (INMG), dem TROPOS, dem Max-Planck-Institut für Biogeochemie in Jena (MPI-BGC) und der University of York im Vereinigten Königreich betrieben wird. Die Kooperationen auf den Kapverdischen Inseln werden durch die Aufstellung von bodengestützten Fernerkundungsgeräten von TROPOS im GEOMAR Ocean Science Centre Mindelo (OSCM) weiter ausgebaut.

TROPOS ist auch weiterhin am europäischen und nationalen Roadmap-Projekt IAGOS (In-service Aircraft for a Global Observing System) beteiligt und hat zusammen mit seinen nationalen Partnern die Aufbauphase erfolgreich abgeschlossen und im Dezember 2022 den Betrieb aufgenommen.

TROPOS spielt eine zentrale Rolle bei der Entwicklung und Nutzung satellitengestützter Erdbeobachtung und ist an den internationalen Konsortien des ersten Windlidars AEOLUS der Europäischen Weltraumorganisation ESA und des Erdbeobachtungssatellit EarthCARE beteiligt, der eine erwartete Lebensdauer von 10 Jahren hat. Nachdem TROPOS maßgeblich zum großen Erfolg der AEOLUS-Mission beigetragen hat, leitet es nun die Entwicklung der Algorithmen für die Datenprozessoren von zwei der vier Instrumente an Bord des Satelliten: dem Atmospheric Lidar (ATLID) und dem Multi-Spectral Imager (MSI) und koordiniert die Validierungsaktivitäten für EarthCARE.

Im Wettbewerb um einen Exzellenzcluster schafften es beide Projekte der Universität Leipzig in die Endrunde: Die Initiative „Breathing Nature“ verteidigte am 5. Dezember 2024 ihren vollständigen Antrag. Wissenschaftsminister Sebastian Gemkow war ebenfalls in Bonn anwesend und sicherte den

## Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick

TROPOS was represented by Mira Pöhlker. Unfortunately, the cluster application “Breathing Nature” on the interactions between the climate and biodiversity crises was not successful. Under the Excellence Strategy of the Federal Government and the Länder, only the “Leipzig Centre of Metabolism” (LeiCeM) cluster is funded at the Leipzig University in the coming years. Over the next three years, joint project proposals on Breathing Nature topics will initially be promoted in order to intensify cooperation even without funding from the Excellence Initiative.

The Collaborative Research Centre/Transregio (CRC/TRR) 172 “Arctic Amplification: Climate-relevant Atmospheric and Surface Processes and Feedback Mechanisms (AC)<sup>3</sup>” has entered its third and final funding phase after a successful evaluation in June 2023 with the Universities of Leipzig, Bremen and Cologne as well as the AWI and TROPOS. The overarching goal is to achieve fundamental and groundbreaking progress in our understanding of Arctic amplification and to improve the reliability of models for predicting dramatic warming in the Arctic.

The excellent cooperation with the (AC)<sup>3</sup> and MOSAiC consortia, including the Alfred Wegener Institute for Polar and Marine Research and other polar research groups continue to strengthen as we go from the Arctic to the Antarctic. TROPOS is strongly involved in the global initiative Antarctica InSync (Antarctica International Science & Infrastructure for Synchronous Observation) utilizing our partnerships in PICCAASO (Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere in Antarctica and the Southern Ocean) notably NIWA in New Zealand and CSIRO in Australia.

In the last two years, TROPOS has intensified its activities with the German research aircraft HALO (High Altitude and Long-Range Research Aircraft) and has been involved in two campaigns on chemistry of the atmosphere over the Pacific and particle formation processes and their interaction with clouds in the Southern Ocean under the leadership of TROPOS.

TROPOS has also expanded its cooperation with the Max Planck Institute for Chemistry (MPIC) and is involved in the measurements and scientific publication of data from the Amazon Tall Tower Observatory (ATTO) in the tropical rainforest as part of the joint collaboration. Together with the University of Miami and the MPIC, TROPOS is responsible for measuring the physical parameters of aerosols at the Barbados Atmospheric Chemistry Observatory (BACO).

TROPOS continues to be involved in developing the ERATOSTHENES Remote Sensing Centre of



Fig. / Abb. 16: Kick-off meeting of the new Leibniz Science Campus BioSmoke on 11 November 2025 at TROPOS. / Auftaktreffen des neuen Leibniz Science Campus BioSmoke am 11.11.25 am TROPOS. © Tilo Arnhold, TROPOS

Projekten die volle Unterstützung des Freistaates zu. TROPOS wurde durch Mira Pöhlker vertreten. Leider war der Clusterantrag „Breathing Nature“ zu den Wechselwirkungen zwischen Klima- und Biodiversitätskrise nicht erfolgreich. Im Rahmen der Exzellenzstrategie von Bund und Ländern wird an der Universität Leipzig in den kommenden Jahren nur der Cluster „Leipzig Centre of Metabolism“ (LeiCeM) gefördert. In den nächsten drei Jahren sollen zunächst gemeinsame Projektanträge zu Breathing-Nature-Themen vorangetrieben werden, um die Zusammenarbeit auch ohne Förderung durch die Exzellenzinitiative zu intensivieren.

Der Sonderforschungsbereich/Transregio (SFB/TRR) 172 „Arktische Verstärkung: Klimarelevante atmosphärische und oberflächenbezogene Prozesse und Rückkopplungsmechanismen (AC)<sup>3</sup>“ ist nach einer erfolgreichen Evaluierung im Juni 2023 mit den Universitäten Leipzig, Bremen und Köln sowie dem AWI und TROPOS in seine dritte und letzte Förderphase eingetreten. Das übergeordnete Ziel ist es, grundlegende und bahnbrechende Fortschritte in unserem Verständnis der arktischen Verstärkung zu erzielen und die Zuverlässigkeit von Modellen zur Vorhersage der dramatischen Erwärmung in der Arktis zu verbessern.

Die hervorragende Zusammenarbeit mit den Konsortien (AC)<sup>3</sup> und MOSAiC, darunter mit dem Alfred-Wegener-Institut für Polar- und Meeresforschung und anderen Polarforschungsgruppen, wird weiter gestärkt. Wir begeben uns von der Arktis in die Antarktis. TROPOS ist stark an der globalen Initiative Antarctica InSync (Antarctica International Science & Infrastructure for Synchronous Observation) beteiligt und nutzt dabei unsere Partnerschaften im Rahmen von PICCAASO (Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere

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*Fig. / Abb. 17: The ATTO Observatory (Amazon Tall Tower Observatory), with a 325-metre-high steel tower, is a research station in the Amazon rainforest, about 150 km north of Manaus. It is jointly operated by scientists from Brazil and Germany. TROPOS is involved in the measurements and evaluations through its cooperation with the MPIC. / Das Observatorium ATTO (Amazon Tall Tower Observatory) mit einem 325 m hohen Stahlturm ist eine Forschungsstation im Amazonas-Regenwald, etwa 150 km nördlich von Manaus. Sie wird gemeinsam von Wissenschaftlern aus Brasilien und Deutschland betrieben. TROPOS ist über die Kooperation mit dem MPIC an den Messungen und Auswertungen beteiligt. © Mira Pöhlker, TROPOS*

Excellence (ECoE) in Cyprus into a leading digital innovation hub (DIH) for Earth observation and geodata. In June 2024, the Ground-based remote sensing site (GBS) of the Cyprus Aerosol and Cloud Remote Sensing Observatory (CARO) has finally been equipped with a second container lab that houses a 35-GHz cloud radar of type Mira-35 and a microwave radiometer of type HATPRO. The implementation of the equipment within the CARO-GBS was jointly realized by a team of 4 members of the Remote Sensing Department of TROPOS and the members of the CARO team of the Eratosthenes Center of Excellence (ECoE) in Limassol. In the course of the EXCELSIOR project, linking CARO-GBS aerosol and cloud observations with satellite observations is set to become another key focus for the CARO team, as the ECoE is to be developed into a centre for joint space- and ground-based remote

in Antarctica and the Southern Ocean), insbesondere mit NIWA in Neuseeland und CSIRO in Australien.

In den letzten zwei Jahren hat TROPOS seine Aktivitäten mit dem deutschen Forschungsflugzeug HALO (High Altitude and Long-Range Research Aircraft) intensiviert und war unter der Leitung von TROPOS an zwei Kampagnen zur Chemie der Atmosphäre über dem Pazifik und zu Partikelbildungsprozessen und deren Wechselwirkung mit Wolken im Südlichen Ozean beteiligt.

TROPOS hat außerdem seine Zusammenarbeit mit dem Max-Planck-Institut für Chemie (MPIC) ausgebaut und ist im Rahmen der gemeinsamen Zusammenarbeit an den Messungen und der wissenschaftlichen Veröffentlichung von Daten aus dem Amazon Tall Tower Observatory (ATTO) im tropischen Regenwald beteiligt. Zusammen mit der Universität Miami und dem MPIC ist TROPOS für die Messung der physikalischen Parameter von Aerosolen am Barbados Atmospheric Chemistry Observatory (BACO) verantwortlich.

TROPOS ist weiterhin an der Entwicklung des ERATOSTHENES Remote Sensing Centre of Excellence (ECoE) in Zypern zu einem führenden digitalen Innovationszentrum (DIH) für Erdbeobachtung und Geodaten beteiligt. Im Juni 2024 wurde die bodengestützte Fernerkundungsstation (GBS) des Cyprus Aerosol and Cloud Remote Sensing Observatory (CARO) endlich mit einem zweiten Containerlabor ausgestattet, in dem ein 35-GHz-Wolkenradar vom Typ Mira-35 und ein Mikrowellenradiometer vom Typ HATPRO untergebracht sind. Die Installation der Geräte innerhalb des CARO-GBS wurde gemeinsam von einem Team aus vier Mitgliedern der Fernerkundungsabteilung des TROPOS und den Mitgliedern des CARO-Teams des ECoE in Limassol durchgeführt. Im Rahmen des EXCELSIOR-Projekts wird die Verknüpfung von CARO-GBS-Aerosol- und Wolkenbeobachtungen mit Satellitenbeobachtungen zu einem weiteren Schwerpunkt für das CARO-Team, da das ECoE zu einem Zentrum für gemeinsame weltraum- und bodengestützte Fernerkundungsanwendungen ausgebaut werden soll. Im Mai 2025 feierte das ECoE sein fünfjähriges Bestehen. Es hat sich zu einem regionalen Forschungs- und Innovationszentrum entwickelt, das mehr als 100 Mitarbeitende beschäftigt, an über 50 Forschungsprojekten beteiligt ist und mehr als 15 Millionen Euro an wettbewerbsorientierten Projekten einwirbt.

TROPOS beteiligt sich an der Nationalen Initiative für Erdsystemmodellierung (NatESM). Diese Initiative zielt darauf ab, den Einsatz zukünftiger

## Transfer in science and society – overview / Transfer in Wissenschaft und Gesellschaft – Überblick

sensing applications. In May 2025, ECoE celebrated five years since its foundation. It has become a regional research and innovation hub, employing more than 100 people, participating in over 50 research projects and securing more than 15 million euros in competitive projects.

TROPOS participates in the National Initiative for Earth System Modelling (NatESM). This initiative aims to promote and efficiently utilise the use of future supercomputers for components of simulation-based climate research in Germany.

The DFG-funded research unit C3SAR (Cloud 3d Structure And Radiation) aims for a better understanding of the role of 3d structure and variability of clouds on their radiative effects and remote sensing. Beyond activities in four out of five project groups, TROPOS contributes to C3SAR by hosting the spokesperson and the coordinator. Further members in the research unit are the universities of Hannover, Cologne and LMU in Munich as well as the Deutscher Wetterdienst in Lindenberg and Offenbach. The first 4-year funding phase of the research group began in October 2024.

TROPOS is also participating in the new DFG Research Training Group “Economics of Connected Natural Commons (ECO-N)” at Leipzig University, which is researching the sustainable use of natural commons.

Significant collaborations also exist with important research institutes in China and the Philippines through adjunct and guest professorships. The most important partners here are Fudan University in Shanghai, Shandong University with the School of Environmental Science and Engineering in Qingdao, Jinan University in Guangzhou, and University of the Philippines.

Collaboration in research and teaching was agreed with the Federal University Oye, Ekiti in Nigeria with a MoU, which resulted from a very successful research stay at TROPOS by a member of this university.

Supercomputer für Komponenten der simulationsbasierten Klimaforschung in Deutschland zu fördern und effizient zu nutzen.

Die von der DFG geförderte Forschungsgruppe C3SAR (Cloud 3d Structure And Radiation) hat sich zum Ziel gesetzt, die Rolle der 3D-Struktur und Variabilität von Wolken für ihre Strahlungseffekte und die Fernerkundung besser zu verstehen. Über die Aktivitäten in vier von fünf Projektgruppen hinaus leistet TROPOS einen Beitrag zu C3SAR, indem es den Sprecher und den Koordinator stellt. Weitere Mitglieder der Forschungsgruppe sind die Universitäten Hannover, Köln und LMU München sowie der Deutsche Wetterdienst in Lindenberg und Offenbach. Die erste vierjährige Förderphase der Forschungsgruppe begann im Oktober 2024.

TROPOS beteiligt sich auch am neuen DFG-Forschungsgruppe „Economics of Connected Natural Commons (ECO-N)“ an der Universität Leipzig, das sich mit der nachhaltigen Nutzung natürlicher Gemeingüter befasst.

Bedeutende Kooperationen bestehen auch mit wichtigen Forschungsinstituten in China und auf den Philippinen durch außerordentliche Professuren und Gastprofessuren. Die wichtigsten Partner sind hier die Fudan-Universität in Shanghai, die Shandong-Universität mit der Fakultät für Umweltwissenschaften und Ingenieurwesen in Qingdao, die Jinan-Universität in Guangzhou und die Universität der Philippinen.

Eine Zusammenarbeit in Forschung und Lehre wurde mit der Federal University Oye Ekiti in Nigeria mit einem Memorandum of Understanding vereinbart, das aus einem sehr erfolgreichen Forschungsaufenthalt eines Mitglieds dieser Universität am TROPOS hervorgegangen ist.

## Facts and figures / Zahlen und Fakten



as of 31.12.2025

**197 / 72** female

**Employees**

**139 / 49** female

**Scientists**

**43 / 22** female

**Doctoral candidates**

2024 / 2025

**7 / 7**

**Doctoral theses**

**6 / 12**

**Master of Science**

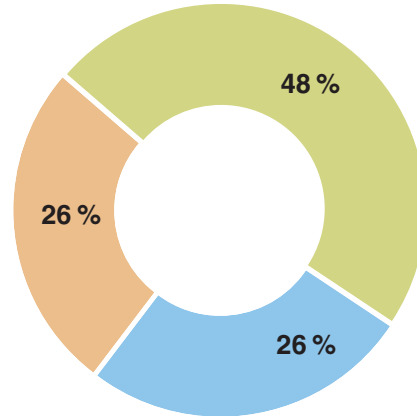
**8 / 3**

**Bachelor of Sciences**

as of 31.12.2025

**21,5 Mio €**

**Budget in total**



- Federal Ministry of Education and Research
- The Free State of Saxony
- External Funding



2024 / 2025

**124 / 130**

**Publications  
(peer-reviewed)**

**263 / 193**

**Reviews**

**9 / 12**

**Scientific events**

2024 / 2025

**29 / 18**

**Campaigns**

2024 / 2025

**41 / 54**

**National  
cooperations**

**50 / 56**

**International  
cooperations**

2024 / 2025

**27 / 17**

**Public events**

**15 / 13**

**Press releases**

**110 / 115**

**Media publications**

## Articles





# The Leibniz ScienceCampus BioSmoke: Investigating smoke and bioaerosols in a changing climate

Ina Tegen, Robert Wagner, Yarê Baker, Benedikt Gast, Hartmut Herrmann, Jason Müller, Thomas Müller, Mira Pöhlker, Patric Seifert, Yifan Yang

**Der Leibniz Wissenschaftscampus (ScienceCampus, LSC) „Rauch und Bioaerosole in einem sich wandelnden Klima“ (BioSmoke) hat zum Ziel, das wissenschaftliche Verständnis der Auswirkungen und Wechselwirkungen von Rauch und biologischen Partikeln aus Vegetationsbränden innerhalb des Klimasystems zu verbessern. Zunehmende Dürreperioden erhöhen das Risiko und die Intensität schwerer Waldbrände. Diese Brände setzen große Mengen an Partikeln und Spurengasen frei, die die Luftqualität beeinträchtigen, die Strahlungsbilanz der Erde verändern und die Vegetationsdynamik in den betroffenen Regionen beeinflussen. Dies ist besonders relevant in Fällen, in denen die intensive Hitze der Brände Pyrokonvektion verursacht, die Rauchpartikel bis in die obere Troposphäre und untere Stratosphäre transportieren kann. Dort können Rauchsichten über lange Zeiträume verbleiben und über Entfernungen von Tausenden von Kilometern transportiert werden, wodurch sie das Strahlungsgleichgewicht der Erde und die Wolkenprozesse beeinflussen können. Der LSC BioSmoke vereint das Fachwissen aus verschiedenen wissenschaftlichen Disziplinen, das für die Untersuchung der Prozesse innerhalb des miteinander verbundenen Systems aus Atmosphäre, Klima und Vegetation erforderlich ist. Durch die Kombination von Kompetenzen in den Bereichen Atmosphären- und Biodiversitätsforschung, Aerosole, Wolken und atmosphärische Prozesse, Analyse der Verbrennung von Biomasse sowie Wasser- und Energiekreisläufe will das LSC die Einflussfaktoren und Auswirkungen der Freisetzung von Aerosolpartikeln aus Vegetationsbränden klären. Zu den ersten wissenschaftlichen Ergebnissen zählen Beobachtungen hoher Rauchsichten mittels Fluoreszenz-Lidar-Messungen, Modellstudien zu Rauchsichten, die durch Pyrokonvektion verursacht werden, Analysen der durch Brände verursachten Emission von Bodestaubpartikeln sowie chemische Alterungsexperimente. Darüber hinaus gab es eine spezielle Feldkampagne, die sich auf die Probenahme von Rauch aus kontrollierten experimentellen Vegetationsbränden konzentrierte.**

## Introduction

Changes in the global climate have amplified the frequency and intensities of extreme weather events, including droughts, that enhance wildfire risk worldwide [e.g., *Bowman et al.*, 2020]. Such vegetation fires release significant quantities of smoke - an aerosol mixture of soot, organics, and bioaerosols - that interact with radiative forcing, cloud microphysics, and atmospheric chemistry. Strong heat release by intense fires can cause so-called pyroconvection that has the potential to transport smoke particles as high as the stratosphere, where it can remain over time periods of several months to years, enhancing the potential impacts of smoke particles in the climate

system significantly. Despite their importance, the processes linking vegetation fires, aerosol emissions, and climatic impacts remain inadequately quantified due to the complexity of the atmosphere–biosphere system and the diversity of involved disciplines. Understanding these processes - and particularly their dependence on vegetation type, combustion conditions, and atmospheric transport - is critical for improving climate models. Furthermore, the interaction of smoke with cloud processes has implications for weather prediction, hydrological cycles, and ecosystem responses.

The Leibniz ScienceCampus ‘Biosmoke’ aims to fill these gaps through an integrated research program that unites atmospheric science, biodiversity

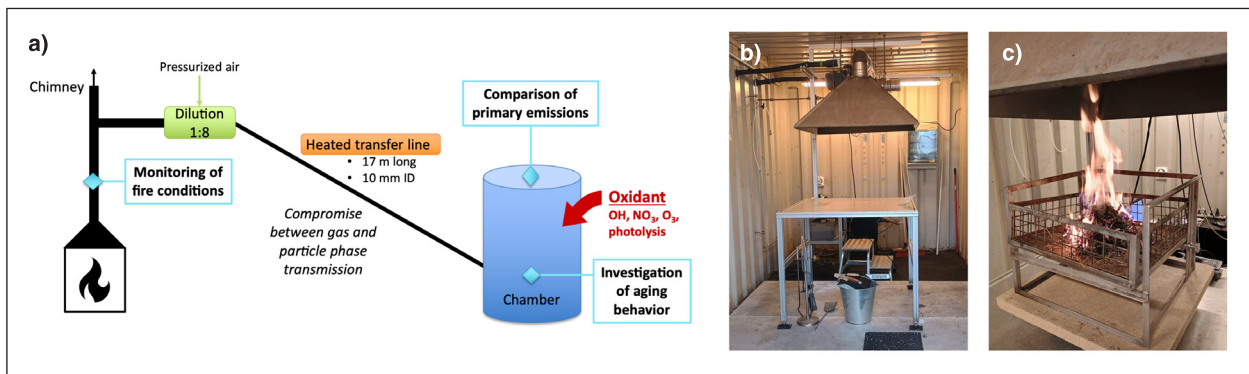


Fig. 1: (a) Experimental set-up. From left to right: Leibniz Biomass Burning Facility (LBBF), transfer line, atmospheric chemistry department chamber (ACD-C); (b) Set-up with smoke hood and sampling lines to the chamber; (c) Burning forest litter set up on weighing scale.

research, combustion analysis, remote sensing, as well as transport and process modelling. Utilizing the extensive and unique experimental and observational infrastructure that is available at the partner institutions in Leipzig, it has the goal to clarify the mechanisms by which smoke and bioaerosols influence climate and atmospheric processes, and quantify the effects of smoke on clouds, radiation, and climate.

### The Leibniz ScienceCampus Framework

Leibniz ScienceCampi (LSC) are intended to promote cooperation between Leibniz institutes and universities on a clearly defined, socially and scientifically relevant research theme. Its overarching goal is to create a visible research centre that has a stronger impact than individual projects and supports long-term cooperation between different institutions and disciplines.

Bringing together researchers from Leibniz institutes and universities, along with additional partners, enables the combined methodological, disciplinary and infrastructural strengths of each partner to be utilised, which would not be possible if they were working alone. This also allows to address complex scientific questions through interdisciplinary approaches. LSC receive funding for up to eight years and are designed to attract additional funding, thereby broadening the scope of research on the topic supported by the LSC. The LSC 'BioSmoke' is funded by the Leibniz Association and Leipzig University, as well as through internal TROPOS funding. It has started in October 2024. TROPOS is responsible for the coordination of the campus. Additional partners, the German Biomass Research Centre (DBFZ) and the Helmholtz Centre for Environmental Research (UFZ), contribute expertise in biomass combustion analysis, water and energy cycles, and ecological dynamics.

### Research within the LSC 'BioSmoke'

The scientific programme of the LSC 'BioSmoke' encompasses three major research clusters, each investigating key elements of the impact of smoke and bioaerosols. Highlights of TROPOS's research within the BioSmoke framework include controlled combustion experiments in the laboratory and the implementation of field studies, as well as remote sensing of smoke layers and modelling of pyroconvective particle transport and further wildfire emissions.

#### Laboratory Combustion Experiments.

Controlled combustion experiments are performed by the Atmospheric Chemistry Department at TROPOS and by DBFZ to determine emissions from diverse plant species under standardized conditions within the framework of the LSC 'BioSmoke' (Figure 1). For these experiments diverse biomass samples have been collected and prepared, including for example, leaves and needles from 50 different tree species in the arboretum in Großpösna, as well as biomass samples in a region in Portugal that is known for the frequent occurrence of wildfires. The leaves were sorted by type and air-dried (Figure 2). Sample properties such as leaf curvatures and material densities are measured that will allow for the identification of differences in the combustion process. Measurements of gases and particles from burned plant material during the combustion experiments will help to quantify smoke particle size distributions and its chemical composition. In the framework of the combustion experiment it will be also examined how combustion parameters - such as temperature, moisture content, plant types and biochemical composition - influence aerosol characteristics. The results will later be incorporated in parameterizations used in emission inventories and atmospheric models and thus improve our understanding of how wildfire smoke properties can vary by vegetation type and fire behaviour. In



Fig. 2: Dried and sorted leaf samples stored at DBFZ.

addition, smoke aging is being investigated by dedicated chamber experiments, including studying the role of the presence of mineral particles, that may be emitted together with smoke, on chemical processes and the optical properties of the particles. Mineral dust particles in fire plumes can provide surfaces for condensation and chemical reactions, influencing the formation and aging of secondary organic aerosols that are being produced from burning vegetation. As part of an interdepartmental project at TROPOS, emissions from plant burning are photochemically aged with and without the presence of dust particles in the Atmospheric Chemistry Department Chamber ACD-C. Changes in the chemical properties of the gaseous smoke components and particle properties due to oxidation processes are investigated by online measurements. The results will provide unique insights into chemical processes of complex aerosol mixtures within smoke plumes from wildfires.

**Field Measurements.** A key project within the LSC ‘BioSmoke’ involves field measurements of smoke properties at a site where controlled vegetation burning is carried out. The location of the selected

field campaign is in south-eastern Spain, at a site located approximately 100 km south-east of Albacete, where controlled burns are carried out twice yearly. At this location, prescribed burning is used to reduce fuel load and thereby prevent large wildfires. The campaign was conducted in collaboration with Prof. Jorge de las Heras of the University of Castilla-La Mancha, who has extensive experience of prescribed burning experiments. Researchers from the TROPOS Atmospheric Microphysics department and the Institute of Biology of the Leipzig University participated in the field campaign that took place in October 2025 (Figure 3). Before the burning experiment, the vegetation was mapped, and the functional plant traits related to fire behaviour were recorded. Analyses of vegetation measurements that were taken during and after the fire will provide insight into how the fire has changed the ecosystem and air quality. During the burning period, the TROPOS backpack measurement system was used to measure physical properties of smoke aerosols, building on the expertise gained during successful deployment in previous field campaigns. Additionally, a set of low-cost sensor units were mounted on trees in and around the burning area to measure particle concentrations, CO<sub>2</sub>, temperature, relative humidity, volatile organic species, and NO<sub>x</sub>. Filter samples were also collected for subsequent chemical and optical analyses at TROPOS.

**Remote sensing.** Smoke layers can be identified by optical fluorescence lidar measurements as smoke particles are linked to biological matter. The fluorescence lidar technique can improve the identification and detection of aerosols in elevated layers. *Gast et al. 2025* [see also article by *Gast et al.* in this Annual Report] describe the enhanced detection capabilities of fluorescence lidar in the case of optically thin smoke layers in the Upper Troposphere/Lower Stratosphere (UTLS) region. In some of the cases,



Fig. 3: Impressions from the controlled burning field campaign in southeastern Spain (Fotos: Yifan Yang).

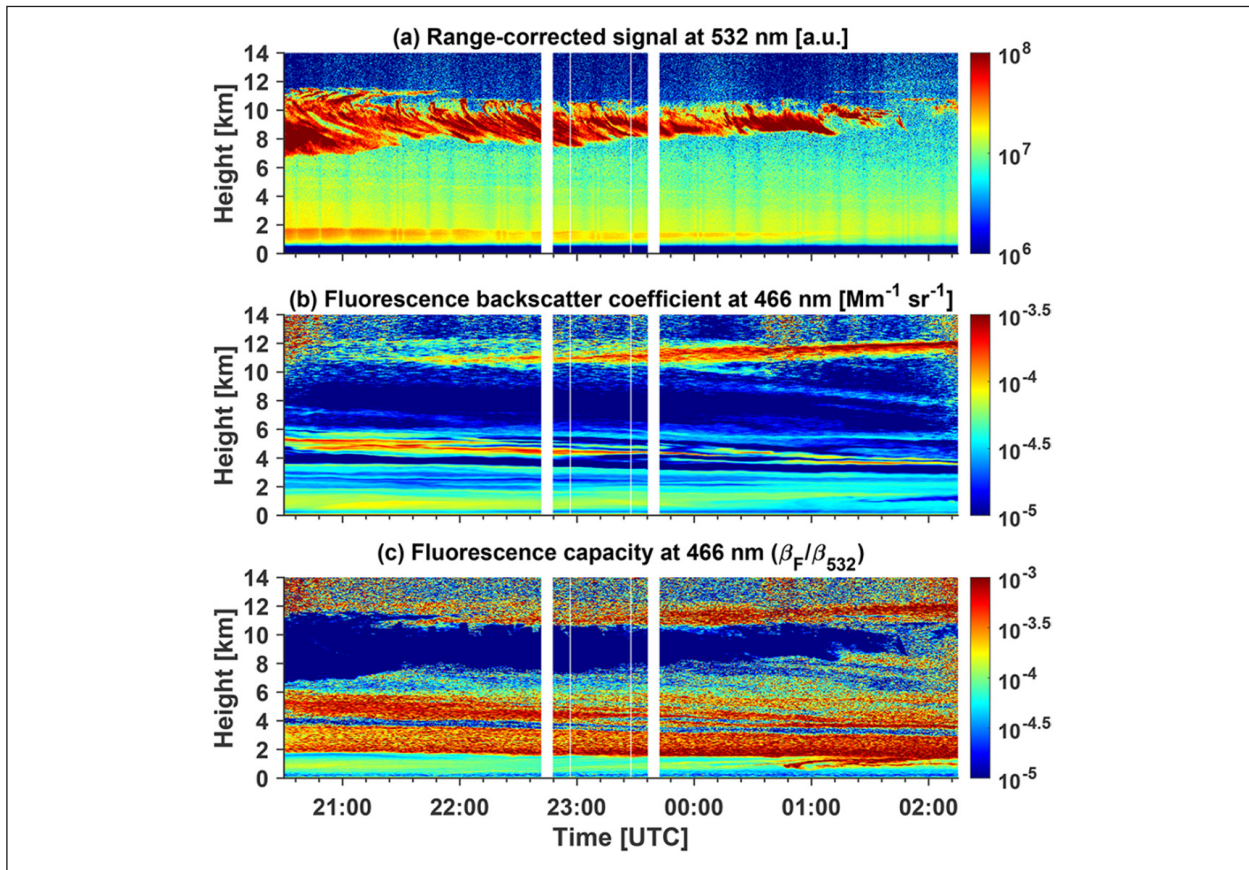


Fig. 4: Height–time distributions of (a) the range-corrected lidar signal at 532 nm, (b) the fluorescence backscatter coefficient and (c) the fluorescence capacity measured with the MARTHA system on 29–30 May 2023 show the formation of cirrus clouds at 7–11.5 km height (top panel) at the location of smoke layers revealed by enhanced values of the fluorescence backscatter coefficient [Gast et al., 2025].

fluorescence measurements clearly revealed smoke layers that were undetectable using only regular elastic-backscatter channels. Recent measurements by the Remote Sensing Department of TROPOS using the fluorescence technique suggest that such thin smoke layers often occur in the UTLS and can potentially impact cirrus cloud formation through heterogeneous ice nucleation (Figure 4).

In addition to ground-based lidar measurements, retrievals from space-borne lidar measurements on board the Earth Cloud, Aerosol and Radiation Explorer [EarthCARE, see Bley et al. in this issue] satellite are valuable to track long-range transport of wildfire smoke from its source towards remote regions. For example, by the end of May 2025 huge wildfires in Canada led to the formation of several pyrocumulonimbus clouds, which injected large amounts of biomass-burning aerosol up to the lower stratosphere. Near the fires an aerosol optical depth (AOD) as high as 3 was measured in the ultraviolet (UV) [Haarig et al., 2025]. In early June, the first large smoke plume reached Europe, while at that time a high smoke load was identified with a fluorescence lidar at Leipzig. In addition to identifying horizontal smoke transport

pathways, the measurements also identified changes in the vertical distribution of the smoke over the course of the early summer for this case.

Further studies using satellite remote sensing to investigate the role of smoke in radiation and cloud processes are being conducted by project partners at the Institute for Meteorology of Leipzig University. This includes an investigation of the effects of smoke particles on liquid water and ice-containing clouds based on a recently developed retrieval [Choudhury and Tesche, 2022] that provides a consistent method for converting extinction coefficients from space-based CALIPSO lidar measurements into aerosol type-specific aerosol numbers and concentrations of cloud condensation nuclei. Indirect effects of smoke particles on clouds resulting from changes in radiative heating due to absorption of solar radiation by the soot-containing smoke particles within and above the clouds are also investigated using satellite observations. Using recently developed cloud radar Doppler spectra-based techniques for the determination of cloud phase and riming, the impact of smoke on cloud microphysical evolution will be investigated and estimates if and how these particle types affect the

precipitation formation will be obtained. This is used to investigate the subsequent evolution of mixed-phase cloud systems focusing on the evolution of the liquid-to-ice partitioning and the role of riming and aggregation processes in precipitation formation [Kalesse-Los *et al.*, 2022].

Remote sensing is also used to observe above-ground biomass changes due to fire events including the field site in south-eastern Spain by a combination of Earth observation and drone-based sensor systems and in-situ analysis to characterize the ecosystems regarding their structure and fuel properties.

**Atmospheric Modelling.** Pyrocumulonimbus (PyroCb) clouds are severe thunderstorms that occasionally develop above intense wildfires and can transport smoke into the stratosphere, where they can impact Earth's energy balance. For example, during the Australian bushfires of 2019/2020, pyroCbs injected significant amounts of smoke into the atmosphere at levels, comparable to those of a major volcanic eruption [Heinold *et al.*, 2022]. While the extreme heat of strong wildfires can trigger the formation of PyroCbs, the additional heat released during the condensation of water vapor is also an important factor in the dynamics of such clouds. Modelling in the framework of the LSC 'Biosmoke'

focuses on modelling pyro-convective processes in the TROPOS Modelling Department, taking into account the conditions for development of convective plumes above a strong heat source caused by vegetation fires, and on mineral dust particles that are emitted from the ground during wildfires due to the strong winds associated pyro-convective updraft.

Using the ICON atmospheric model in a km-scale resolution setup, Müller *et al.* [2025] investigated how fire-generated plumes evolve and under which conditions they transition into pyroCbs. They further examined how much heat is required for this transition and how variations in heat and water vapor emissions affect the plume behaviour. The results show that the transition to a pyrocumulus cloud does not occur gradually, but in fact very abruptly once the heat release from the fire exceeds a certain threshold (Figure 5). Stronger heat and water vapor emissions create even larger clouds with higher water content and higher plume temperatures. This study clarifies that in a fully developed pyrocumulus cloud, heat and water vapor emissions contribute equally to determining the height of the cloud.

A generally overlooked source of particulate emissions caused by wildfire events are mineral dust particles. Mineral dust is a key component of the Earth system, affecting climate through radiative forcing, cloud formation, nutrient transport, and air

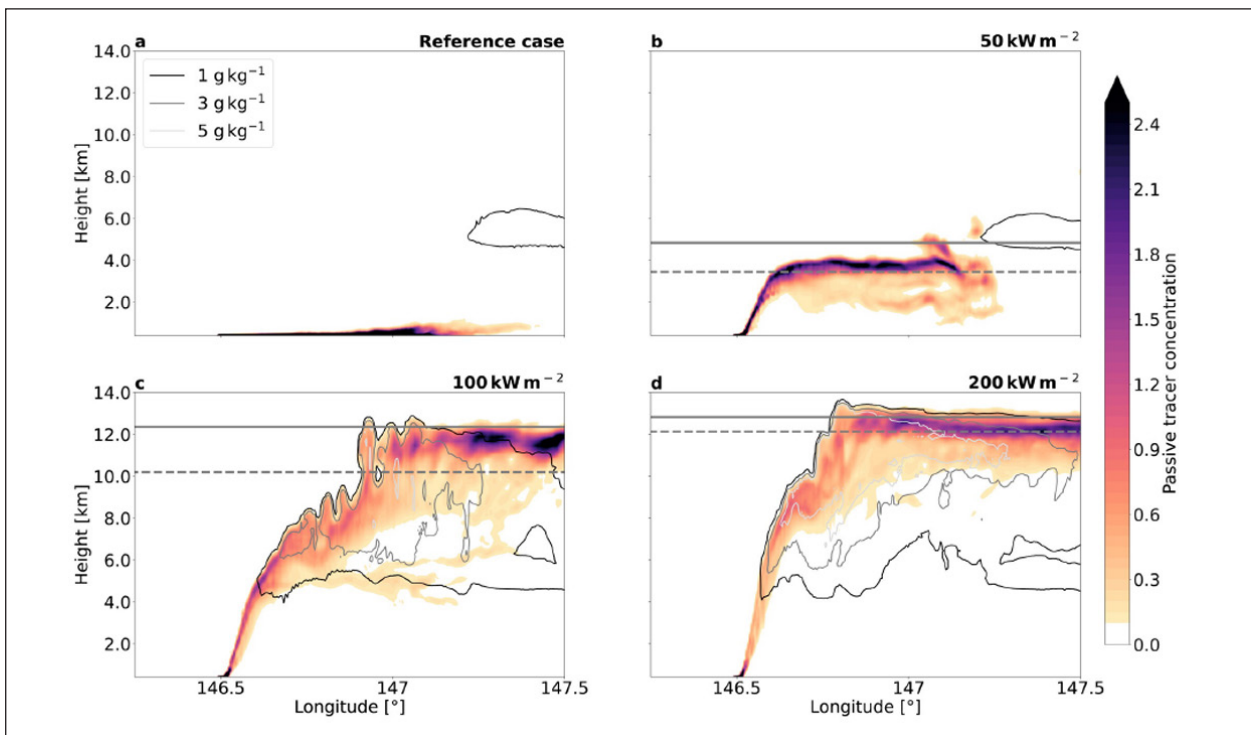


Fig. 5: Cross sections of modelled latitude-mean passive tracer concentrations of a (a) reference run without heat release by the fire and (b-d) three model runs with varying sensible heat fluxes from 50–200  $\text{kW m}^{-2}$  and no additional water vapor flux after a simulation time of two hours. The plume top height is marked by the solid line and the median height is marked by the dashed line [Müller *et al.*, 2025].

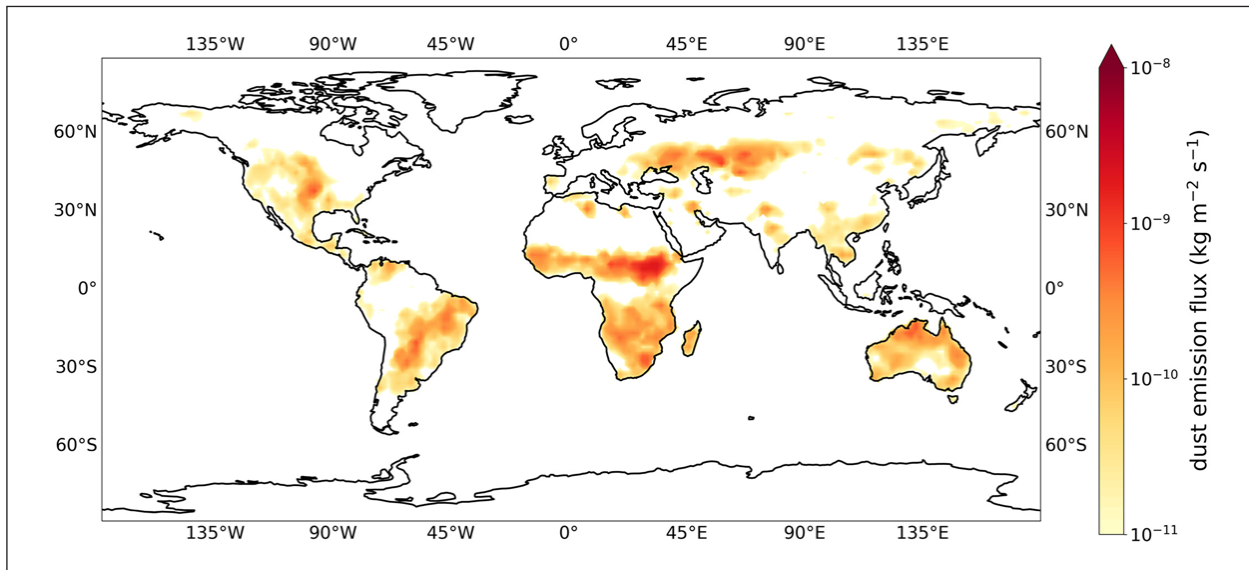


Fig. 6: Averaged fire driven dust emission fluxes simulated with ICON-HAM over the simulation period 2004–2013 [Wagner and Schepanski, 2025].

quality. Observations indicate that fires can mobilize dust by removing ground-covering vegetation, exposing the bare soil, and generating fire-induced turbulence and strong near-surface wind enhancements. In Wagner and Schepanski [2025], the authors developed a new model parameterization that links fire activity to dust emission fluxes, using satellite-derived fire radiative power (FRP) as a proxy for fire intensity and combining it with environmental controls such as soil properties, surface roughness, wind speed, and vegetation cover. This parameterization is implemented into the global aerosol-climate model ICON-HAM, which explicitly simulates aerosol microphysics and interactions with atmospheric dynamics. The authors performed decadal simulations for the period 2004–2013 with and without the new fire-dust scheme, such that the contribution of fire processes to atmospheric dust loading could be quantified. The results show that fire-driven dust emissions are substantial, amounting to about 15–21% of total global dust emissions in the model. These emissions are particularly interesting because they are not confined to desert regions where dust emissions normally occur. Instead, fire-driven dust emission originates predominantly from savannas, grasslands, agricultural areas, and seasonally dry regions that are not typically considered major dust sources. The spatial and temporal patterns of fire-related dust follow regional fire seasons rather than purely meteorological wind regimes, introducing additional variability into the global dust cycle. Including fire-driven dust alters the simulated atmospheric dust burden and its regional distribution, with potential implications for radiative forcing, cloud processes, and long-range transport of mineral particles, in particular

as it is co-emitted with smoke aerosol. The study demonstrates that neglecting fire-related dust emissions leads to an underestimation of dust sources in many regions and seasons, particularly in areas experiencing frequent biomass burning (Figure 6). They conclude that vegetation fires represent a significant and previously underrepresented component of the global dust cycle and argue that fire-driven dust emissions should be included in Earth system models to improve simulations of aerosols, climate feedbacks, and air quality.

These model studies help identify key processes in particle emissions from wildfires and will serve as basis for further model studies of aerosol–cloud–climate interactions. The ultimate goal of these model studies is to reduce uncertainties in climate modelling associated with aerosol–cloud interactions and particle emissions from wildfires.

### Future Directions

Looking ahead, the LSC ‘BioSmoke’ intends to integrate studies across its different research clusters to advance understanding of the physical properties of smoke, effects of chemical processes on smoke properties and impact of smoke on clouds, radiation and climate. This knowledge will support improved model parameterizations of smoke emissions, smoke particle optical properties, transport, and atmospheric lifetime, including the transport of smoke from intense wildfires into the UTLS as well as, interactions between smoke and clouds.

Investigating differences in smoke properties associated with vegetation types will provide a basis for studying interactions among biodiversity change,

wildfire smoke, and climate feedbacks under a changing climate with increasing climate extremes. Further research on particle emissions from vegetation fires will include also primary biological particles, such as bacteria, that are released during fire events and may affect ice and precipitation formation in clouds as such particles are effective ice nuclei. Additional expertise will be included into the LSC to address the health impacts of wildfire smoke.

### Outreach

The research within the LSC 'BioSmoke' contribute to a deeper understanding of the climate system's response to emissions of biogenic and combustion aerosols. The scientific results of the LSC are shared with the science community by publications and conference contributions and as part of an annual dedicated workshop in Leipzig. In parallel, the LSC communicates its research to the broader public through outreach activities, including participation in events such as the Long Night of Science and

Children's University as well as a regular newsletter and through its website (<https://www.leibniz-biosmoke.de/en/>).

### Conclusion

The LSC 'BioSmoke' represents a scientific initiative coordinated at TROPOS that is addressing an emerging important aspect of the highly complex interactions in the climate system: how wildfire smoke and related particle emissions influence atmospheric processes and climatic forcing. This knowledge is becoming increasingly important as smoke becomes more prevalent in the atmosphere due to the intensification of wildfires. By integrating laboratory experiments, field measurements, advanced remote sensing, and numerical modelling, the LSC aims to bridge disciplinary boundaries, create new insights into aerosol–climate interactions involving wildfire emissions, and serves as a focus point to attract wider collaboration on smoke research in Leipzig.

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### Cooperation

Leipzig University  
Deutsches Biomasseforschungszentrum (DBFZ)

# First results from EarthCARE

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**Etwa eineinhalb Jahre nach dem Start des EarthCARE-Satelliten (Earth Cloud, Aerosol and Radiation Explorer) liefern dessen Instrumente bereits eindrucksvolle neue Einblicke in die vertikale Struktur von Aerosolen und Wolken. Erste Fallstudien am TROPOS demonstrieren das hohe Potenzial der kombinierten aktiven und passiven Fernerkundung. Ein exzellentes Beispiel dafür ist die Beobachtung des Transports einer großräumigen Waldbrand-Rauchwolke in der Stratosphäre von Kanada bis nach Europa. EarthCARE-Messungen konnten genutzt werden, um die optischen Eigenschaften der Rauchwolke während des Transports zu charakterisieren und die Ausbreitung in der Stratosphäre zu bestimmen. Ein weiteres besonderes Ereignis war der direkte Überflug von EarthCARE über den Hurrikan Humberto über dem tropischen Atlantik. Sein multispektraler Bildgeber (MSI) lieferte dabei hochaufgelöste horizontale Information über die Cumulonimbuswolke des Hurrikans. Das Atmosphären-Lidar ATLID und das Wolkenradar CPR ermöglichten zudem erstmals eine quantitative Erfassung der vertikalen Wolken-, Niederschlags- und Aufwind-Struktur entlang der Satellitenbahn, die direkt durch das Auge des Hurrikans führte. Noch nie zuvor konnte ein Hurrikan mit solch einer Kombination von Geräten von einem Satelliten vermessen werden. Die Validierung der Wolken- und Aerosolprodukte wird wesentlich durch TROPOS vorangetrieben - eine Grundvoraussetzung für wissenschaftliche Studien. Mit seinem globalen Netzwerk bodengebundener Beobachtungsstationen sowie zusätzlichen Satellitendaten der Meteosat Third Generation leistet das Institut einen zentralen Beitrag zur Qualitätssicherung und Weiterentwicklung der Aerosol- und Wolkenprodukte von ATLID und MSI. Forschende des Instituts konnten daher erste globale Statistiken von Aerosol- und Wolkenprodukten erstellen, die das Potential und den hohen wissenschaftlichen Wert von EarthCARE für das Verständnis atmosphärischer Prozesse weiter unterstreichen.**

## Introduction

The Earth Cloud, Aerosol and Radiation Explorer (EarthCARE) is a joint mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), which carries a unique set of active and passive instruments: the Atmospheric Lidar (ATLID), the Cloud Profiling Radar (CPR), the Multi-Spectral Imager (MSI), and the Broad-Band Radiometer (BBR). The two active instruments ATLID and CPR provide vertical profiles of the aerosol and cloud structure, while the imager MSI sets the observations into the horizontal context (150 km swath). From the synergistic observations, the atmospheric scene along the satellite track is constructed and the radiation at the top of the atmosphere is calculated. The results are compared to the measurements of the fourth instrument on board, the radiometer BBR, to achieve global radiation closure. The datasets offer an exceptional high level of detail that has not been achieved by any previous satellite mission, thus

significantly advancing the characterisation of clouds and aerosol from space.



Fig. 1: TROPOS scientists together with colleagues from ESA and the EarthCARE algorithm developer team during the launch event at the European Space Operations Centre (ESOC) in Darmstadt, Credit: ESA/J. Mai.

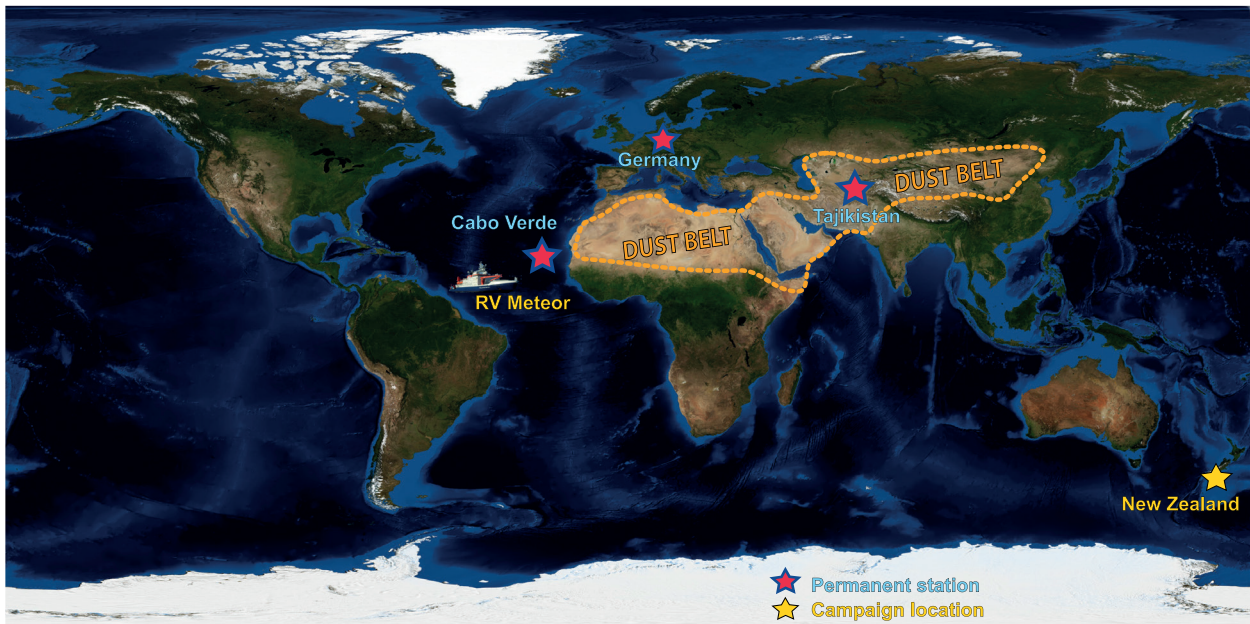


Fig. 2: Global network observations of TROPOS used for the validation of EarthCARE cloud and aerosol products [Baars et al., 2026].

On 28 May 2024, the EarthCARE satellite was launched into space. Several scientists of TROPOS could attend the event at the European Space Operations Centre (ESOC) in Darmstadt and felt great relief and excitement after the successful launch (Fig. 1). TROPOS has been involved in the development of the mission with scientific studies and as scientific advisor for more than 25 years. The Remote Sensing Department (RSD) contributed several algorithms for ATLID and MSI, which are part of the EarthCARE processing chain. As readiness and applicability of the algorithms could only be demonstrated with synthetic test scenarios before launch, the scientists involved were particularly excited to finally apply the results of many years of work to real atmospheric data. Through their active participation in the EarthCARE Data Innovation and Science Cluster (DISC), TROPOS researchers remain deeply involved in EarthCARE and are key players for the success of the mission. They contribute to (1) algorithm development and hardware monitoring, (2) numerous validation activities through TROPOS observational networks and longtime experience, and (3) novel scientific findings based on EarthCARE observations.

TROPOS is responsible for the maintenance and evolution of several aerosol and cloud processors for MSI and ATLID in ESA's operational processing chain. This role provides in-depth insight into the strengths and limitations of EarthCARE products and enables the generation of robust statistics and high-quality data analysis. TROPOS works on MSI Level 1 data quality assurance and is strongly involved in the hardware monitoring of ATLID, in close cooperation

with ESA. Furthermore, RSD scientists develop novel experimental products to retrieve, e.g., estimates of cloud-relevant aerosol properties such as cloud-condensation-nucleus (CCN) and ice-nucleating-particle (INP) concentrations from ATLID observations, which will enable future global aerosol-cloud-interaction studies [see Hofer et al. in this issue].

TROPOS leads the German Initiative for the Validation of EarthCARE (GIVE) and coordinates the European validation activities in the framework of ACTRIS, the Aerosol, Clouds and Trace Gases Research Infrastructure. In this context, a dedicated pilot study was initiated within the HORIZON-2020 project ATMO-ACCESS to prepare the European remote sensing community for the intense validation efforts of the novel satellite mission. In all these activities, TROPOS builds on its global lidar network (PollyNET) with key validation stations in Leipzig, Mindelo (Cabo Verde) and Dushanbe (Tajikistan), supplemented by mobile platforms operated at remote sites such as Invercargill (New Zealand) or on research vessels like RV Meteor (Fig. 2). Measurements from ACTRIS are also used to feed the so-called MSI Tool, which has been specifically developed in collaboration with the Free University of Berlin (FUB) to simulate MSI-like radiances and brightness temperatures from sub-orbital measurements for validation purposes [Preusker et al., 2026].

On top of the global ground-based facilities, TROPOS uses observations from two multi-spectral imagers: The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard Meteosat Second Generation and the Flexible Combined Imager (FCI) aboard

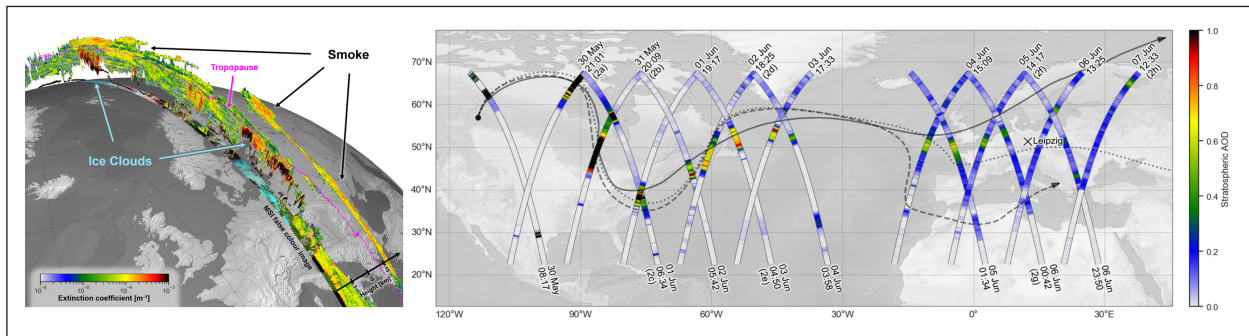


Fig. 3: ATLID captured a plume of Canadian wildfire smoke transported over the Atlantic Ocean between 30 May and 7 June 2025. Left: Smoke plume observed over Europe at around 17 km altitude. Right: HYSPLIT trajectories (black lines) and ATLID cross-sections (coloured) were used to track the stratospheric smoke plume [Haarig et al., 2025].

Meteosat Third Generation, not only for validation of the MSI measurements, but also to provide a large-scale spatial and temporal context to the EarthCARE measurements.

Besides the involvement in hardware monitoring, algorithm development and validation activities, TROPOS researchers produced first scientific highlights using, e.g., unique EarthCARE observations of Canadian smoke plumes in the stratosphere or the direct overpass over the eye of hurricane Humberto, which will be presented in the next section. Moreover, TROPOS is working on preliminary climatological studies based on the first year of global EarthCARE observations.

### Highlights from EarthCARE's first year in orbit

Within its first year in orbit, EarthCARE has already demonstrated remarkable capabilities in observing clouds and aerosols with an unprecedented level of detail. A great example are the stratospheric smoke layers from intense wildfires in Canada at the end of May and beginning of June 2025. EarthCARE's lidar ATLID could detect the smoke layers close to the source, where the smoke was injected by pyro-cumulonimbus events into the lower stratosphere. The wildfire smoke intrusions into the stratosphere were comparable to moderate volcanic eruptions and reached stratospheric aerosol optical depths (SAOD) of up to 3.2 [Haarig et al., 2025]. These strong smoke plumes were transported from North America towards Europe (Fig. 3), and EarthCARE observations were used to track the evolution of the smoke's optical properties and the plume heights. The stratospheric smoke particles are non-spherical in shape as indicated by the enhanced depolarisation ratio of  $0.26 \pm 0.02$  observed with ATLID, which is in line with previous observations [Haarig et al., 2018]. The novel capability of ATLID to measure the

extinction coefficient directly (in contrast to NASA's former CALIPSO mission) revealed a slight decrease of the lidar ratio (i.e., extinction-to-backscatter ratio), an important quantity in aerosol typing with lidar, within the first days of transport. ATLID is perfectly suited to provide the exact plume height and showed an increase of the plume top from 13.6 km above Canada to 17.4 km above Europe, which corresponds to an average daily ascend of 420 m, with stronger lofting rates at higher SAODs close to the source [Haarig et al., 2025]. The self-lofting of smoke plumes can be explained with light absorption by the smoke particles, which heats the layer and creates additional buoyancy. The smoke plume passed over Leipzig, and the ground-based lidar systems MARTHA [see Gast et al. in this issue] and PollyXT [Engelmann et al., 2025] were used to validate the ATLID observations.

EarthCARE observed considerable smoke emissions from North American and Siberian wildfires to the troposphere and stratosphere in 2025. Future work is planned to perform comprehensive estimates of the total smoke load in the northern hemisphere that could be used to evaluate aerosol transport models. Especially in the Arctic, the smoke accumulated from the ground up into the stratosphere since late May 2025.

Another highlight of the first year of EarthCARE observations was its direct overflight of the eye of hurricane Humberto in the North Atlantic on 28 September 2025 at 18:30 UTC (Fig. 4). It is a rare event for a profiling satellite to hit the eye of a hurricane. The cyan colours in the natural color RGB (Fig. 4a) indicate ice clouds, while the reddish colours show water clouds. The MSI cloud top height product in Fig. 4b [Hünerbein et al., 2024] impressively shows the steep eye wall, almost reaching down to the ocean surface. While the hurricane cloud tops indicate a mix of cirrus ice shield and overshooting deep convection, the cloud water path product [Hünerbein et al., 2024] identifies areas where most of the liquid

and ice water is contained, including the surrounding deep convective rain belt at around 23° and 27°N. The ATLID measurements confirm that the associated storm cloud system reaches altitudes of up to 17 km and further reveal a gradual decrease of the cloud top height from the center of the hurricane to the outer region of the anvil (Fig. 4e). EarthCARE’s unique synergistic view is augmented with additional information about updraft and downdraft motions inside the cloud system provided by the CPR (Fig. 4d). For the first time, these satellite-based measurements reveal updrafts within the eye wall as well as strong downdrafts associated with intense precipitation in the rain band near 23°N. In a collaboration between the remote sensing and the modelling departments, this

unique EarthCARE observation is now being used as a case study for running and evaluating sub-kilometre limited-area hurricane simulations [see *Cremer et al.* in this issue]. The comparison with EarthCARE observations allows investigation of how model resolution, CCN perturbation and cloud micro-physical model assumptions influence the simulated micro-physical structure of tropical storms.

### Validation of EarthCARE products

TROPOS uses its high-performance ACTRIS stationary and mobile facilities to validate the profiling measurements of EarthCARE. Figure 5 shows an example for the TROPOS outpost at Mindelo, Cabo

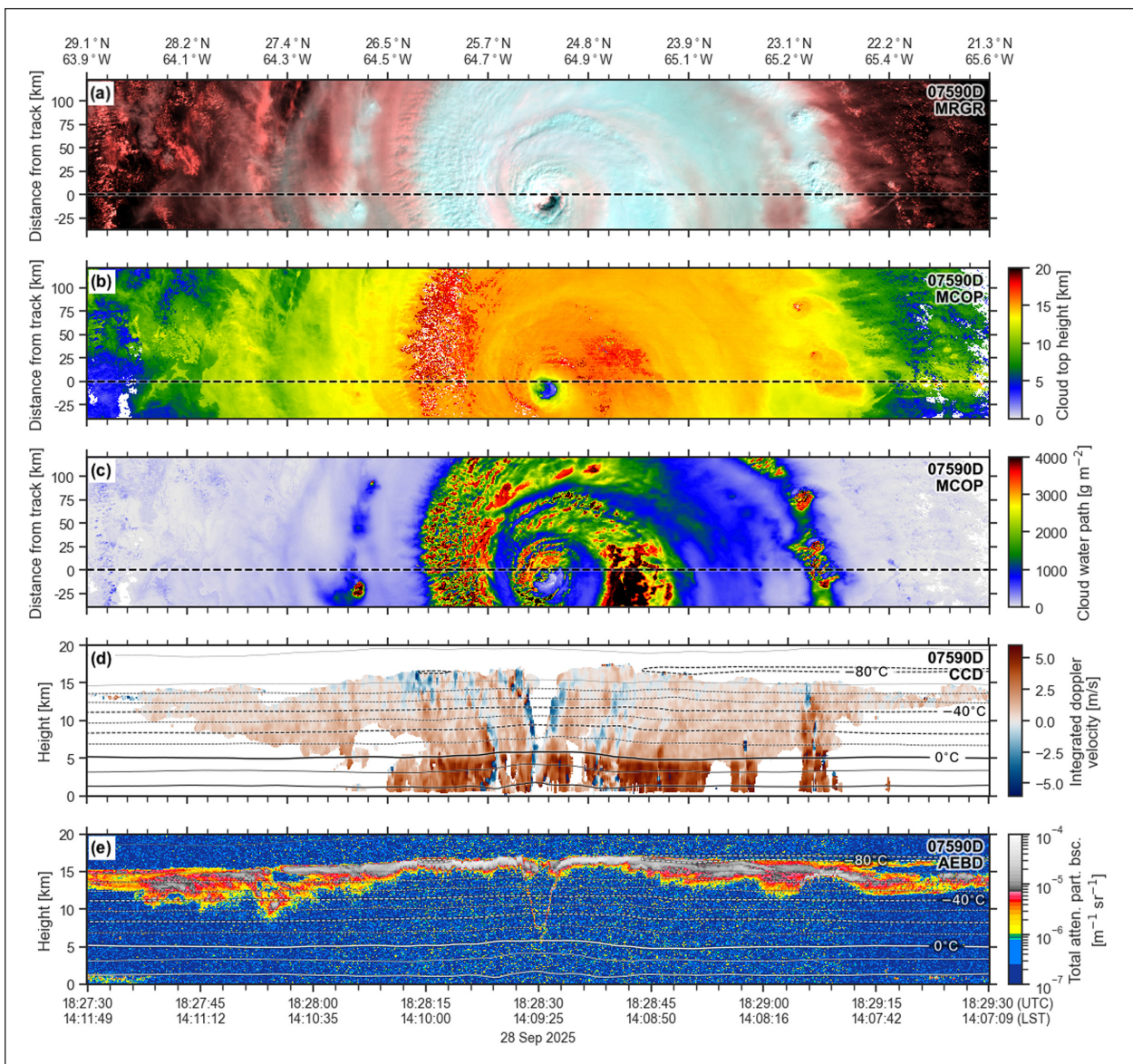


Fig. 4: Rendezvous with a hurricane – EarthCARE flies over hurricane Humberto on 28 September 2025 at 18:30 UTC. Shown is frame 07590D observed from three different instruments: The upper three panels show the 150 km MSI swath (a: natural color RGB, b: cloud top height, c: cloud water path), d) shows the radar Doppler velocity measured by CPR and e) the lidar attenuated particle backscatter measured by ATLID.

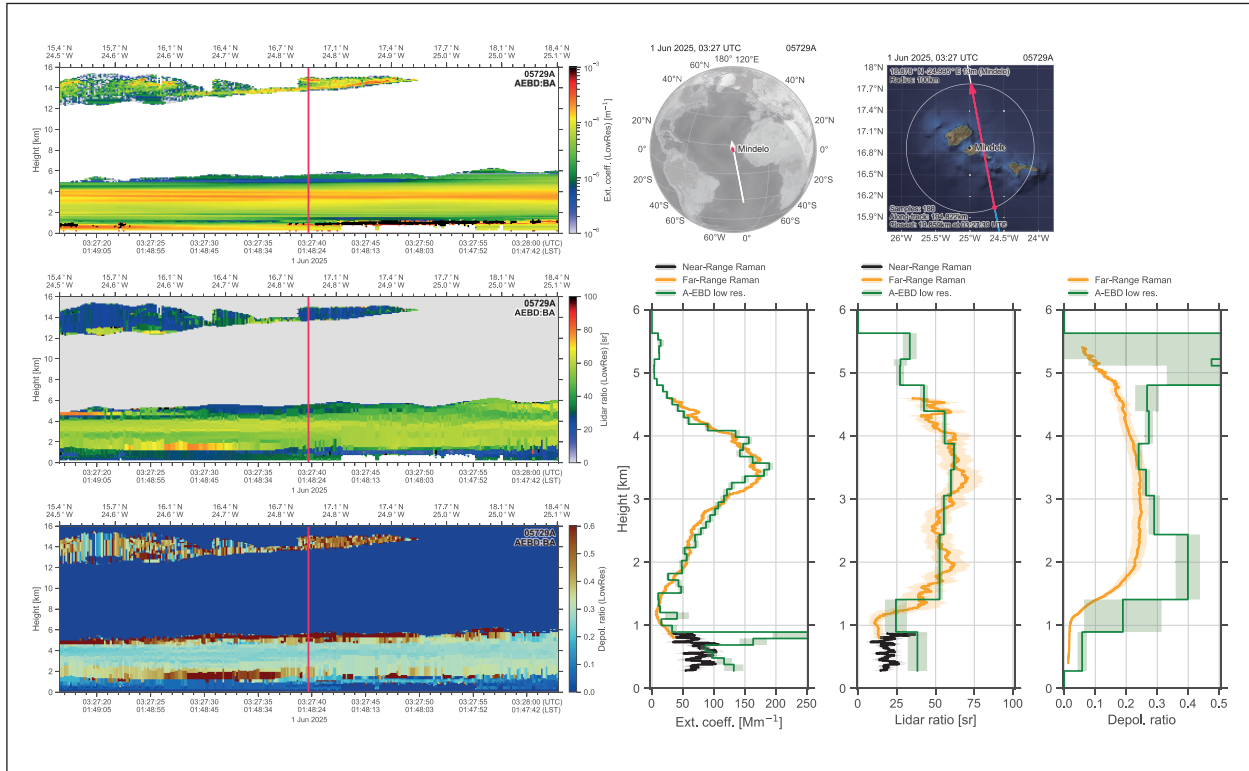


Fig. 5: Comparison of the ATLID aerosol products with ground-based PollyXT measurements at Mindelo, Cabo Verde, on 1 June 2025.

Verde, for which EarthCARE's ground track was as close as 20 km to the ground-based reference site (Fig. 5, top right). The EarthCARE lidar observations, namely the time-height plots of the ATLID extinction, backscatter and depolarisation product (A-EBD), are shown in Figure 5, left panels, for the region between 15.4 and 18.4°N. The reference site at Mindelo is indicated by a red vertical line. A pronounced dust layer with strong extinction values (yellow and reddish colours in the upper left panel of Fig. 5) at altitudes of 1 to 5 km is visible. The dust is characterised by lidar ratios between 40 and 60 sr (Fig. 5, middle left panel) and elevated particle depolarisation ratio values  $>0.2$  (Fig. 5, lower left panel), in agreement with many previous studies on the intensive properties of Saharan mineral dust [e.g., *Haarig et al.*, 2022]. Below the Saharan dust layer (or Saharan Air Layer – SAL), the marine boundary layer is visible, which was partly cloud-topped (white colours in the backscatter product). The marine boundary layer (MBL) is usually characterised by lidar ratios below 30 sr and low depolarisation ratios [*Bohlmann et al.*, 2018; *Haarig et al.*, 2017]. Partly, high-altitude cirrus clouds are visible extending south of 17.5°N. Due to their high variability, these clouds are not considered for the direct comparison with the ground-based observations.

Figure 5 (bottom right) shows the direct comparison of particle extinction coefficient, lidar ratio and depolarisation ratio measured with the PollyNET lidar

[*Baars et al.*, 2016] and with ATLID (A-EBD, low resolution). Excellent agreement is found for the extinction coefficient and the lidar ratio in the height range of 1.3 to 5 km, i.e., within the SAL. Within the MBL (below 1 km), the extensive quantities deviate slightly, which is most probably due to local atmospheric differences and cloud contamination in the ATLID profiles (see strong peak at about 800 m in the ATLID profile). Nevertheless, marine aerosol conditions are evident in both observations, although ATLID overestimates the lidar ratio with values of about 38 sr, which is clearly too high for marine particles [*Floutsi et al.*, 2023]. Concerning the particle depolarisation ratio, very good agreement is found in the height range of maximum dust load at 3.5 km altitude with values around 0.24. However, in regions with less dust loads above and below (lower extinction), the retrieved values deviate. Here, A-EBD provides higher depolarisation ratio values (maximum of 0.4 at 2 km) than measured with the ground-based reference.

Next to single case studies, the ATLID depolarisation ratio was validated on a statistical basis using several overpasses over PollyNET stations (Fig. 6, left panel). ATLID's overestimation of the depolarisation ratio in the aerosol regime (below a depolarisation ratio of 0.3), which was found in the case study above, could be confirmed by the statistical validation. However, in cirrus clouds, where the depolarisation ratio exceeds 0.3, an underestimation of the

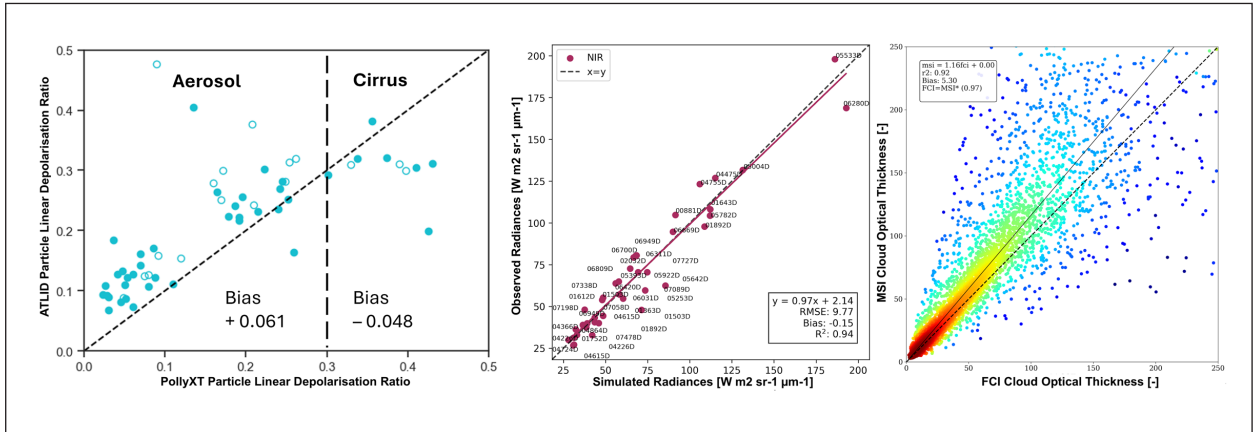


Fig. 6: Left: Validation of ATLID L2 particle linear depolarisation ratio (PLDR) against ground-based PollyNET observations. Middle: Validation of MSI NIR radiances using simulated radiances from the MSI Tool with ground-based ACTRIS observations as input. Right: Comparison of the MSI cloud optical thickness against collocated cloud optical thickness from the Optimal Cloud Analysis (OCA) of FCI.

depolarisation ratio was found. Together with ESA and the DISC partners, we are investigating the root cause of this changing bias to improve ATLID’s depolarisation ratio before the next complete reprocessing of the EarthCARE data. The depolarisation ratio is the essential quantity for aerosol typing [see *Haarig et al.* in this issue].

In addition to the validation activities for the aerosol and cloud products, TROPOS strongly supports the calibration and validation of MSI-measured radiances, as even small radiance biases can have large impact on the derived aerosol and cloud products. During the commissioning phase, TROPOS scientists found that the MSI radiances are biased compared to well calibrated imagers like SEVIRI on board Meteosat Second Generation and FCI on board

Meteosat Third Generation. Therefore, an ad-hoc vicarious calibration of the MSI visible, short-wave infrared and near-infrared bands has been conducted using corresponding spectral bands of FCI to improve the MSI radiances and, consequently, to make them more robust for the cloud algorithms [*Bley et al.*, 2026].

As independent validation of these calibrated radiances, we use ground-based profile measurements from ACTRIS sites to simulate the MSI-like radiances and compare them to the real measurements. The middle panel of Figure 6 shows the comparison between observed MSI near-infrared radiances and simulations with the MSI Tool for EarthCARE matchups with ACTRIS stations in Leipzig (TROPOS) and Lindenberg (DWD) within a 16-month

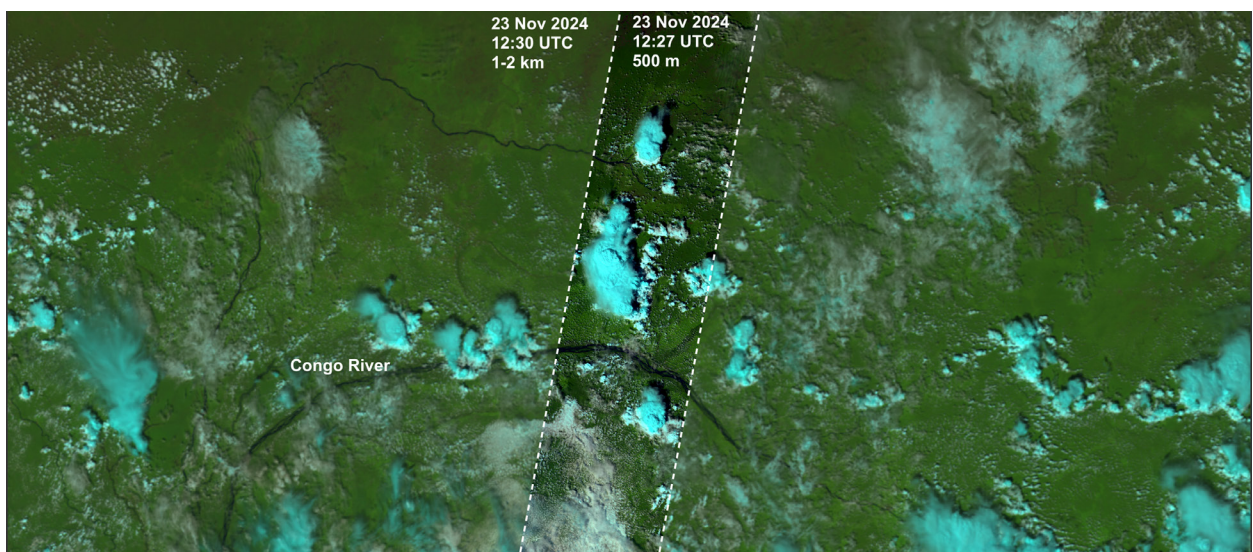


Fig. 7: Natural color RGB image over Central Africa as observed by the Flexible Combined Imager (FCI) on board Meteosat Third Generation and, inside the dashed box, by MSI on board EarthCARE on 23 November 2024 at 12:27 UTC.

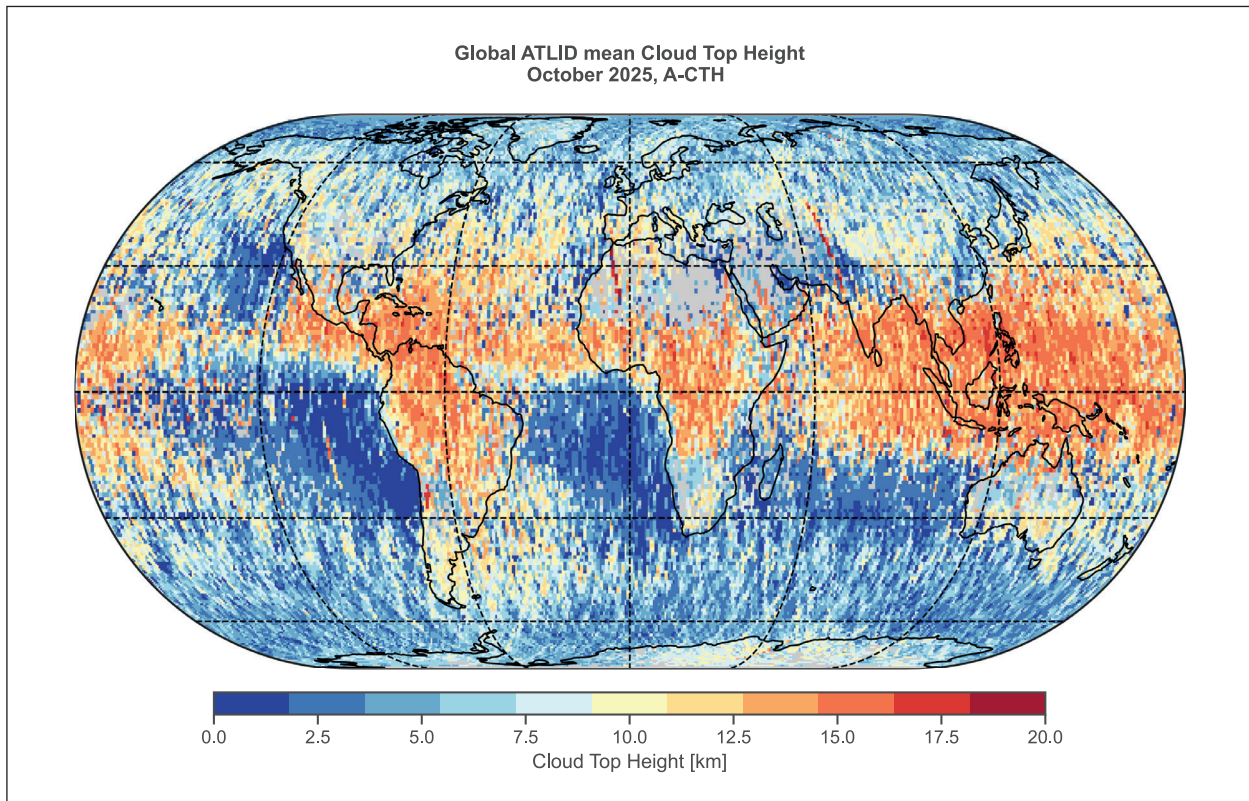


Fig. 8: ATLID-derived mean cloud top height for October 2025.

period. The excellent agreement confirms that the vicarious calibration against FCI has improved the MSI-measured radiances. Figure 6 (right panel) presents a statistical intercomparison of cloud optical thickness retrieved from MSI and FCI indicating that the improvements in the MSI radiances also improved the retrieved cloud products. Such intercomparisons are essential for quantifying biases and uncertainties and for refining retrieval algorithms, thereby ensuring the highest possible product quality for studies of aerosol–cloud–radiation interactions.

Figure 7 shows a subset of an MSI natural color RGB image acquired on 23 November 2024 over Central Africa, focusing on the Congo basin, embedded within an FCI RGB image of the same scene to provide context and to illustrate the higher spatial resolution of MSI (500 m) compared to FCI (1–2 km). The scene shows shallow cumulus clouds over the rainforest and deep convective clouds with overshooting tops (bright cyan colours). MSI not only detects shallow clouds that are not seen by FCI, but also resolves more spatial details of the deep convective clouds, like bright spots and shadows, demonstrating that 3D radiative effects start playing an important role at spatial scales below 1 km [Zinner and Mayer, 2006]. This is the central topic of the Cloud 3D Structure and Radiation (C3SAR) research group (see Macke *et al.* in this issue).

### Maps of global EarthCARE observations

EarthCARE delivers cloud top heights (CTH) in three different products (all developed and maintained at TROPOS), A-CTH, M-COP and AM-CTH, which utilize information from ATLID [prefix “A-”; Wandler *et al.*, 2023], MSI [prefix “M-”; Hünerbein *et al.*, 2023, 2024] and ATLID/MSI synergy [prefix “AM-”; Haerig *et al.*, 2023], respectively. Because of the different measurement principles and sensitivities to cloud properties of the two instruments, the respective CTH products can differ significantly. ATLID can determine the geometric CTH for both ice and water clouds with a physical accuracy of approximately 300 m (according to mission requirements). After approval of the good data quality and overall stable processor performance, comprehensive global statistics and long-term climatologies are being created at TROPOS. Figure 8 provides an example of such a global statistic for the ATLID-derived mean CTH for October 2025. As anticipated, the highest cloud top heights (above 13 km) were observed in the tropical regions and can be typically associated with deep convective and cirrus clouds. The lowest cloud top heights were observed in the Southern Hemisphere with heights less than 4 km.

Figure 9 displays an MSI-derived monthly composite of aerosol optical thickness (AOT) at 670 nm for September 2025 [Docter *et al.*, 2023]. High

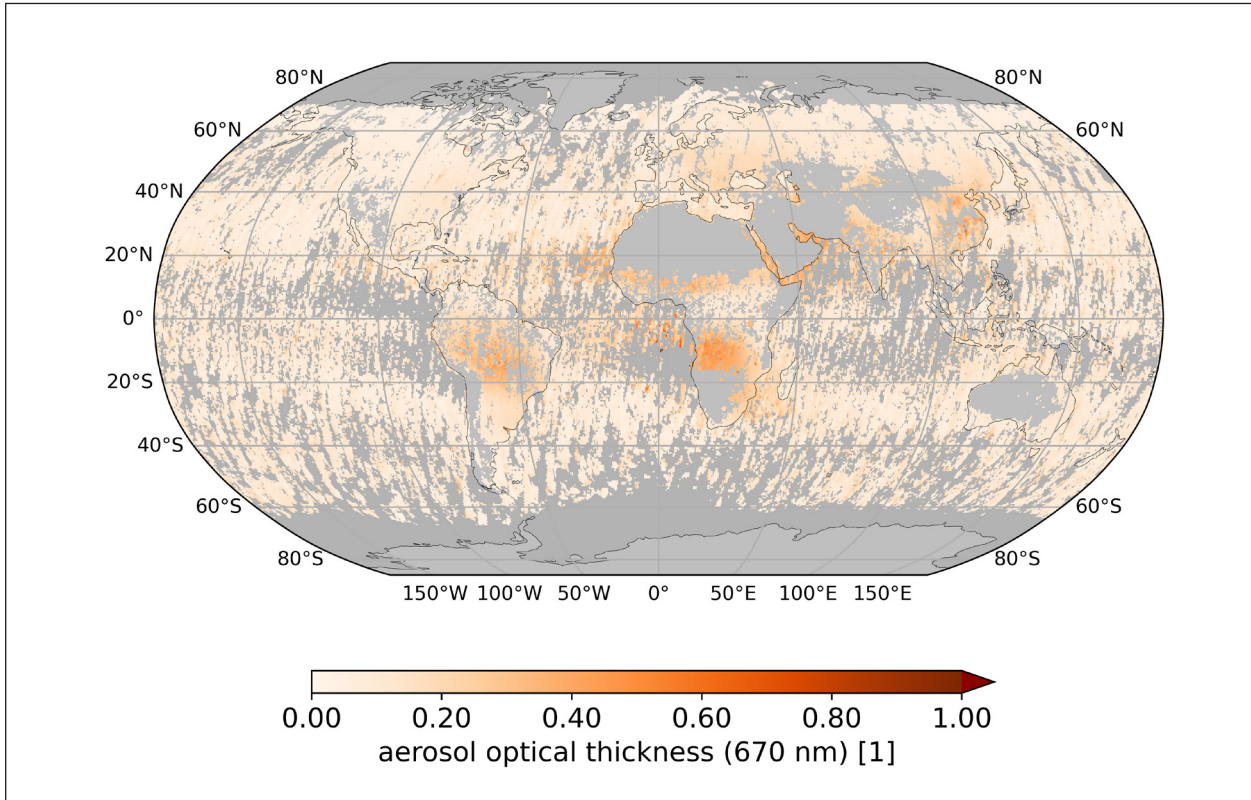


Fig. 9: Monthly composite of MSI-derived aerosol optical thickness at 670 nm for September 2025.

aerosol loads in the Amazon and Central Africa are visible, representing high air pollution caused by forest fires. Also, high AOT due to Saharan dust transport above the Tropical Atlantic and air pollution over eastern Asia are visible in the figure.

### Conclusion and outlook

Around one and a half years after the launch of ESA's EarthCARE satellite on 28 May 2024, the first results from data analysis, validation activities and global statistics conducted at TROPOS impressively demonstrate the great potential of the mission. EarthCARE is the first and currently only mission delivering synergistic observations from four instruments, the Atmospheric Lidar (ATLID), Cloud Profiling Radar (CPR), Multi-Spectral Imager (MSI) and Broadband Radiometer (BBR). TROPOS has been involved in the mission development since the beginning of the preparation phase more than 25 years ago and is responsible for several ATLID and MSI cloud and aerosol algorithms. Through its strong role in the Data Innovation and Science Cluster (DISC), TROPOS is deeply involved in EarthCARE and a key contributor to the success of the mission.

TROPOS operates global ground-based active remote sensing instruments in the framework of PollyNET and ACTRIS, e.g., at Cabo Verde, Tajikistan,

New Zealand and on shipborne platforms. Combined with its in-depth expertise in lidar technology and algorithm development, the institute naturally has a leading position in the validation activities for EarthCARE. Therefore, TROPOS coordinates the German Initiative for the Validation of EarthCARE (GIVE) and the European ACTRIS validation activities for EarthCARE (AECARE). As a result, TROPOS is pioneering some of the first EarthCARE science topics such as smoke intrusions into the stratosphere and the development of hurricanes. The global data coverage of EarthCARE provides unprecedented observations from remote regions and thus perfectly complements the institute's studies on contrasting environments. The fact that ESA recently updated the mission lifetime to 10 years (and potentially more) gives the intensive efforts at TROPOS an even more promising perspective to perform long-term global research and climate-relevant process studies.

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# Photochemistry in the sea-surface microlayer (SML) influenced by a phytoplankton bloom during a mesocosm study

Olenka Jibaja Valderrama, Daniele Scheres Firak, Thomas Schaefer, Manuela van Pinxteren, Khandeh Wadinga Fomba, Hartmut Herrmann

**Die Sea-Surface Microlayer (SML) bildet die dünne Grenzschicht zwischen Ozean und Atmosphäre und spielt voraussichtlich eine entscheidende Rolle in der Atmosphärenchemie auf globaler Ebene. Als biologisch reichhaltige Umgebung, die starker aktinischer Strahlung ausgesetzt ist, stellt die SML potenziell einen Hotspot für photochemische Reaktionen dar, die für die Umwandlung und den Kreislauf organischer Verbindungen relevant sind. TROPOS ist aktiv an diesem Forschungsthema beteiligt und wirkt im Projekt BASS (Biogeochemical processes and Air-sea exchange in the Sea-Surface microlayer) mit. Ziel des Projekts ist es, die Rolle der SML in klimarelevanten Prozessen zu klären und das Bewusstsein für ihre Bedeutung in der Klimaforschung zu schärfen. In diesem Kontext untersucht die vorliegende Studie die photochemische Produktion und den Abbau von Carbonylverbindungen sowie die photochemische Oxidationskapazität in Proben der umgebenden SML und des Underlying Water (ULW). Die natürlichen Meerwasserproben wurden im Rahmen einer Mesokosmenstudie entnommen, in der durch die kontrollierte Zugabe anorganischer Nährstoffe eine Phytoplanktonblüte induziert wurde. Unsere Ergebnisse zeigen einen Einfluss der biologischen Aktivität auf die Photochemie von Carbonylverbindungen in der SML und deren Auswirkungen auf die Emission flüchtiger organischer Verbindungen (VOCs) in die Meeresatmosphäre. Sie weisen auf die komplexe Wechselwirkung biotischer und abiotischer Faktoren an der Luft-Meer-Grenze hin und unterstreichen die Relevanz der marinen Photochemie für biogeochemische Prozesse.**

## Introduction

The sea-surface microlayer (SML) is the uppermost boundary layer of the ocean. With a thickness typically between 1 and 1000  $\mu\text{m}$ , the SML potentially covers up to 70 % of the Earth's surface [Wurl *et al.*, 2011]. This unique environment is enriched both in dissolved organic matter (DOM) and inorganic matter, and it is directly exposed to strong solar radiation, making it a zone of intense photochemical activity [Zafiriou, 1977]. The SML naturally acts as an interface between the underlying water (ULW) and the atmosphere, and many transfer processes, such as those involving particles or trace gases, will be mediated through the SML and its respective properties [Wurl *et al.*, 2017; Engel *et al.*, 2017]. Clearly, based on its biological, chemical and physical properties, the SML can be distinguished from ULW.

Under exposure to sunlight, coloured dissolved organic matter (CDOM) and humic substances in

seawater undergo photochemical reactions that form species like carbonyl compounds. Field-based measurements provided evidence of oceanic production of aldehydes like formaldehyde, acetaldehyde, glyoxal, methylglyoxal, propanal, and hexanal; and ketones like acetone [de Bruyn *et al.*, 2011; Kieber *et al.*, 1990; Mopper and Stahovec, 1986; Mopper *et al.*, 1991; van Pinxteren and Herrmann, 2013; Zhu and Kieber, 2019, 2018]. However, uncertainties remain regarding the rates in which these processes occur and their interplay with biological events. Furthermore, investigations on the photochemistry in seawater of additional carbonyl compounds with potential relevance in the marine environment are, to this moment, still limited.

Both the fate of DOM and the formation of volatile organic compounds (VOCs) in seawater are highly impacted by its photochemical oxidation capacity, governed by the sunlight-driven production of excited triplet-state CDOM ( $^3\text{CDOM}^*$ ) and reactive oxidants,

such as hydroxyl radicals (OH), superoxide radicals ( $O_2^-$ ), singlet oxygen ( $^1O_2$ ), excited DOM triplets and hydrogen peroxide ( $H_2O_2$ ). These processes occur alongside or even exceed biological pathways of transformation of DOM, so the estimation the photochemically-produced oxidants is essential to get more insights into the oxidative potential of the air-sea interface.

TROPOS is actively involved in increasing our current understanding of the reactivity of the SML, particularly through the investigation of abiotic SML-specific photochemical reactions, heterogeneous oxidation processes, and radical-driven reactions. In the present report, investigations on the photochemical activity of SML and ULW samples collected during a mesocosm study are presented. In this mesocosm study, a phytoplankton bloom was induced by the controlled addition of inorganic nutrients. The photochemistry of the seawater samples was assessed through the compound-specific concentration changes of carbonyl compounds before and after irradiation, alongside measurements of the photooxidation capacity to elucidate potential formation and degradation pathways of seawater samples at different bloom stages. The 17 carbonyl compounds analysed in the present study were acetophenone, acrolein, benzaldehyde, biacetyl, butanal, crotonaldehyde, glyoxal, heptanal, hexanal, isovaleraldehyde, methacrolein, methylglyoxal, methyl vinyl ketone (MVK), octanal, propanal, trans-2-hexenal and trans,trans-2,4-hexadienal. Experimental evidence demonstrates enhanced photochemical activity of carbonyl compounds in the SML relative to the ULW, particularly in periods of higher biological productivity, thereby offering new insights to integrate biologi-

cal processes and photochemistry in the air-sea boundary.

## Methods

### Seawater sampling during the field campaign.

Ambient SML and ULW (40 cm depth) samples were collected during a mesocosm experiment conducted at Sea-sURface Facility (SURF), located at ICBM in Wilhelmshaven (Germany), between May 18<sup>th</sup> and June 16<sup>th</sup>, 2023. SML samples were collected daily using the glass plate technique, while ULW samples were obtained via suction using a syringe connected to a polypropylene tube submerged to 40 cm.

A controlled phytoplankton bloom was induced through the stepwise addition of silicate, phosphorous and nitrogen as inorganic nutrients. Based on chlorophyll *a* concentrations monitored in the ULW by *Bibi et al.* [2025], three distinct bloom phases were defined: (1) an initial pre-bloom phase, with lower chlorophyll *a* levels prior to nutrient addition (May 18<sup>th</sup> to May 26<sup>th</sup>); (2) a nutrient-induced bloom phase, (May 27<sup>th</sup> to June 4<sup>th</sup>), characterized by a rapid increase in phytoplankton mass; (3) a post-bloom phase, marked by the gradual decline in phytoplankton biomass (June 5<sup>th</sup> to June 16<sup>th</sup>) [*Bibi et al.*, 2025].

As reported by *Bibi et al.*, dissolved organic carbon (DOC) concentrations increased during the phytoplankton bloom phase, and remained elevated in the post-bloom phase of the study. A detailed description of the mesocosm setup, and the operational and sampling protocols are available in *Bibi et al.* [2025].

**Photochemical reactor.** For carbonyl compound photochemistry investigations, ambient SML and ULW samples were irradiated for 5 hours with a light

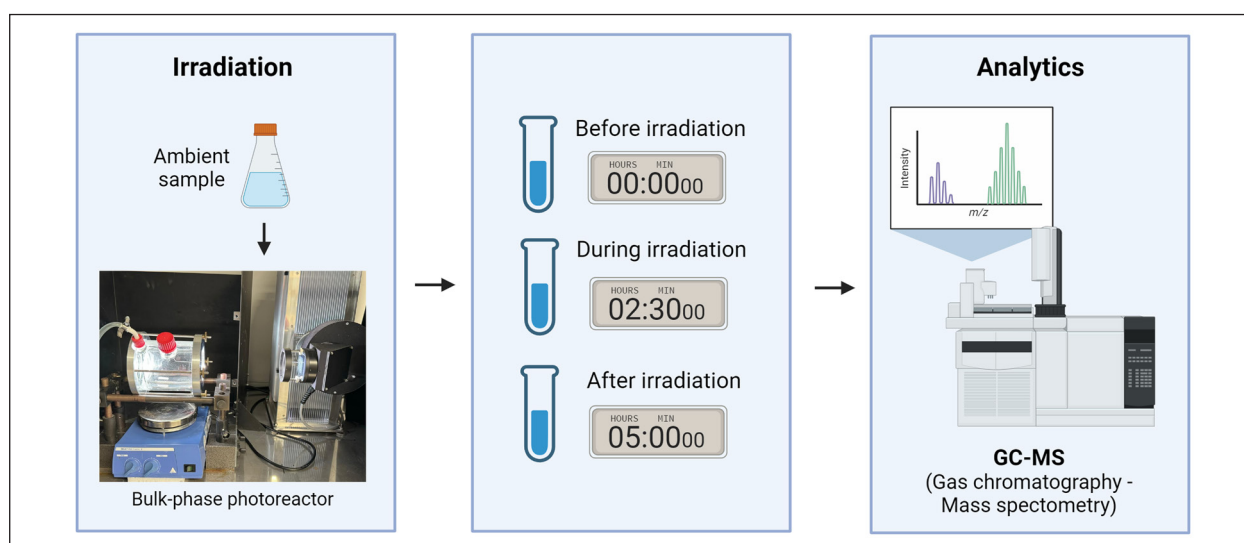


Fig. 1: Workflow for the analysis of photochemical production of carbonyl compounds in the SML and ULW samples.

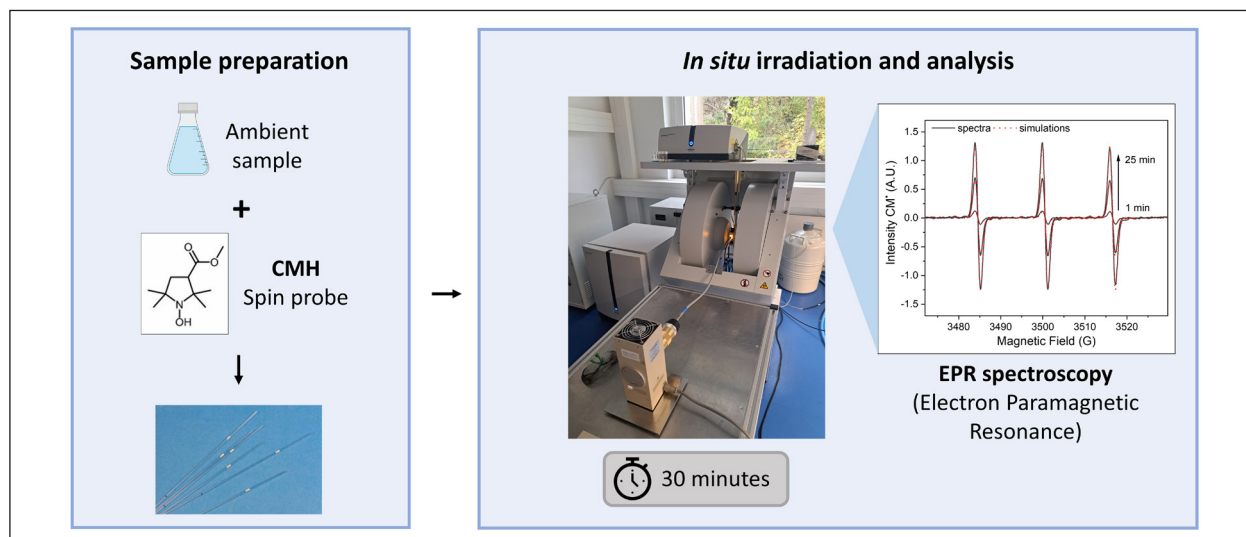


Fig. 2: Workflow for the analysis of the photooxidation capacity in the SML and ULW samples.

source that simulated the actinic radiation in the sea surface in a temperature-controlled ( $25 \pm 0.5^\circ\text{C}$ ) aqueous-phase cylindrical glass photoreactor (length: 9.5 cm, internal diameter: 6 cm). The solar simulator consisted of a 1000 W Xenon lamp coupled with an air mass filter (AM1-5G) that was positioned 20 cm away from the photoreactor (Fig. 1). Aliquots of 10 mL were collected at three time points: (1) before irradiation, (2) after 2.5 hours and (3) after 5 hours of irradiation. After the 5 hours of irradiation, all the collected aliquots were either immediately processed together for the gas chromatography-mass spectrometry (GC-MS) analysis, or stored at  $-20^\circ\text{C}$  for later electron paramagnetic resonance (EPR) analysis and trace metal analysis.

**Analytical method for the quantification of carbonyl compounds.** The analysis of the target carbonyl compounds in the filtered seawater samples was carried out using a method based on derivatization with a *o*-(2,3,4,5,6-pentafluorobenzyl) hydroxylamine (PFBHA) reagent, followed by solvent extraction and gas chromatography-mass spectrometry analysis (GC-MS). This method was originally developed at TROPOS for marine samples by *van Pinxteren and Herrmann* [2013], and further optimized by *Rodigast et al.* [2015] for application to other environmental samples [*Rodigast et al.*, 2015; *van Pinxteren and Herrmann*, 2013].

**Analytical method for the estimation of the photooxidation capacity.** The *in situ* spin-probing experiments were performed using EPR spectroscopy. The EPR resonator was coupled with an optical fiber accessory preceded by a 1.0 mm filter irradiated with a 150 W Xenon arc lamp. SML and ULW samples

were added with the spin probe 1-hydroxy-3-methoxy-carbonyl-2,2,5,5-tetramethyl pyrrolidine (CMH), transferred to a capillary tube, centered in the resonator, and subsequently irradiated in the presence of CMH for 30 minutes (Fig. 2). This method was developed at TROPOS by Scheres Firak et al. for its application to environmental samples [*Scheres Firak et al.*, 2025]

**Analytical method for the measurement of trace metals.** Trace concentrations of iron (Fe) and copper (Cu) were measured directly from the seawater samples using a benchtop total reflection X-ray fluorescence (TXRF) spectrometer. This method was originally developed at TROPOS by *Fomba et al.* for the investigation of trace metal concentrations in particulate matter (PM) and cloud water [*Fomba et al.*, 2013; *Fomba et al.*, 2020], and further optimized for its application to seawater samples in the present study.

## Results and Discussion

### Concentrations of carbonyl compounds in irradiated samples under bloom and non-bloom conditions

Figure 3 illustrates the individual concentrations in the seawater samples of the 17 carbonyl compounds in four categories: SML before irradiation (A), SML after 5 hours of irradiation (B), ULW before irradiation (C), and ULW after 5 hours of irradiation (D).

Carbonyl concentrations varied considerably between SML and ULW, and across bloom phases. Total carbonyl concentrations were generally higher in samples collected during the bloom phase compared to the pre- and post-bloom phases, with exception of the SML sample collected on June 8<sup>th</sup> (A). In that

day, the concentration of propanal before irradiation reached 4027 nmol L<sup>-1</sup>, a value significantly higher than in the irradiated counterpart (B). Propanal and hexanal were the most abundant compounds during the bloom phase, suggesting that their formation is favoured under conditions of high biological productivity.

Throughout all bloom phases, the SML (A and B) had consistently higher concentrations than the ULW samples (C and D) both before and after irradiation. Before irradiation, values in the SML (A) ranged from 201 to 762 nmol L<sup>-1</sup> in the pre-bloom phase, 984 to 4591 nmol L<sup>-1</sup> in the bloom phase, and 647 to 4894 nmol L<sup>-1</sup> in the post-bloom phase; while in the ULW (C) they were significantly lower (e.g., 136 to 366 nmol L<sup>-1</sup> in the bloom phase). After 5 hours of irradiation, the concentrations of carbonyl compounds increased further, reaching up to 6026 nmol L<sup>-1</sup> in the SML (B) during the bloom phase and 419 nmol L<sup>-1</sup> in the ULW (D). This suggests the light-driven production of aldehydes and ketones, probably via direct photolysis, photochemical oxidation or photosensitized reactions. These observed SML enrichments for all the aldehydes and ketones under evaluation are in agreement with previous studies for glyoxal, methylglyoxal, propanal and butanal [Zhou and Mopper, 1997; van Pinxteren and Herrmann, 2013], and provide novel insights on the behaviour of a larger pool of carbonyl

compounds with potential relevance in the marine environment, such as MVK or methacrolein. Overall, these findings indicate that the unique physical and chemical environment in the surface of the sea, richer in organic compounds compared to ULW, favours the production of these carbonyl compounds.

These trends could be attributed to several factors, such as the diverse chemical composition, reactivity, optical properties and availability of the DOM in the different water layers. Surface waters are typically characterized by their enrichment in more photoreactive and autochthonous DOM, contrasting with the more degraded and refractory compounds in the underlying waters [Wagner et al., 2020; Yang et al., 2022].

Our data shows higher concentrations of carbonyl compounds generally during the phytoplankton bloom phase (Fig. 3), suggesting a strong direct or indirect influence of biological productivity on the availability of precursors for the production of aldehydes and ketones. Higher concentrations were partly found in the post-bloom compared to the pre-bloom. This pattern is in agreement with the parallel increase of the DOC levels with the phytoplankton abundance in the bloom phase, and with how these levels also remained high in the post-bloom phase [Bibi et al., 2025]. Fresh biological material produced during phytoplankton blooms is a source of photochemically active DOM. For instance, *Emiliana huxleyi*, a specie

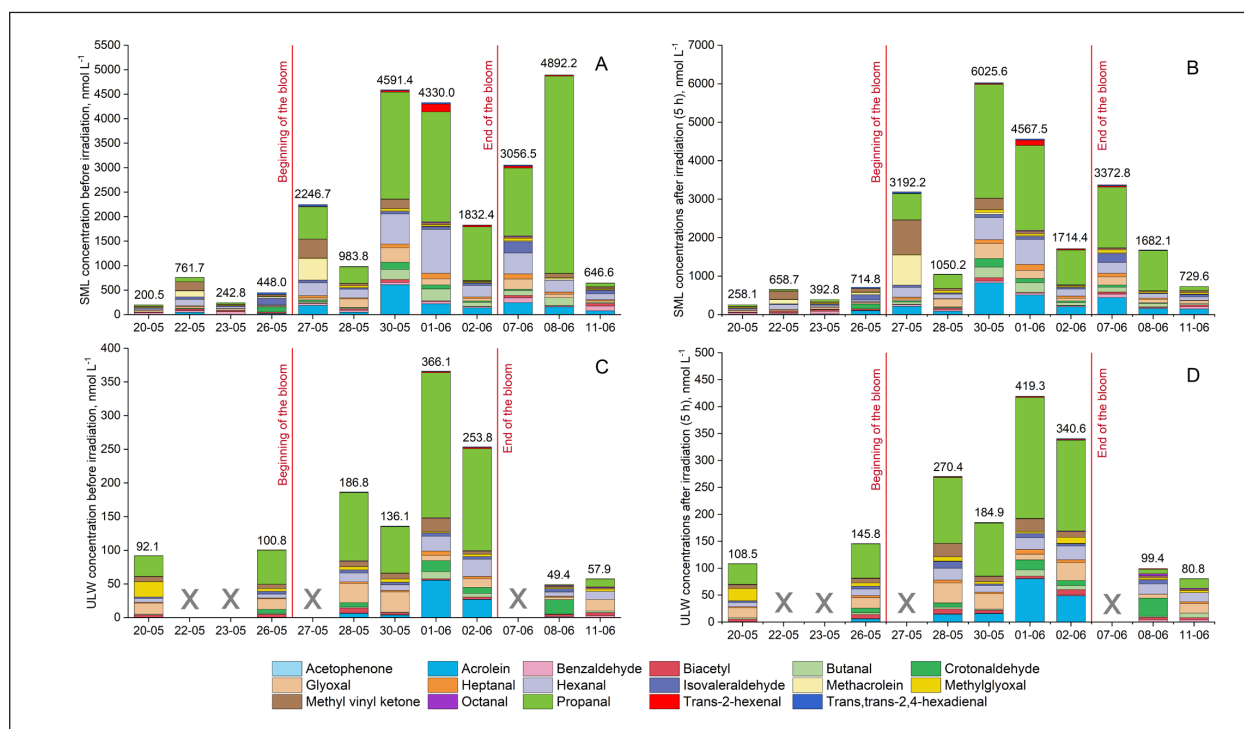


Fig. 3: Speciation of 17 carbonyl compounds in SML samples before irradiation (A) and after 5 hours of irradiation (B), and ULW samples before irradiation (C) or after irradiation (D). The red lines separate the three phases of the mesocosm experiment.

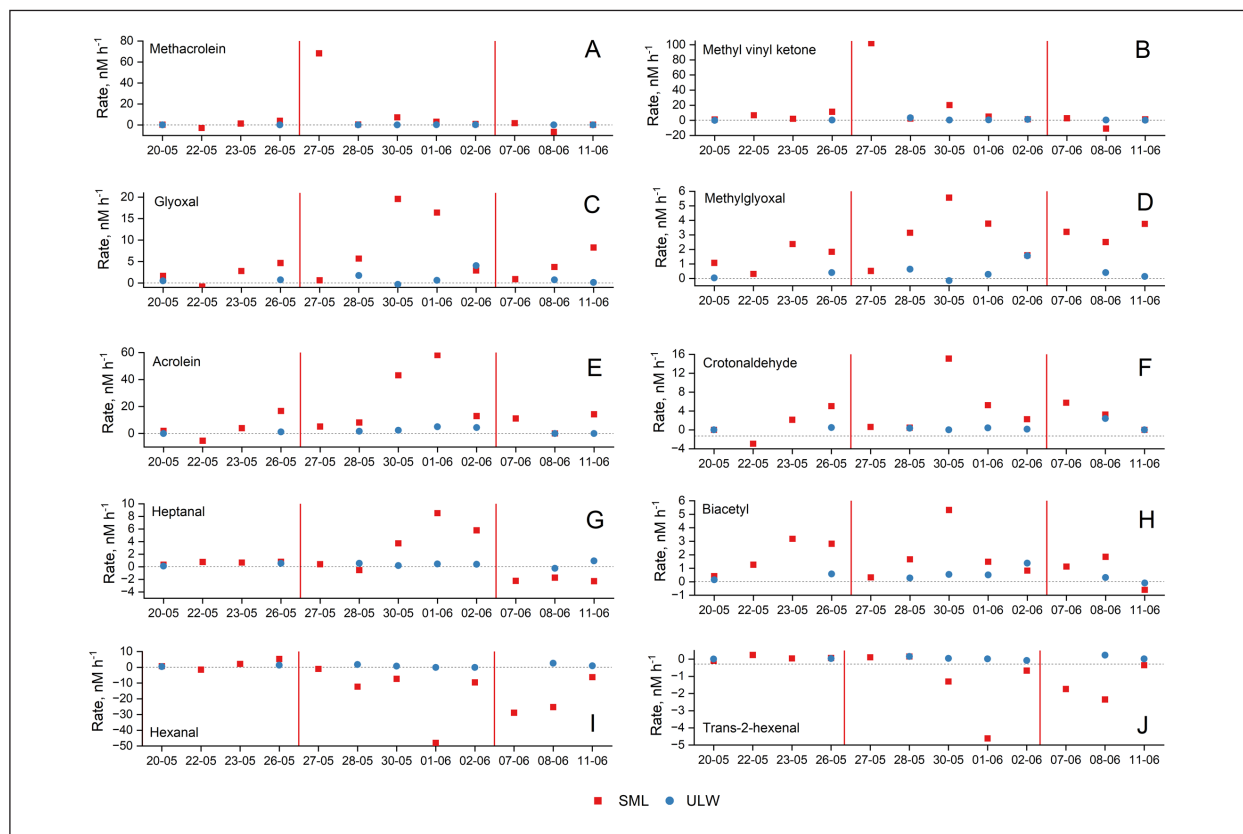


Fig. 4: Comparison of photochemical formation and degradation rates of methacrolein (A), MVK (B), glyoxal (C), methylglyoxal (D), acrolein (E), crotonaldehyde (F), heptanal (G), biacetyl (H), hexanal (I) and trans-2-hexenal (J) in the SML (red) and in ULW (blue).

of photosynthetic coccolithophore that dominated at the early bloom phase [Bibi *et al.*, 2025], is characterized by its efficient photochemical production of isoprene, a volatile precursor of several carbonyl compounds [Shaw *et al.*, 2003; Sinha *et al.*, 2007]. Furthermore, the major fatty acids from other diatoms like *Phaeodactylum triconutum* might be precursors of carbonyl compounds through oxidation reactions [Schobert and Elstner, 1980]. Oxidative stress during blooms and photochemical degradation of DOM are linked to the massive production of ROS, which may trigger processes like isoprene oxidation and lipid peroxidation, leading to the release of aldehydes and ketones.

Altogether, this experimental evidence indicates that phytoplankton blooms influence not only the biological activity in seawater but may also modulate abiotic processes, particularly in the SML, by changing DOM chemical composition and reactivity.

**Photochemical production rates under bloom and non-bloom conditions.** The photochemical formation and degradation rates of the 17 carbonyl compounds, expressed in  $\text{nM h}^{-1}$ , was investigated in both SML and ULW samples (Fig. 4 and Fig. 5). In the three phases of the mesocosm study, the carbonyl

compounds in the SML samples (red) presented consistently higher photochemical production rates than in the ULW (blue). The red lines separate the three phases of the mesocosm study: pre-bloom (May 20<sup>th</sup> to May 26<sup>th</sup>), bloom (May 27<sup>th</sup> to June 2<sup>nd</sup>) and post-bloom (June 7<sup>th</sup> to June 11<sup>th</sup>). Photochemical production rates in the SML and ULW of the 17 carbonyl compounds were classified in two major categories, based on how their time-resolved photochemistry was influenced by the phytoplankton bloom:

- **Photochemistry influenced by the bloom:** Ten out of 17 compounds showed enhanced photochemical formation or degradation in the SML during the phytoplankton bloom: MVK, methacrolein, glyoxal, methylglyoxal, acrolein, crotonaldehyde, heptanal, biacetyl, hexanal and trans-2-hexenal. Interestingly, the temporal behaviour of the production rates of isoprene oxidation products had a characteristic pattern: methacrolein (A) and MVK (B), both primary isoprene products, had peak productions in the early stage of the bloom; while glyoxal (C), methylglyoxal (D) and acrolein (E), all secondary isoprene products, dominated the later stage of the bloom. This pattern suggests a dynamic photochemical response regarding isoprene formation to the

changes in the composition of DOM throughout a phytoplankton bloom. Enhanced photochemical degradation of hexanal (I) and trans-2-hexenal (J) was also observed during the bloom phase. This coincides with the expected generation of large quantities of ROS, such as OH radicals, superoxide and singlet oxygen linked to oxidative stress in phytoplankton blooms [Cho et al., 2022]. These species would be massively available during the bloom to degrade hexanal and trans-2-hexenal, a process similar to what has been observed in the gas phase [Jiménez et al., 2007]. These trends suggest an influence of the stage of the phytoplankton bloom in the photochemical activity of 10 carbonyl compounds in the SML, presumably due to the elevated concentrations of photochemically active precursors and higher oxidative stress in the bloom phase.

- **Photochemistry independent of the bloom:**

The photochemistry of seven out of the 17 compounds showed no clear influence of the bloom: butanal, isovaleraldehyde, benzaldehyde, trans,trans-2,4-hexadienal, octanal and acetophenone (Fig. 5). These compounds may be possibly derived from a mixture of both biogenic and anthropogenic sources, with less influence of the bloom intensity compared to the compounds in the previous sub section. Propanal (A) and butanal (B) were the most photochemically active compounds in this category. They are

small aldehydes commonly linked to the oxidation of larger organic molecules, which could explain their abundance in the different phases of the study. The photochemical activity of the aromatic carbonyls, benzaldehyde (E) and acetophenone (F), peaked in the pre- and post-bloom phases and was relatively lower than for the other compounds. This could suggest an increased presence of humic-like DOM derived from anthropogenic activity or terrestrial sources, which is less labile but still photochemically active. The production of octanal (C) and trans,trans-2,4-hexadienal (G) is also comparatively lower, likely because it requires the preservation of longer carbon chains and more complex structures.

In general, the high photochemical production rates observed in the later stage of the bloom and during the post-bloom phase of the experiment may be explained by the photochemical degradation of lipids and humic-like compounds as precursor molecules, which could represent a higher proportion of the DOM due to the beginning of the phytoplankton decay from viral cell lysis, senescence or grazing.

The findings for glyoxal and methylglyoxal in non-bloom phases are consistent with published photochemical production rates from SML samples collected in the Bahamas, Delaware Bay (USA) and Biscayne Bay (USA), which range between 0.75 and 5.8 nM h<sup>-1</sup> for glyoxal, and 0.3 and 2.5 nM h<sup>-1</sup> for

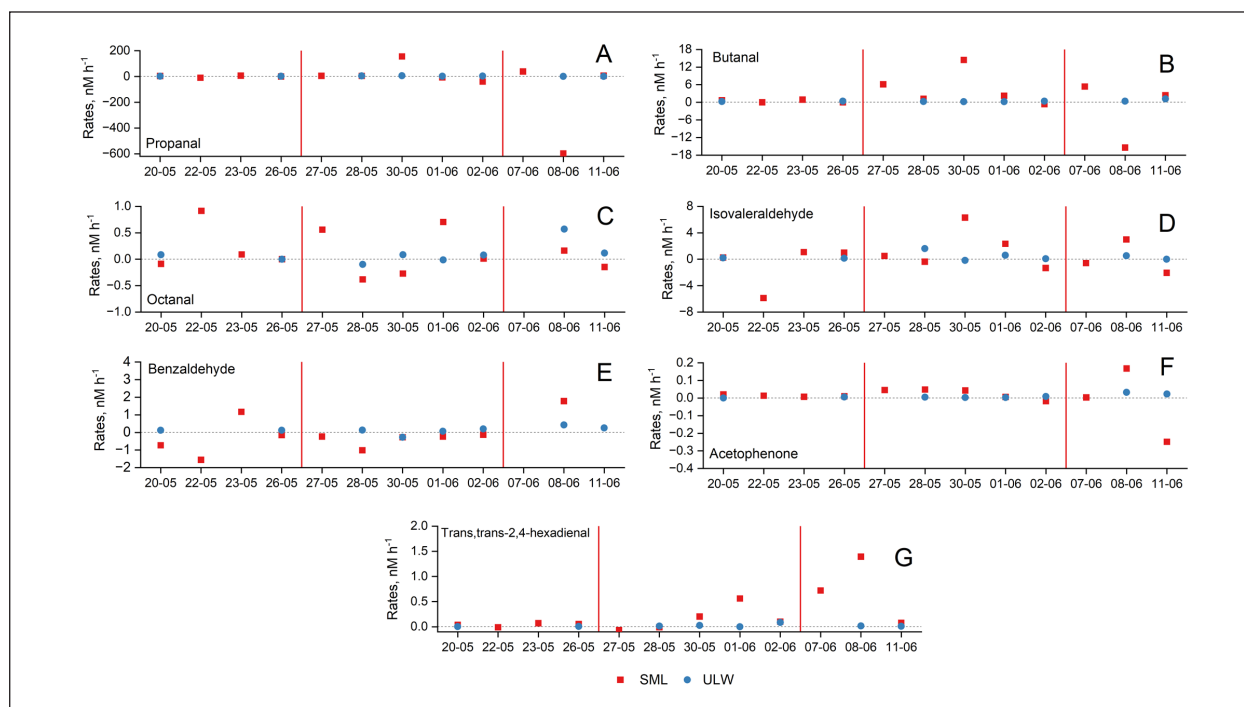


Fig. 5: Comparison of photochemical formation and degradation rates of propanal (A), butanal (B), octanal (C), isovaleraldehyde (D), benzaldehyde (E), acetophenone (F) and trans,trans-2,4-hexadienal (G) in the SML (red) and in ULW (blue).

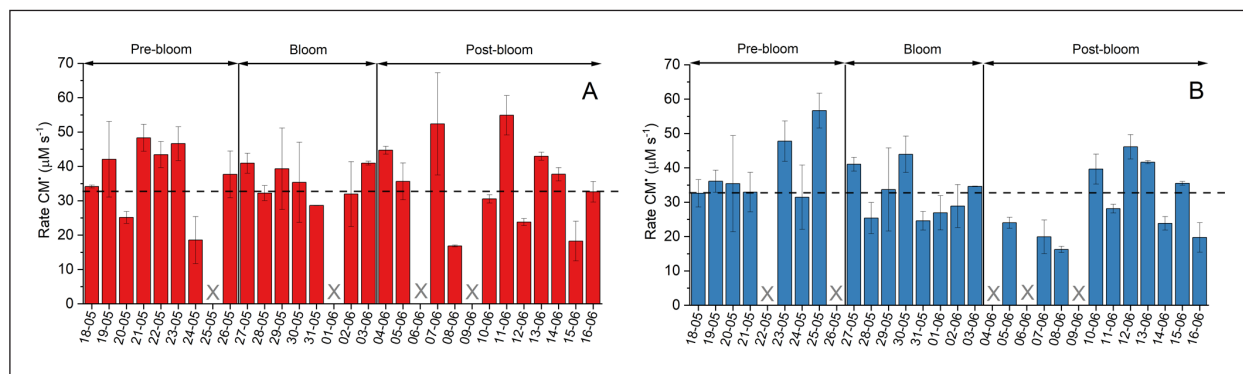


Fig. 6: The overall CM radical formation in different samples after photon-flux correction for SML (A) and ULW (B) samples. The dashed line represents the mean CM radical formation rate considering all samples.

methylglyoxal [Mopper and Stahovec, 1986; Zhou and Mopper, 1997]. On the other hand, the higher photochemical formation rates found during the bloom phase for these two compounds were comparable with those reported by Zhou and Mopper for SML samples (up to  $15.5 \text{ nM h}^{-1}$  for glyoxal and  $9.7 \text{ nM h}^{-1}$  for methylglyoxal), collected in the Biscayne Bay in the presence of foam on the sea surface [Zhou and Mopper, 1997]. Likewise, rates of photochemical formation reported in the ULW align well with those determined in the present study [Zhu and Kieber, 2018; Zhou and Mopper, 1997]. Higher photochemical activity in short-chain aldehydes was observed, compared to literature values: Zhou and Mopper reported formation rates between  $1.3$  and  $7.4 \text{ nM h}^{-1}$  for C3 aldehydes, and between  $0.4$  to  $4.2 \text{ nM h}^{-1}$  for C4 aldehydes [Zhou and Mopper, 1997]. Despite the lower magnitudes compared to the present study, Mopper and Stahovec also observed photochemical degradation of propanal ( $-0.75 \text{ nM h}^{-1}$ ) in surface water samples from the Biscayne Bay [Mopper and Stahovec, 1986].

By connecting phytoplankton bloom dynamics and the temporal trend of the photochemical products, these results stress the crucial role of the SML as a dynamic air-sea boundary and its potential implications for the production of VOCs to the marine atmosphere. These findings are of high relevance for refining atmospheric models in the marine environment, as climate change is projected to cause shifts in nutrient and sunlight availability, thereby influencing phytoplankton blooms and marine carbon cycling [Thomalla et al., 2023; Dai et al., 2023].

#### Photooxidation capacity under bloom and non-bloom conditions

Investigations of photooxidation capacity in the seawater samples are essential to understand how the sunlight-driven production of reactive intermediates influences the transformation of DOM. The

photooxidation capacity of SML and ULW samples was tested using CMH as a radical probe in EPR experiments by monitoring the light-induced formation of CM radicals.

The formation of CM radicals occurred in all samples and increased linearly during the monitored time. These values were then represented in bar plots that illustrate the overall budget of oxidants photochemically generated in the samples (Fig. 6). The overall photochemical oxidation capacity of the samples did not seem to be affected by the addition of nutrients. It was also, on average, similar for both SML and ULW samples, with values around  $34 \mu\text{M s}^{-1}$ .

While nutrient levels can indirectly influence the redox capacity of seawater samples through phytoplankton blooms, they ultimately did not appear to control it. The oxidation potential of the samples seemed to be primarily determined by the presence and availability of electron donors and acceptors. Although the complexity of the mesocosm samples makes it difficult to attribute the oxidation properties to individual species, a dominant class of redox-active compounds known to be present in seawater are metal ions. To evaluate if these processes might have an influence on the observed results for the mesocosm study, the concentrations of Cu and Fe in SML and ULW samples were quantified. TXRF measurements demonstrated the presence of Cu and Fe in the pre-bloom phase (May 20<sup>th</sup>) and during the bloom (June 2<sup>nd</sup>). Cu concentrations in the SML and in the ULW were  $0.3$  and  $0.2 \mu\text{mol L}^{-1}$  on May 20<sup>th</sup>, and  $0.5$  and  $0.3 \mu\text{mol L}^{-1}$  on June 2<sup>nd</sup>. Fe concentrations in the SML and in the ULW were  $1.2$  and  $1.0 \mu\text{mol L}^{-1}$  on May 20<sup>th</sup>,  $9.2$  and  $1.8 \mu\text{mol L}^{-1}$  on June 2<sup>nd</sup>. The distribution of redox-active trace elements in the SML and ULW samples was relatively uniform, as expected from previous studies [Siems et al., 2024]. The observed trace metal concentrations might contribute to the high observed redox activity of the samples in the *in situ* EPR experiments; nevertheless, future

research should focus on exploring to what extent these processes influence the overall photochemistry in the SML.

## Summary

The SML is a unique and dynamic environment characterized by its high concentrations of DOM and its direct exposure to strong solar radiation, making it a potential hotspot for photochemical reactions. TROPOS is actively involved in the study of the reactivity of the SML, particularly through the investigation of abiotic SML-specific photochemical reactions, heterogeneous oxidation processes, and radical-driven reactions. In this report, we present insights on the photochemistry in SML and ULW samples collected during a mesocosm experiment where a phytoplankton bloom was induced by the controlled addition of inorganic nutrients. Two complementary aspects were explored: (1) photochemical production of 17 atmospherically-relevant carbonyl compounds, and (2) overall photooxidation capacity of the system.

All the target carbonyl compounds were consistently enriched in the SML compared to ULW, supporting the role of the SML as a distinct habitat for abiotic processes. The concentrations in the SML of acetophenone, acrolein, biacetyl, butanal, crotonaldehyde, glyoxal, heptanal, hexanal, methacrolein, methylglyoxal, MVK, octanal, propanal and trans-2-hexenal were higher during the phytoplankton bloom, which is likely the phase of the higher biological productivity and enrichment in reactive materials. The photochemical activity in the SML of acrolein,

biacetyl, butanal, crotonaldehyde, glyoxal, heptanal, hexanal, methacrolein, methylglyoxal, methyl vinyl ketone, propanal and trans-2-hexenal (isoprene- and lipid-derived products) was particularly higher under bloom conditions, suggesting a link between photochemical reactivity and bloom-induced DOM composition changes. The photochemical production rates of glyoxal and methylglyoxal calculated in this study are similar to those previously published under comparable conditions. To complement these findings, the photooxidation capacity of SML and ULW samples along the mesocosm experiment has been evaluated via EPR spectroscopy. The estimated overall photooxidation rates remained similar in the three phases of the bloom, and they were comparable between the SML and ULW samples. These results suggest that the photooxidation capacity in the samples was primarily driven by the presence of redox-active species, such as metal ions, rather than by biological processes.

Overall, these findings reveal that phytoplankton blooms enhance photochemical production of carbonyl compounds in the SML, but appear to have limited direct impact in the photooxidation capacity of these systems. These results suggest that photochemistry in the SML is governed by the complex interaction between biological activity and chemical composition, including DOM and trace metals. This work provides a novel perspective on how photochemical processes respond to biological events in the sea surface, and points to them as potential sources of VOCs to the marine atmosphere.

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University of Hamburg  
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# Marine polysaccharides - Important constituents of ice-nucleating particles in remote marine regions

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**Abgelegene Meeresregionen zeichnen sich durch eine starke Bewölkung aus, die sich erheblich auf die Strahlungsbilanz der Erde auswirkt. Für Klimaprognosen ist es von großer Bedeutung, die Eisbildung in diesen Wolken darzustellen. Daher ist es wichtig, die Quellen der eisbildenden Partikel (INPs) zu verstehen, denn INPs ermöglichen die primäre Eisbildung. Hier berichten wir über Polysaccharide aus der marinen Biosphäre, die unter anderem von den vier in dieser Studie untersuchten marine Pilze und Pseudopilze produziert werden und als eisbildende Makromoleküle (INMs) fungieren. Durch Ableitung physikalisch fundierter Parametrisierung dieser polysaccharidischen INMs konnten polysaccharidische INP aus globalen Modellsimulationen abgeleitet und mit derzeit verfügbaren Beobachtungen verglichen werden. Es konnte gezeigt werden, dass marine Polysaccharide im Temperaturbereich -15 bis -20°C im Mittel 44 % (22 – 100 %) zur gesamten INP Anzahlkonzentration marinen Ursprungs beitragen. Die Ergebnisse unterstreichen die Bedeutung biologischer INMs als Teil der INP Population in abgelegenen Meeresregionen.**

## Introduction

Ice-nucleating particles (INPs) induce primary ice formation in clouds. Therefore, INPs impact the clouds' radiative balance, precipitation formation and are very relevant for understanding climate sensitivities [Tan *et al.*, 2016]. For remote marine regions, such as the Southern Ocean where the concentration of INPs is naturally low [McCluskey *et al.*, 2018c; Tatzelt *et al.*, 2022] discrepant representations of cloud phase exist in atmospheric models leading to significant biases in cloud radiative effect [Vergara-Tempardo *et al.*, 2018]. A deeper understanding of INP sources, including mineral dust and sea spray aerosol (SSA) [DeMott *et al.*, 2016; Zhao *et al.*, 2023], INP transport, and the underlying ice nucleation mechanisms at the molecular level, is essential for improving climate modeling. This applies in particular to climate hot spot regions such as the Arctic and the Southern Ocean, which are quite unexplored and very sensitive

[DeMott *et al.*, 2010; Murray *et al.*, 2021; Wendisch *et al.*, 2023].

The role of the ocean as a source of INPs is well known, with microorganisms and their by-products being carriers of ice activity, which are transported into the atmosphere via sea spray aerosols (SSA) [Wilson *et al.*, 2015; DeMott *et al.*, 2016; McCluskey *et al.*, 2017; McCluskey *et al.*, 2018a; Creamean *et al.*, 2018]. During phases of high biological activity in the ocean such as phytoplankton blooms, more INPs might be produced that can be aerosolized [Wilson *et al.*, 2015; DeMott *et al.*, 2016; McCluskey *et al.*, 2017; McCluskey *et al.*, 2018a].

Indications have been found that marine microorganisms produce organic compounds that are responsible for the ice-nucleating ability [Wilson *et al.*, 2015; McCluskey *et al.*, 2017; McCluskey *et al.*, 2018a; Alpert *et al.*, 2022] and these compounds are frequently enriched in the surface microlayer [Wilson *et al.*, 2015; Hartmann *et al.*, 2021]. Different types of

marine microorganisms have been found to induce ice nucleation. These are algae [Ickes et al., 2020], bacteria [McCluskey et al., 2017; Beall et al., 2021], fungi [Beall et al., 2021], haloarchaea [Creamean et al., 2021] and viruses [Adams et al., 2021]. As primary contributors to biomass production and degradation, marine fungi are gaining recognition for their significant role in the carbon cycle [Hasset et al., 2019]. Fungi and pseudofungi are understudied, particularly in terms of their geographical and annual distribution [Hasset et al., 2019], and their potential role as INPs.

Ice-nucleating macromolecules (INMs) such as specific proteins and polysaccharide are responsible for the activity of biogenic INPs [Pummer et al., 2015; Hartmann et al., 2022]. Little is known about the chemical identity of marine biogenic INMs so far. Indications were found that proteinaceous and saccharidic compounds are present in planktonic microbes and their exudates [Wolf et al., 2019; Zeppenfeld et al., 2019; Alpert et al., 2022]. Targeted measurements of their chemical composition are needed to quantify the contribution of specific ice nucleation active components in marine INPs.

To predict atmospheric INP concentrations over remote marine regions, two main INP sources are commonly included in models: marine organics from SSA and mineral dust [e.g., Chatziparaschos et al., 2024]. State-of-the-art parameterization based on unspecified INP concentration or properties of bulk aerosol such as surface area or categories of aerosol main constituents are applied as proxies [DeMott et al., 2010]. Thereby, mostly polynomial or log-linear relationships between temperature and INP concentration are assumed [e.g., Wilson et al., 2015; Harrison et al., 2019]. Although this approach is consistent with the observed temperature-dependent INP concentrations, it is not a reliable method for extrapolation to a wider temperature range, as there is no physical basis. Apart from mineral dust, INP concentrations are usually estimated using indirect proxies, i.e. it is not accounted for the various chemical aerosol components that cause ice nucleation [e.g., Vergara-Temprado et al., 2017].

This report summarizes the study of Hartmann, Schrödner and Zeppenfeld et al. [2025], which is a result of a TROPOS cross-departmental project. In the following it is called HSZ25. The study evaluates the global relevance of marine polysaccharides as INPs by investigating the ice nucleation activity of four aquatic fungi and thraustochytrid as well as standard polysaccharides. A physics-based INP parameterization of these substances was developed and applied to global model simulations. Finally, the modelled INP concentrations were compared to observations in marine regions.

## Experimental Methods

To investigate the importance of marine polysaccharides as INPs, a wide variety of methods were used, including the following:

- **Biological analyses:** culture collection and cultivation of fungi and thraustochytrid (*T. striatum*, *T. pullulans*, *N. diffluens*, *P. chrysogenum*) from Arctic marine plankton and nearshore Arctic sediment in Tromsø and taxonomic analyses of Arctic marine air and surface water samples during polar night
- **Microphysical and chemical analyses:** determination of ice nucleation activity of microbial samples, standard polysaccharides and targeted chemical test to constrain chemical nature of INMs and quantification of total combined carbohydrates and total organic carbon
- **Modelling:** development INP Parametrization for marine polysaccharides based on classical nucleation theory and application of derived INP Parametrization to global model simulations [Bergman, 2021; Bergman et al., 2022] for different INP modes (mineral dust and marine polysaccharides), derivation of global impact by comparing modelled INP concentrations with globally available atmospheric INP observations

## Polysaccharides responsible for ice nucleating activity of marine microbes

In our study, marine fungi and thraustochytrids were found in ambient aerosol during polar night in the marine Arctic. As a basis for further investigations, we isolated and cultivated two yeast fungi (*T. pullulans*, *N. diffluens*), a filamentous fungus (*P. chrysogenum*) and a thraustochytrid (*T. striatum*).

We studied the ice nucleation activity of these marine microbes (light blue dots, Fig. 1) and observed -15 °C significant spread of about three orders of magnitude. The comparison with other INP types reveals that marine fungi and thraustochytrid initiate freezing at a higher temperature than most mineral dusts (above -18 °C) and at a lower temperature than biological INMs (mainly proteinaceous) from terrestrial sources (below -8 °C). The similar temperature dependencies observed among the different microbes, as indicated by a parametrization based on classical nucleation theory (CNT; shown in HSZ25, Fig. 2), strongly suggest that a common chemical class of INMs is responsible for the observed ice activity, which is examined in detail below:

- **To explore the chemical class of the INMs** contained in the microbial cultures, several physical and chemical tests were done. Filtration

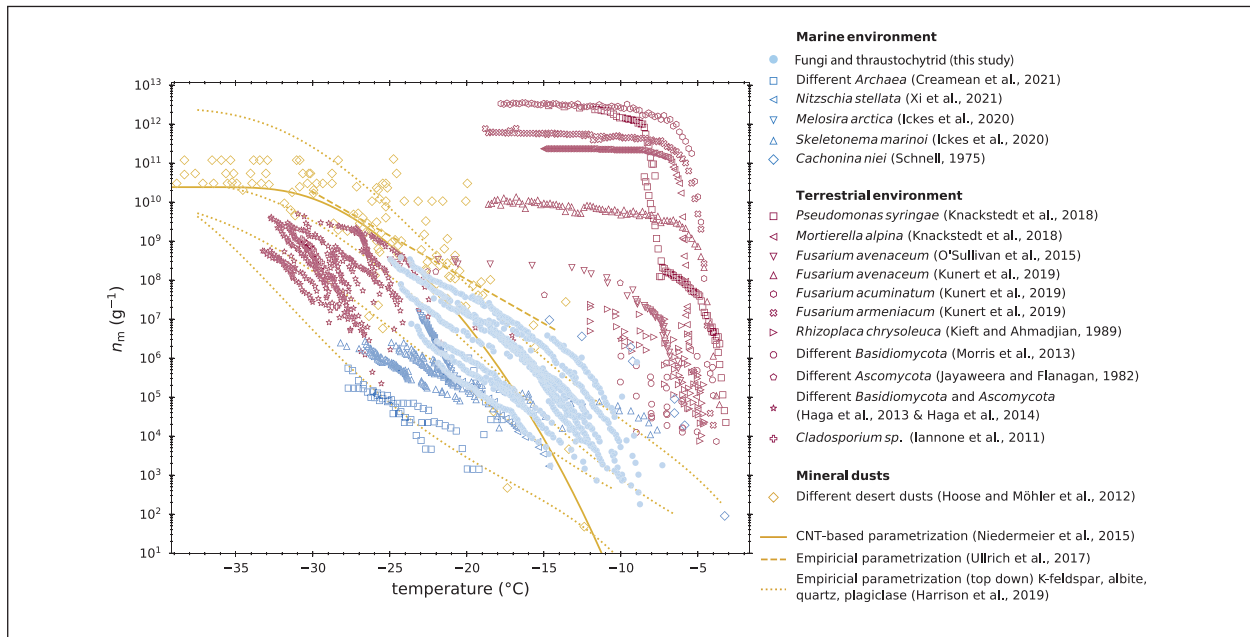


Fig.1: Ice nucleation mass site density  $n_m$  shown for terrestrial and marine microbes, mineral dust and in this study analyzed marine fungi and thraustochytrid. The source of Fig.1 is HSZ25 with further detail and references which can be found <https://pubs.acs.org/doi/10.1021/acs.est.4c08014> for reuse permission is needed from ACS.

(<0.2  $\mu\text{m}$ ) indicated that INMs are mainly associated with microbial cells or aggregates, while a smaller fraction occurs in dissolved or colloidal form. INM concentrations remained unchanged after heating, suggesting that the ice-nucleating material is non-proteinaceous, as proteins in most cases denature at a high temperature and lose their functionality [e.g., Pummer et al., 2015]. In contrast, treatment of the *T. pullulans* with strong acid (0.05 M  $\text{H}_2\text{SO}_4$ , 100  $^\circ\text{C}$ , 72 h; Fig. S2B in HSZ25) significantly reduced the ice activity, implying that hydrolysable macromolecules were disintegrated into non-ice-active components. In conjunction with heat resistance, this indicates that ice-active polysaccharides are present either as free molecules or attached to microbes or particulate debris. Further tests using calcium chloride and filtration indicate an acidic nature of polysaccharidic INMs in the dissolved fraction as the macromolecules form microgels by cross-linking in the presence of divalent calcium cations [e.g., Meng and Liu, 2016]. We propose that particulate INMs, while not explicitly studied here, could form three-dimensional networks. Solution of alginic acid, behaved similarly to the microbial culture aliquots (Fig. S2F in HSZ25).

- **To research polysaccharidic INMs**, standard polysaccharides (laminarin,  $\lambda$ -carrageenan,  $\kappa$ -carrageenan, alginic acid, agar, cellulose, xanthan gum, and a lipopolysaccharide) were

analyzed. All of them show ice nucleation but with a broad variability (Fig. S3 in HSZ25). The most ice-active polysaccharides were agar and long-chained alginic acid, both being negatively charged polysaccharides with ability to form gels and showing similar behavior as the microbial culture aliquots. In general, we find evidence for an influence of the molecular weight or chain length and the sequence of monosaccharides within the polysaccharide chain on ice nucleation activity, but this alone does not appear to be the decisive factor. The effect of three-dimensional structure on the catalytic efficiency of ice nucleation remains unclear and will be subject of future studies.

- **To approximate the mass of polysaccharides**, the total mass and type of carbohydrates was determined in the particulate and dissolved phases (Tab. 3 in HSZ25). The composition of monosaccharides in the microbial samples showed a complex mixture of different carbohydrates and a total fraction of 4-66 % to total organic carbon mass. The monosaccharide footprint indicates agar or agar-like ice nucleating polysaccharides in the microbes, whereas alginic acid is excluded by the absence of mannuronic acid.

The ice nucleation site density normalized to carbon content of measured total combined carbohydrates (C-TCCCHO, Fig. 2) showed a high agreement and a significant reduction in spread

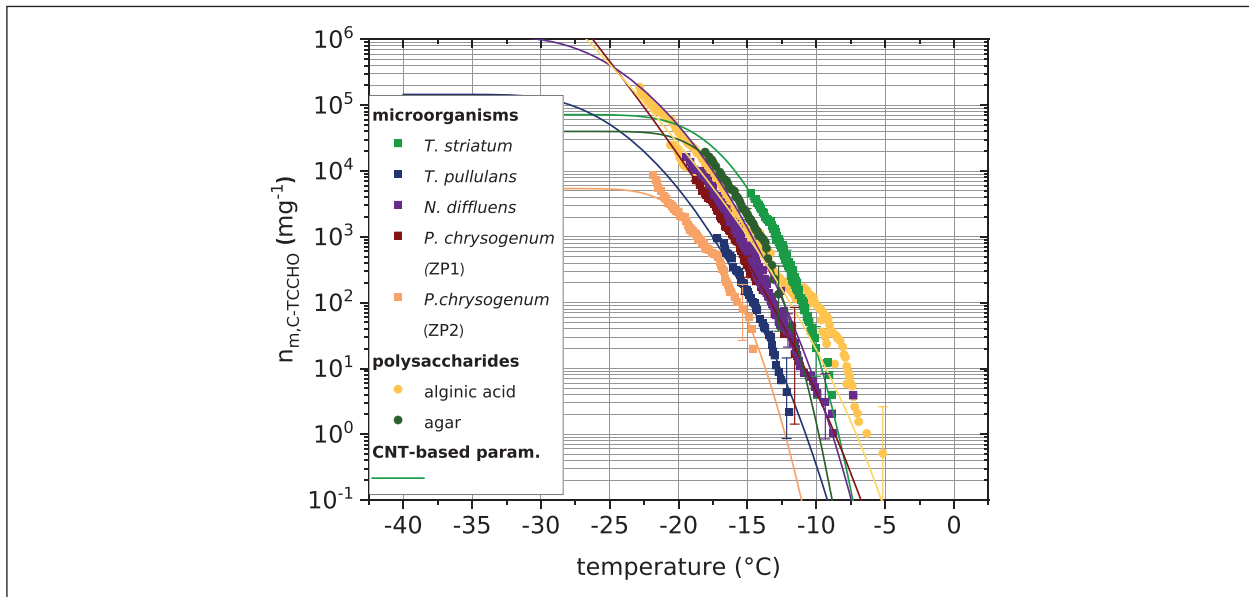


Fig. 2: High agreement observed in the ice nucleation activity of marine fungi, thraustochytrid and polysaccharides. The ice nucleation site density normalized to mass of measured C-TCCHO as function of temperature  $n_{m,C-TCCHO}$  is given and fitted using CNT-based model. The further applied CNT parametrization of *T. striatum* is applied for HSZ25 parameterization. The source of Fig. 2 is HSZ25 which can be found <https://pubs.acs.org/doi/10.1021/acs.est.4c08014>, for reuse permission is needed from ACS.

between of different microbial samples as without normalization (Fig. 1). This is a very strong indication for a causal relationship between combined total carbohydrates and ice nucleation activity. We therefore parametrized polysaccharide-derived INP in marine organic aerosol using the ice nucleation number site density normalized to C-TCCHO.

In summary, INMs produced by the investigated marine fungi and thraustochytrid are polysaccharides present either freely or bound to microbial cells or fragments. As marine polysaccharides (e.g., alginic acid and agar) are produced by many marine organisms, including globally distributed macro- and microalgae, their global relevance is likely substantial for ice formation. Given their similar freezing behaviour when normalized to C-TCCHO (Fig. 2) and diverse biological sources, it is justified to assess INA polysaccharides directly rather than individual organisms when evaluating global impacts.

### Marine polysaccharides relevant INPs in remote marine regions

The contribution of marine polysaccharidic INMs to global INP budget is assessed using the HSZ25 parameterization, applied to marine polysaccharide concentrations inferred from simulated sea salt mass [Bergman, 2021; Bergman et al., 2022] and observed polysaccharide fractions in sea spray aerosol (0.5% in

the accumulation mode and 0.1% in the coarse mode, e.g., Zeppenfeld et al. [2021]), in addition to mineral dust INPs [Niedermeier et al., 2015]. The resulting INP concentrations were evaluated against globally available observations from the marine atmosphere at temperatures between  $-15\text{ °C}$  and  $-20\text{ °C}$  (Fig. 3).

It is remarkable that mineral dust is ubiquitous in Earth's atmosphere and even at low concentrations in remote marine regions it provides a significant contribution to the INP budget below  $-15\text{ °C}$  [e.g., Vergara-Temprado et al., 2018]. However, note that by taking into account only mineral dust as INP source into account (gray dots) the model underestimates the INP concentration for  $T > -15\text{ °C}$ .

The modelled INP concentration increased significantly and lead to better agreement when also INMs from marine polysaccharides are considered (Fig. 3, colored dots). Furthermore, when considering clean marine INPs [McCluskey et al., 2018b] HSZ25 parameterization of marine polysaccharides represents on average 44 % (22–100 %) of all observational data within  $-15$  to  $-20\text{ °C}$ . When considering only Southern Ocean INP data the proportion is even higher.

To identify geographical regions, where marine polysaccharides have a significant influence on the INP budget, Fig. 4 shows the fraction of polysaccharidic INMs to the total INPs. At  $-15\text{ °C}$  to  $-16\text{ °C}$ , annual-mean INP concentrations from marine polysaccharides are comparable to, or exceed, those from

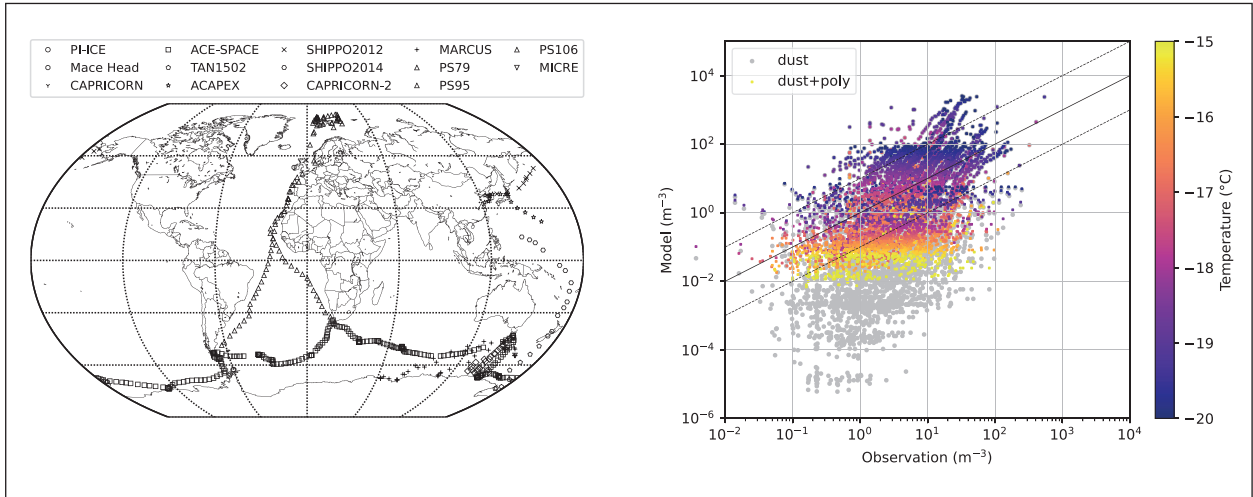


Fig. 3: Campaigns and locations of measured INP concentrations (left) and modeled in comparison with observed INP concentrations between  $-15$  °C and  $-20$  °C (right). The source of Fig.3 is HSZ25 and SI which can be found <https://pubs.acs.org/doi/10.1021/acs.est.4c08014>, for reuse permission is needed from ACS.

mineral dust across most marine regions, particularly in the Southern Hemisphere. The relevance of marine polysaccharides decreases with decreasing temperature as mineral dust becomes more important as INP. As a main conclusion, in remote marine regions ice nucleating polysaccharides are an important contributor to the atmospheric INP population in a temperature range relevant for mixed-phase clouds.

### Implications for INP modeling

We show that in the remote marine atmosphere a significant fraction of ambient INP number concentration from  $-15$  °C to  $-20$  °C can be described by a single chemical component - marine ice nucleating polysaccharides. The applied parameterization function based on classical nucleation theory

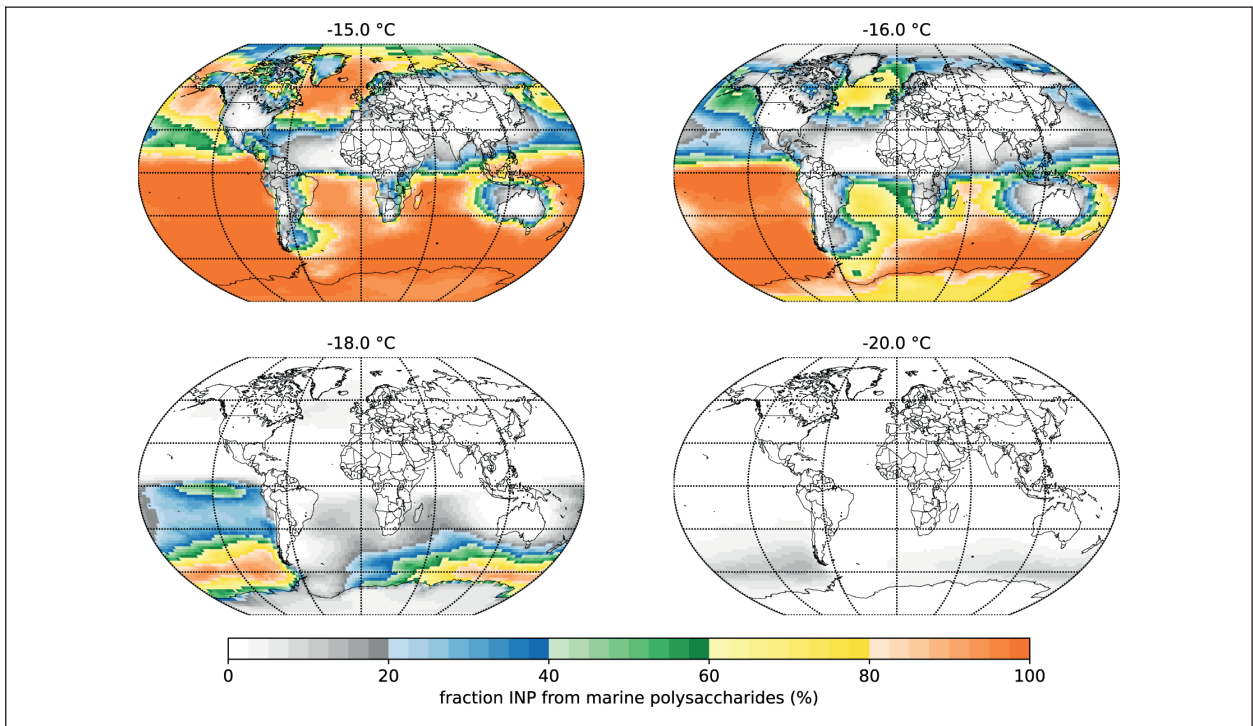


Fig. 4: Fraction of INP derived from marine polysaccharides per sum of modeled INPs (mineral dust + marine polysaccharides) in the lower most model layer. Annual mean INP concentrations were obtained from polysaccharides estimated via sea salt concentrations and mineral dust simulated by a global model. The source of Fig.4 is HSZ25 which can be found <https://pubs.acs.org/doi/10.1021/acs.est.4c08014>, for reuse permission is needed from ACS.

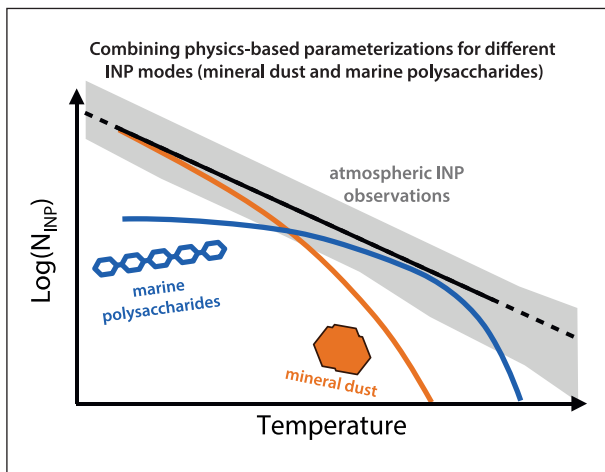


Fig. 5: Sketch of parameterization concept. Fig. 5 is adopted from HSZ25, <https://pubs.acs.org/doi/10.1021/acs.est.4c08014>.

has advantageous properties, i.e., it can reproduce natural INP-specific limits such as a realistic onset of freezing and an upper concentration at low temperature (Fig. 5). This concept is also applicable to other sources of INP types, allows for a combination of

multiple INP types (Fig. 5) enabling a reproduction of multimodal or seemingly linear behavior on the log-scale and facilitates a time-dependent description using ice nucleation rates. This study presents a new approach to improve process understanding of atmospheric ice formation by describing the total INP concentration using a combination of chemical classes that are causally linked to ice nucleation. The substantial impact of biological aerosol constituent on the atmospheric INP budget highlights the relevance of coupling of biosphere and atmosphere. In future, we expect a reduction of anthropogenic aerosol emissions and hence aerosol from natural sources will become even more relevant for mixed-phase cloud microphysics and cloud radiative forcing.

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## Cooperation

Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany: Atmospheric Microphysics Department, Department of Modeling Atmospheric Processes, Atmospheric Chemistry Department  
Department of Arctic and Marine Biology, UiT – The Arctic University of Norway, Tromsø, Norway

# A scalable two-way coupled Euler-Lagrange particle tracking algorithm

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**Disperse Mehrphasenströmungen sind allgegenwärtig in Naturvorgängen sowie in technischen Anwendungen. Die Euler-Lagrange-Methode (EL) ist ein numerischer Ansatz zur Modellierung dieser Strömungen. Hierbei wird die kontinuierliche Phase in einem Euler-Netz berechnet, während die disperse Phase mit einem Lagrange'schen Ansatz behandelt wird. Eine zweiseitige Kopplung, bei der beide Phasen aufeinander einwirken, ist entscheidend für die genaue Simulation von Systemen wie Wolken oder anderen Partikelströmungen. Trotz ihrer Einfachheit ist die EL-Methode rechenintensiv. Moderne heterogene Hochleistungsrechner mit CPU-GPU-Kombinationen wurden bisher nicht optimal für EL-Simulationen genutzt, da Herausforderungen wie Synchronisationsbarrieren, Lastverteilung und mangelnde Skalierbarkeit bestanden. Um diese Probleme zu lösen, wurde der Algorithmus SCALE-TRACK (Scalable two-way coupled Euler-Lagrange particle tracking algorithm) entwickelt. Er nutzt asynchrone Kopplung, chunk-basierte Partitionierung und cachefreundliche Datenstrukturen, um effiziente EL-Simulationen auf Exascale-Systemen zu ermöglichen. Exzellente starke und schwache Skalierung konnten auf einem High-Performance-Computing-**

## **Cluster mit bis zu $256 \times 10^9$ Partikeln auf 256 GPUs nachgewiesen werden.**

Disperse multiphase flows are ubiquitous in natural phenomena such as aerosol dispersion, sediment transport, and cloud formation, as well as in technological applications like inhalers, mixing processes, and internal combustion engines. The Euler-Lagrange (EL) method is a key numerical approach for modelling these flows, where the continuous phase (e.g., gas or liquid) is solved in an Eulerian framework, while the dispersed phase (e.g., particles or droplets) is tracked in a Lagrangian framework [Crowe *et al.*, 1977]. Two-way coupling, where both phases influence each other, is essential for accurately simulating clouds [Chen *et al.*, 2025] or other turbulent particle-laden flows [Michaelides *et al.*, 2017].

Despite its simplicity, the EL method is computationally intensive. Modern heterogeneous high-performance computing (HPC) architectures (combining CPUs and GPUs) have not been fully leveraged for EL simulations due to challenges like synchronization

barriers, load imbalances, and poor scalability.

To address these limitations, the SCALE-TRACK algorithm was developed. It employs asynchronous coupling, chunk-based partitioning, and cache-optimized data structures to enable efficient exascale EL simulations, which will be explained below.

## **Algorithm description**

SCALE-TRACK is implemented in Julia, using coroutines for asynchronous task management. It interfaces with OpenFOAM® for Eulerian simulations, receiving fluid fields and feeding back Lagrangian source terms. CPUs handle communication and scheduling, while GPUs execute particle tracking.

## **Domain Decomposition and Data Structure.**

SCALE-TRACK decouples the partitioning of Eulerian and Lagrangian domains. Unlike traditional methods where partitions align for both phases, Lagrangian partitions ("chunks") can overlap and dynamically adjust. Each chunk represents a subset of particles

enclosed in rectangular bounding boxes, enabling efficient identification of required Eulerian data and minimizing communication overhead.

SCALE-TRACK uses structure of arrays data layouts, optimising vectorisation and memory access. Chunk sizes and distributions are dynamically optimised to balance computational load and reduce inter-node communication. Particles are initialized using a Hilbert curve method to ensure compact spatial distribution.

**Asynchronous Two-way Coupling.** SCALE-TRACK processes Eulerian and Lagrangian phases independently on CPUs and GPUs, respectively, with reduced synchronization barriers. The Eulerian phase is solved on CPUs using fluid dynamics equations, incorporating either the actual current source terms (e.g., momentum) from the Lagrangian phase, or predicted values, if the source terms are not available yet. Meanwhile, the Lagrangian phase is computed on GPUs, where particles are tracked using the latest available Eulerian data. Source terms from the Lagrangian phase are asynchronously exchanged with the Eulerian solver, eliminating the need for synchronized time-step alignment. This decoupled approach allows both phases to progress at their own pace, maximizing resource utilization. Introduced numerical discrepancies are addressed through the predictor-corrector method.

**Predictor-Corrector Method for Error Reduction.** To mitigate errors from asynchronous updates, SCALE-TRACK employs a predictor-corrector scheme. Source terms for the current time step  $S_{est,n}$  are estimated by extrapolating from prior values as  $2S_{n-1} - S_{est,n-1}$ , where  $S_{n-1}$  is the true source from the previous time step and  $S_{est,n-1}$  is the prior prediction. This formulation leverages the assumption of gradual temporal changes in source terms, ensuring conservation over time.

### Validation

A test case involving moving particles in a quiescent fluid was compared to an analytical solution. Without error correction, asynchronous coupling introduced significant discrepancies in both phases. The predictor-corrector method reduced these errors to  $\sim 0.1\%$ , matching the precision of conventional EL simulations.

SCALE-TRACK was benchmarked against OpenFOAM® in a cloud chamber simulation (Fig. 1). The test case modelled buoyancy-driven flow with two-way coupling for momentum, heat, and mass transfer. While OpenFOAM® could only track  $0.14 \times 10^9$

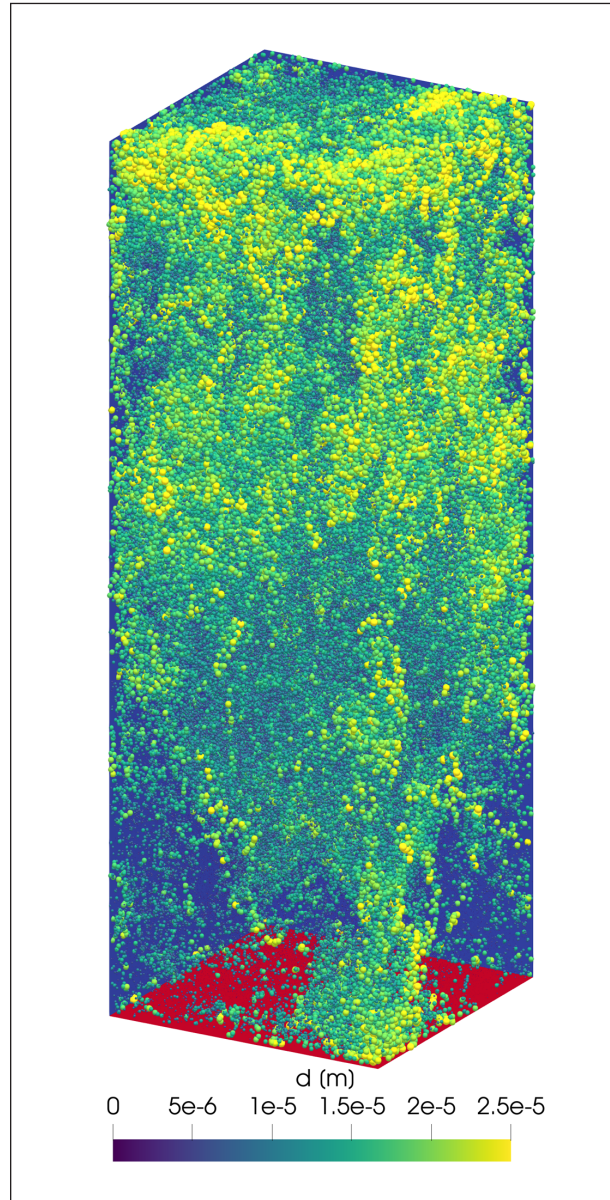


Fig. 1: Snapshot of the simulated convection cloud chamber, showing colour coded diameters and positions of randomly selected droplets (size not to scale).

particles due to memory constraints, SCALE-TRACK simulated  $1.4 \times 10^9$  particles on a single GPU workstation. Key parameters like temperature and water vapor density matched OpenFOAM® results within 0.5%, demonstrating the algorithm's fidelity. For the Lagrangian part, a speed-up factor of 110 was realised.

### Scaling

Scaling runs were performed on MareNostrum5. For strong scaling,  $8 \times 10^9$  particles were distributed across up to 256 GPUs and 2,560 cores on 64 nodes (Fig. 2 left). The Lagrangian phase scaled nearly perfectly even at as low as  $0.312 \times 10^9$  particles/GPU.

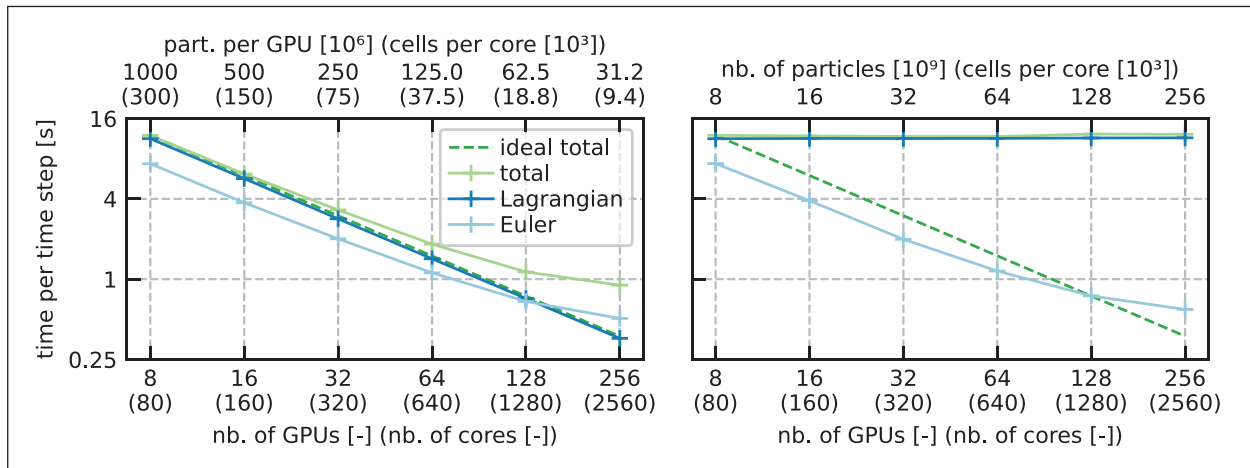


Fig. 2: Results from scaling runs on Mare Nostrum 5. Left: Strong scaling with  $8 \times 10^9$  droplets and  $24 \times 10^6$  cells. Right: Semi-weak scaling with  $1 \times 10^9$  droplets per GPU and  $24 \times 10^6$  cells.

The Eulerian phase showed minor deviations below 40,000 cells/core due to increasing communication costs, a common limitation in such simulations.

“Semi”-weak scaling runs were performed with a fixed Eulerian problem size ( $24 \times 10^6$  cells) and  $1 \times 10^9$  particles/GPU (Fig. 2 right). Computational time per time step remained stable as the number of GPUs increased. The total runtime scaled nearly ideally, driven by the efficient parallelization of particle tracking. The highest particle count was  $256 \times 10^9$  on 256 GPUs.

## Conclusion

SCALE-TRACK represents a breakthrough for EL simulations, combining asynchronous coupling, dynamic chunk partitioning, and heterogeneous architecture optimization. It achieves unprecedented scalability, while accelerating Lagrangian calculations by two orders of magnitude and pushing tractable particle numbers beyond current limitations, enabling high-fidelity applications from cloud modelling to industrial processes.

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## Cooperation

Wikki GmbH, Wernigerode

# Microphysical sensitivities of tropical storms in ICON based on Hurricane Paulette (2020)

Roxana Cremer and Fabian Senf

**Tropische Stürme sind nicht nur beeindruckende Phänomene, sondern auch interessante Fallstudien für mikrophysikalische und dynamische Prozesse in Modellen. Hier wurde der Kategorie 2 Hurrikan Paulette, der im September 2020 auftrat, in unterschiedlichen Konfigurationen simuliert und mit Satellitendaten verglichen. Das Modell kann die Zugbahn von Paulette über einen langen Zeitraum sehr gut wiedergeben. Vor allem der Eisanteil in den Wolken wird jedoch unterschätzt. Während die Ergebnisse einen guten Ansatz bilden, zeigt die Analyse die Schwächen in der Eismikrophysik. Hier besteht Verbesserungspotential, sowohl was das Verständnis der Prozesse und ihrer Zusammenhänge angeht, als auch bei deren Beschreibung in ICON. Durch hoch aufgelöste Simulationen und die Einbindung der spektralen Bin-Mikrophysik SPECS in ICON werden neue Datensätze zur Analyse ermöglicht, die zuvor in dieser Form nicht verfügbar waren.**

## Introduction

Tropical cyclones are impressive phenomena of tropical meteorology and form spatially highly organized structures. To shed more light on microphysical sensitivities and dynamical structure when modelling these storms, the BMBF-funded project IFCES2 built new infrastructure within the German weather and climate model ICON. Parallel execution, communication, and dynamic load balancing is improved to enable high resolution simulations of complex cloud system such as tropical cyclones. Additionally, the spectral bin-microphysics scheme SPECS was coupled to ICON to produce a new dataset of detailed cloud microphysics of one hurricane case study.

## Method

The case study we selected is Hurricane Paulette, which occurred in the North-Atlantic basin in September 2020 and is the longest-lasting tropical cyclone of that year (7-22nd September). Paulette was simulated over one week to catch the storm's evolution with ICON in a limited area mode on a horizontal resolution of 5 km and 2.5 km with several perturbations. The simulations perturb the Cloud Condensation Nuclei (CCN) type and concentration as well as the number of levels, which are defining the vertical resolution of the model. Following the simulations, the hurricane's path was calculated for each experiment

using the tracking tool *tobac* [Heikenfeld *et al.*, 2019; Sokolowsky *et al.*, 2024] based on the relative vorticity of the system and then compared to the observational track of the hurricane [Stewart, 2021] which allows an analysis of the data along the track. Next to experiments with microphysical perturbations and changes to the vertical resolution of the model, the horizontal grid spacing is reduced to hectometre scale.

While global simulations can be performed at horizontal resolutions of approximately 5 km [Weiss *et al.*, 2025] using simplified microphysical schemes, limited-area approaches increasingly push toward higher horizontal resolutions to enable more detailed representations of cloud systems, even on larger-scale. In our work, a new set of simulations were started with higher horizontal resolutions (1.2 km, 600 m, 300 m) based on the calculated tracks.

## Results

The analysis of storm evolution demonstrates that wind speed plays a key role in storm development and deepening. The model setup shows strong internal consistency across the ensemble for the 5 km simulation. At higher resolutions, a broader range of wind speeds emerges across experiments (see Fig. 1 b), offering valuable insight into sensitivity to resolution and model configuration. Across all simulations, wind speeds are systematically lower

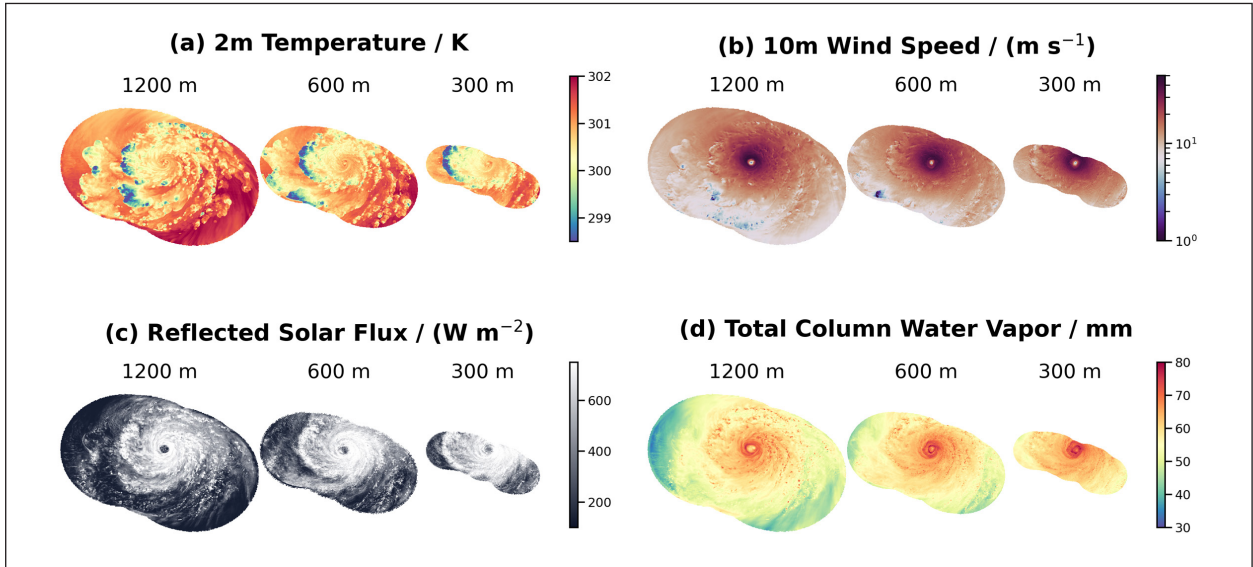


Fig. 1: High-resolution simulation of hurricane Paulette in three horizontal resolutions (1.2 km, 600 m, 300 m) showing the 2m temperature (a), 10 m wind speed (b), reflected solar flux (c) and total column water vapour (d).

than observed, and several simulations of Hurricane Paulette do not reach Category 2 on the Saffir–Simpson scale, which contributes to a slower storm evolution in the model.

Overall, the model captures the large-scale storm structure well, though cloud production is sensitive to

changes in the perturbations of CCN concentrations and adjustments to ICON’s vertical level number. This behaviour becomes evident in the vertical storm structure (Fig. 2), where CCN concentrations influence the horizontal extent and intensity of cloud cover and total cloud mixing ratio. Adjustments to ICON’s vertical levels affect the vertical extent of clouds and

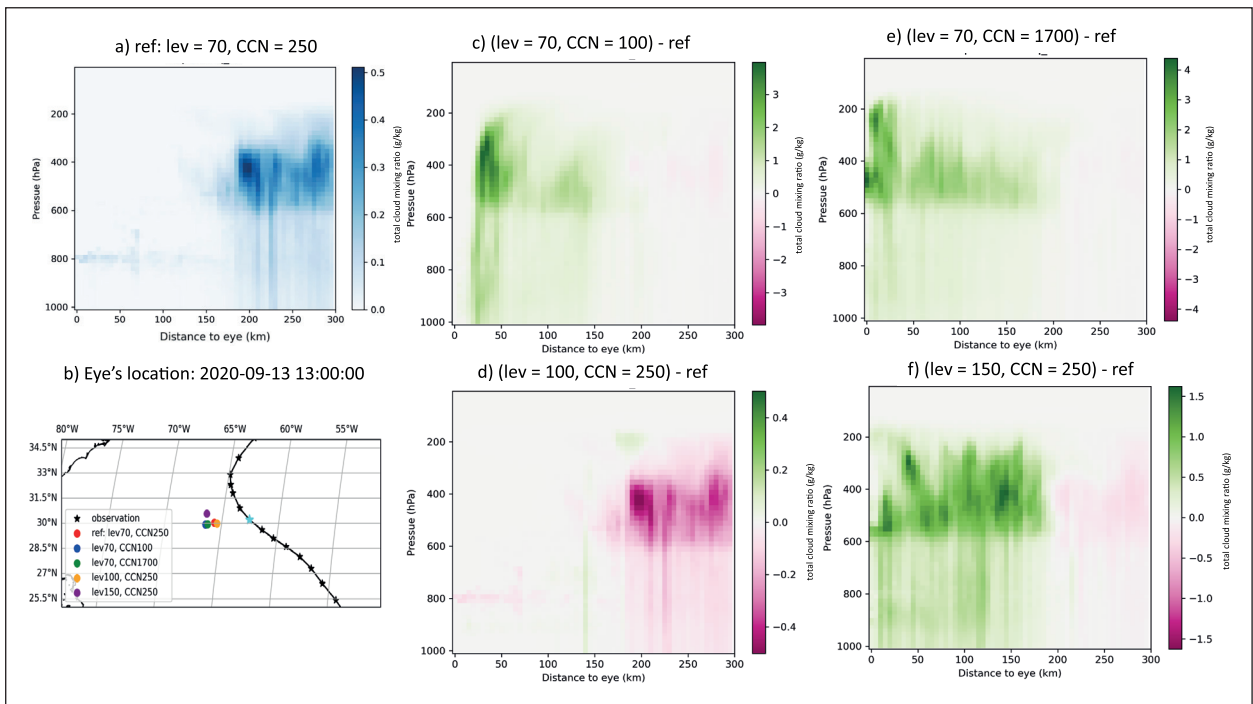


Fig. 2: Vertical distribution of simulated total cloud mixing ratio depending on the distance to the hurricane’s eye. Shown are the reference experiment (a), with the difference of the experiments and the reference (c-f) and the location of the experiment’s eye of the hurricane at the 13th September 2020 at 13 UTC (b). The reference simulation (a) is setup with 70 vertical levels and a CCN concentration of 250, this simulation was subtracted from (c) with 70 vertical levels and 100 CCN, (d) 100 vertical levels and 250 CCN, (e) 70 vertical levels and 1700 CCN and (f) 150 vertical level and 250 CCN.

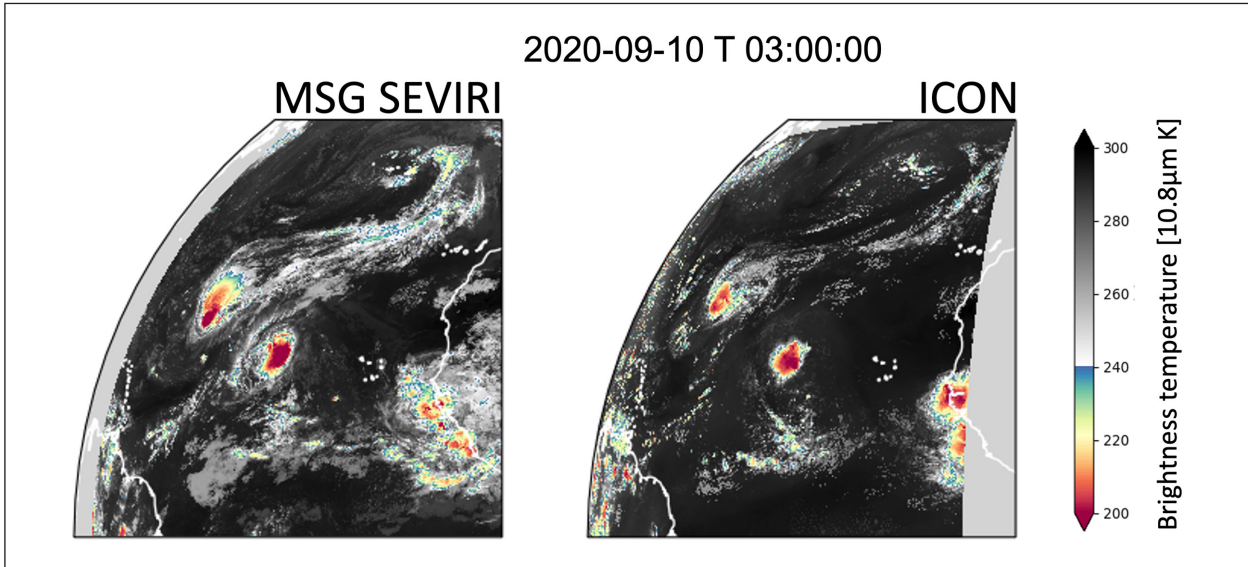


Fig. 3: Brightness temperature comparison of geostationary satellite MSG SEVIRI and ICON simulation transformed into satellite-view for the 10th of September 2020 3am UTC.

appear to limit cloud development, highlighting areas for further refinement.

Comparison with satellite observations shows good agreement in the liquid water path, indicating that warm-cloud processes are well represented. Differences arise in the ice water path, where ice formation is weaker or ice mass dissipates more rapidly than observed. Figure 3 presents ICON simulations rendered to resemble geostationary satellite imagery (MSG SEVIRI). While the simulated storm locations over the Atlantic align well with observations, cloud coverage is lower than seen in satellite data.

In conclusion, the framework developed within ICON provides a strong foundation for investigating storm microphysics at high resolution in limited areas. Integrating SPECS into ICON adds an important new dimension for studying storm microphysical processes and offers promising opportunities to improve cloud microphysics representation, particularly cold-phase processes such as ice formation, growth, and loss within clouds.

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## Cooperation

Multiple national project partners

# Cloud 3D Structure And Radiation (C3SAR) - A new initiative to account for 3D cloud radiative effects

Andreas Macke, Hartwig Deneke, Johannes Hoppich, Anja Hünerbein, Jörg Schmidt, Fabian Senf, Kolja Wagner, Gregor Walter, Jonas Witthuhn

Die DFG Forschungsgruppe C3SAR arbeitet an einer physikalisch basierten Korrektur von Fehlern in der Strahlungsmodellierung und der Fernerkundung von Wolken, die aus einer zu starken Vereinfachung der komplexen geometrischen und mikrophysikalischen Eigenschaften von Wolken in früheren Arbeiten resultieren. Charakteristische 3D-Wolkenstrukturen für unterschiedliche Wolkenregime aus wolkenauflösenden Atmosphärenmodellen und aus synergistischen Satellitenbeobachtungen dienen als Input für Strahlungstransfermodelle unterschiedlicher Komplexität, um die Folgen von Vereinfachungen der Wolkenstruktur zu quantifizieren und physikalisch basierte Wolken-Strahlungs-Korrelationen zu ermitteln. Langfristige, hochwertige bodengestützte Wolken- und Strahlungsbeobachtungen über Deutschland in Kombination mit neuartigen Techniken zur gleichzeitigen Messung der spektralen Strahlungsintensität ermöglichen die Validierung dieser Beziehungen mittels Strahlungsschlussstudien. Aktuelle und neue Generationen von Satellitensensoren liefern die entsprechenden Schließungen am Oberrand der Atmosphäre. Eine groß angelegte Feldkampagne im Sommer 2026 in Lindenberg, Deutschland wird Modellierung, bodengestützte und satellitengestützte Fernerkundung sowie In-situ-Strahlungsmessungen in einer synergetischen Schließungs-Studie zusammenführen, um unsere Fähigkeit zur Beobachtung, zum Verständnis und zur Modellierung der Strahlungseffekte von Wolken zu validieren und damit eine wichtige Quelle der Unsicherheit bei der Vorhersage des zukünftigen Klimas zu reduzieren.

## Motivation and previous work

With a global coverage of 67% to 70% [Stuberach *et al.*, 2017] and an average net (solar and terrestrial) cloud-radiative effect of -18 to -20 Wm<sup>-2</sup> [Henderson *et al.*, 2013; Stephens *et al.*, 2012; Zelinka *et al.*, 2017] clouds play a dominant role in determining the radiation budget and thus the climatic conditions of our planet. The urgent need to understand clouds has driven many long-term and internationally coordinated programmes (e.g., “Earth Radiation Budget Experiment” ERBE, “International Satellite Cloud Climatology Project” ISCCP) to capture the global cloud distribution as well as their radiative effects, often termed as cloud radiative effects, from satellite observations. Still, the exact magnitude of this cloud radiative effects, its regional and temporal distributions are not well understood due to the complex spatiotemporal variability of cloud amount, type and microphysical properties over all scales, which cannot be resolved neither from satellite sensors nor from global modelling approaches. Instead, for satellite remote sensing methods and for large scale modelling to be feasible, clouds are

simplified as plane-parallel homogeneous objects. On the other hand, numerous studies have demonstrated that these common simplifications of cloud geometry led to strong biases in the mean radiation fields [Scheirer and Macke, 2003; Barker *et al.*, 2003] and furthermore fully neglect their radiation noise resulting from their natural spatiotemporal variability. The latter in fact points also to a missing physics in climate modelling, as non-linear systems such as our Earth’s system may respond differently to noisy cloud radiative forcing compared to a mean forcing. Deneke *et al.* [2008] applied a wavelet-based multi-resolution analysis to demonstrate that the correlation of fluxes at the top-of-atmosphere breaks down at high resolutions, representing a fundamental limitation for satellite retrievals of surface fluxes. Based on the same methodology, Madhavan *et al.* [2017] investigated the scale dependence of small-scale variability in surface irradiance based on a unique pyranometer network developed at TROPOS, and its effects on spatial and temporal averaging. Based on 3D-radiative transfer for a large number of 3D cloud fields from cloud resolving atmospheric modelling, Schewski and Macke [2003]

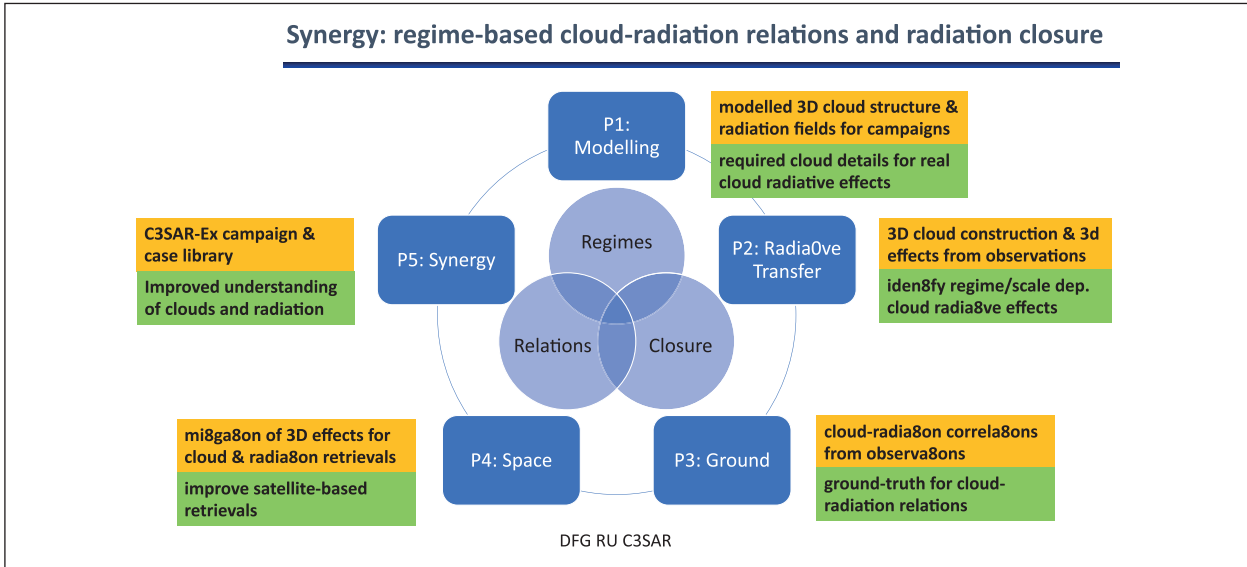


Fig. 1: General interplay of the individual subprojects in the research unit.

were able to show that the domain averaged (and thus climatologically relevant) cloud radiative effects can be explained with only few domain-averaged cloud physical properties to a surprisingly high degree of accuracy. The aim of C3SAR is to derive similar cloud-radiation correlations from state-of-the-art modelling and observations for characteristic 3D cloud regimes and to apply those to climate modelling and passive remote sensing.

**Objectives**

The main goal of this cooperative task is to better understand the role of 3d cloud variability and to provide robust tools in cloud remote sensing and cloud radiative forcing parameterization that account for 3d radiative effects in a feasible and realistic manner. This is achievable only if high resolution modelling and observations of clouds and their radiative properties is working together hand in hand for a sufficiently large amount of 3d cloud scenarios, that covers the major cloud regimes and their natural variability. While such scenarios have previously been available from modelling studies only, they can now also be provided or will soon be available from networks of ground-based remote sensing as well as satellite-based remote sensing on a global scale. So-called atmospheric supersites like the Lindenberg Observatory and further observatories in Germany and Europe in the framework of ACTRIS already provide valuable high-resolution cloud and radiation information and will be substantially updated as part of the national ACTRIS roadmap activities in the next years.

In parallel with the development of observational techniques, spatiotemporal high-resolution modelling has experienced significant breakthroughs in recent

years. First, in the area of regional modelling, it has become possible to describe atmospheric processes, including cloud processes, on incredibly fine hectometer scales.

The work programme in this first phase of C3SAR aims at method developments towards the establishment of physically consistent cloud-radiation relations, a thorough validation by means of co-located 3d-cloud and radiation observations from a joint major field campaign, and first application of the improved cloud-radiation correlations to remote sensing and cloud radiative forcing modelling. The anticipated second phase will apply the improved cloud-radiation relations to specific cloud remote sensing (space-borne and ground based) and characteristic climate areas (cloud generation, low pressure systems, trade wind cumulus, ...). In the end, a global consideration of cloud remote sensing and cloud radiative forcing in climate models with account of 3d effects is anticipated. To address these research goals, five research projects have been designed. Fig. 1 provides a visual schematic of the individual projects and their interplay with each other. A more detailed description of the work programme can be found Macke et al. [2025]

**First results**

C3SAR is a cooperation between TROPOS, the Ludwig-Maximilians-Universität München, the Universität zu Köln, the Leibniz Universität Hannover, and the Deutscher Wetterdienst in Lindenberg and Offenbach. Due to the limited space of a short report, only the work of TROPOS is presented here. It is planned to provide the major outcome of C3SAR as a whole in the next biannual report of TROPOS.

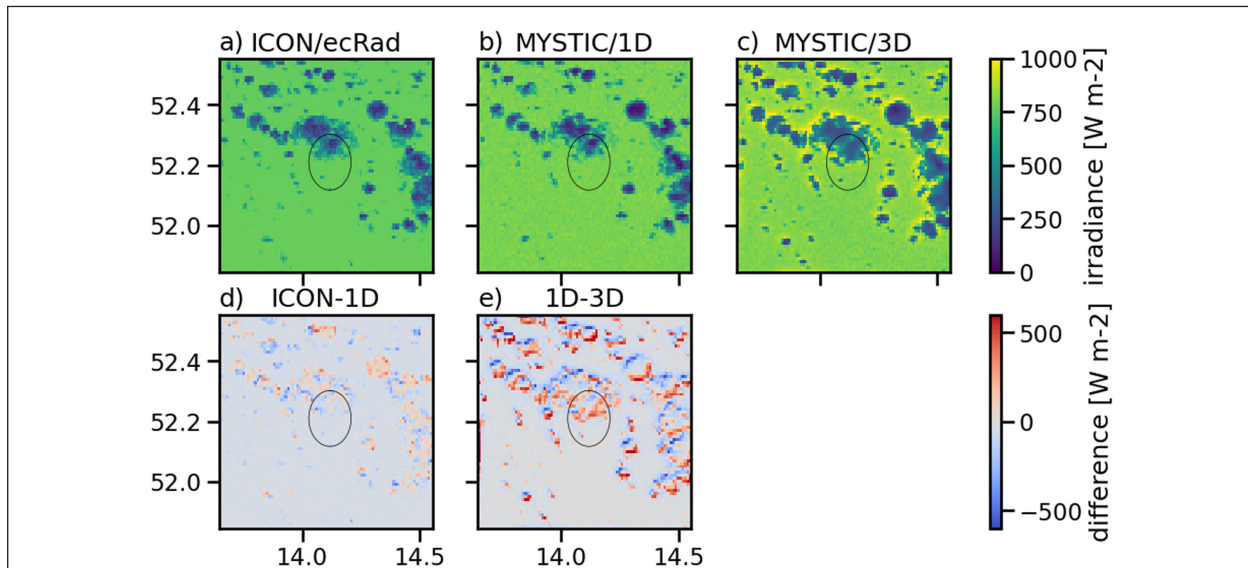


Fig. 2: Short wave surface solar irradiance at 10:00 on 2024-08-06. The 15km radius around Lindenberg is marked. Panel (a) shows results from ICON/ecRad; (b) and (c) show MYSTIC simulations based on ICON cloud data, using the independent column approximation and full 3D radiative transfer. Panel (d) displays the difference between ICON and MYSTIC 1-D results while (e) show the difference between 1D and 3D.

**Project P1 “Modelling of cloud microphysical properties and their radiative effects”:** Modelling the 3D cloud radiative effects is performed as a two-step process: First an ICON-LAM simulation is setup centered at the Lindenberg observatories with three nests of grid resolutions of 1000m, 500m and 250m. The ICON model is run for selected cumulus cloud cases and input parameter are calibrated using observational data provided by the observatory. The cumulus clouds form roughly within the same time period, and the deviation between simulated and observed cloud cover values is less than 15%.

In a second step, ICON cloud microphysics and atmospheric profiles are forwarded to the Monte Carlo solver MYSTIC. This method allows to compare Independent Column Approximation (ICA) and fully 3D radiative calculations. Figure 2 shows a comparison between ecRad (which is the ICON-internal radiation scheme) and MYSTIC for short wave surface solar irradiance at 10 UTC (06 August 2024). Figure 2d) shows the difference between ICON/ecRad irradiance and MYSTIC 1D, both based on the independent column approximation. The source of the constant offset of  $-30\text{Wm}^{-2}$  might be due to differences in the atmospheric extinction properties, including aerosol optics. Figure 2e) shows the difference between the 1D and 3D MYSTIC simulation with differences up to 50% at the cloud edges. These 3D effects are up to twice as high as the model differences. This framework enables physically consistent 3D radiative studies on regional scales larger than most large-eddy simulations and with more realistic cloud scenes than previous idealized studies.

**Project P2 “Structure and Regime dependencies of 3D radiative effects”:** The long-term and high resolution satellite-based Cloud property dAtAset using SEVIRI [CLAAS-3, Benas et al., 2023] is used to identify cloud regimes and to relate those to their characteristic cloud radiative effects. Toward this goal, a Cloud Regime dAtAset based on CLAAS-3 (CRAAS-3) has been created, which builds on its predecessor CRAAS [Tzallas et al., 2022, based on CLAAS-2, Benas et al., 2017]. It is based on joint cloud property histograms of cloud optical thickness, cloud top pressure and thermodynamic phase derived from CLAAS-3 over the European region. Histograms of twenty years of observed daytime cloud scenes are clustered with a refined k-means method into 8 distinct cloud regimes, represented by their centroids, which are the prototypical joint cloud histograms for each regime. This permits analysis of regionality, diurnal and seasonal cycle and long-term trends of cloud regime occurrence as well as their radiative and structural properties, when combining the dataset with complementary measurements.

Fig. 3 (upper plot) shows the average occurrence of the broken cumulus cloud regime in 2015 over Europe. One can easily identify the augmented prevalence of this cloud regime over the sea, along coastlines and over large inland bodies of water particularly over northern Africa. The lower plot shows the centroid of this regime, with red indicating liquid and blue indicating ice cloud tops. It has a cloud fraction of around 46%. The joint cloud histogram suggests that the co-occurrence of broken cumulus

and thin cirrus is common over the investigated domain.

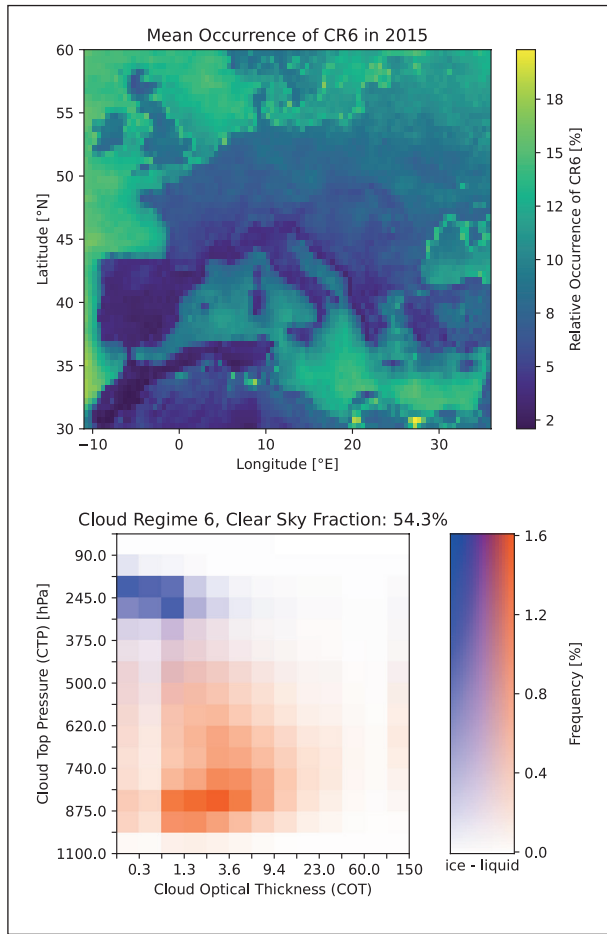


Fig. 3: upper plot: average occurrence of the broken cumulus cloud regime in 2015 over Europe; lower plot: corresponding centroid of this regime.

**Project P4 “Satellite-based cloud remote sensing and 3D effects”:** Cloud properties retrieved from imaging spectrometers are commonly based on simplified one-dimensional assumptions. This is the case for the Multi-Spectral Imager (MSI) onboard the EarthCARE satellite, where pixels are processed independently and clouds are treated as horizontally and vertically homogeneous, leading to inaccuracies in retrieved quantities such as ice water content and effective radius [Hünerbein et al., 2023]. Therefore, cloud structure information contained in MSI data is not exploited.

EarthCARE also carries a cloud profiling radar and a lidar, instruments that provide detailed vertical cloud cross sections along the satellite track. With the synergistic use of these instruments [Mason et al., 2023] more accurate reference values can often be obtained.

Measures of horizontal cloud structure, such as the brightness temperature gradient (representing the slope of the cloud top) and cloud fraction, are combined with pixel-level MSI information to quantify deviations between MSI-only retrievals and the synergy product using XGBoost, a statistical machine learning approach.

Figure 4 shows that accounting for cloud structure improves the estimation of the integrated ice water content of ice clouds, thereby highlighting that imagers contain additional information that is not used in standard cloud property retrievals.

**Project P5 & P6 “3D field campaign and C3SAR coordination”:** The C3SAR field campaign, scheduled from mid-April to August 2026, aims to capture the atmosphere as accurately as possible for use in LES and radiation transfer modeling. We hope

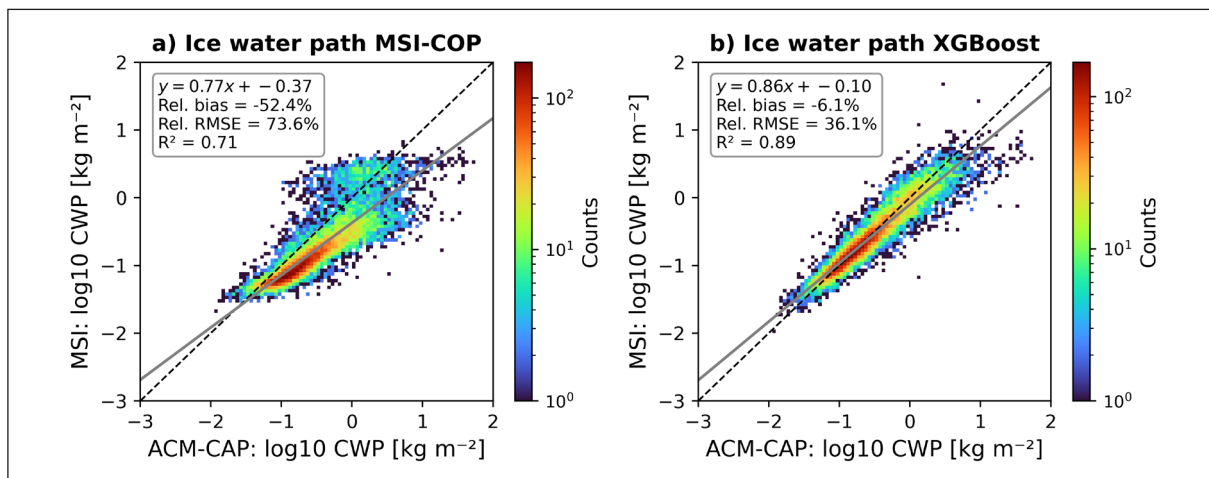


Fig. 4: Comparison of ice water path derived from the ACM-CAP synergy product and from the MSI-only retrieval using the independent pixel approximation (a). In (b), the MSI-derived ice water path is adjusted with additional MSI information, including cloud structure parameters, using the XGBoost machine-learning model.

for a variety of cloud regimes during the campaign period to study their 3D radiative effects. Reference radiation measurements will be taken at Lindenberg, while the Cloudnet suite, including radar, lidar, and microwave radiometer, will be operated at both the Falkenberg and Lindenberg sites. Small-scale variability of solar irradiance is resolved by the pyranometer network PyrNet. Cloud structures are reconstructed stereoscopically from cameras deployed at the two locations. In addition, satellite-based cloud and radiation products from EarthCARE and MTG will

be used. Ultimately, radiation closure integrates satellite remote sensing, ground-based observations, and model outputs. During the campaign, we run a summer school on “3d Radiative Transfer in the Cloudy Atmosphere” at the Lindenberg Meteorological Observatory. From 6 to 12 July, about 12 scientists from the national and international research community will give lectures and run practical exercises. They will cover a broad spectrum of modelling, 3d radiative transfer calculations, remote sensing and cloud in-situ measurements.

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# Exploring methane loss via iron-enhanced multiphase halogen chemistry using CAPRAM-SPARK

Sherin Bran, Marvel Aiyuk, Andreas Tilgner, Hartmut Herrmann

**Diese Studie untersucht den Methanverlust durch eisenverstärkte mehrphasige Halogenchemie unter Verwendung des CAPRAM-SPARK-Modells. Die Photolyse von Eisenchloridkomplexen verstärkt den reaktiven Chlorzyklus in der wässrigen und gasförmigen Phase, wobei  $\text{FeCl}^{2+}$  als wichtiger Chloraktivierungsweg fungiert. Die Chlorproduktion wird stark von der Aerosol-Säure und dem Phasengleichgewicht beeinflusst. Trotz der verstärkten Chloraktivierung wird die Methanoxidation weiterhin von OH dominiert, und die Eisenchloridchemie hat unter den untersuchten Bedingungen nur einen begrenzten Einfluss auf die gesamte Methanentfernung.**

## Introduction

Methane ( $\text{CH}_4$ ) is a major contributor to global warming, and its effective removal from the atmosphere requires strengthening existing oxidation pathways or developing new ones. Chlorine (Cl) atoms represent a promising but still underexplored sink for  $\text{CH}_4$ , as they react much faster with methane than hydroxyl (OH) radicals and are less affected by competing reactions with CO [Burkholder *et al.*, 2020]. Recent global modeling studies suggest that enhanced Cl atom concentrations, for example through direct  $\text{Cl}_2$  emissions from the ocean, could substantially reduce atmospheric methane [Li *et al.*, 2023b]. However, such approaches lack realistic chemical mechanisms and assessments of potential side effects.

In the atmosphere, Cl atoms are produced through the formation and photolysis of reactive chlorine species (RCS) originating from particulate chloride via complex multiphase chemistry (Fig. 1). Two main activation pathways have been identified: photochemical reactions involving reactive nitrogen species, which can negatively affect air quality [Peng *et al.*, 2022], and iron–sea-salt interactions, which provide a promising route to enhance Cl atom production and  $\text{CH}_4$  removal [Wittmer *et al.*, 2015].

Iron–halogen multiphase chemistry strongly depends on aerosol acidity and liquid water content and is well represented within the Chemical Aqueous Phase Radical Mechanism (CAPRAM) framework [Bräuer *et al.*, 2013]. Extending CAPRAM to include recent advances in iron–halogen chemistry enables a realistic assessment of the feasibility, efficiency, and risks of chlorine-based methane mitigation under diverse atmospheric conditions.

## Methodology

This study investigates Cl atom activation via iron–chloride multiphase chemistry using the in-house aqueous-phase chemical mechanism CAPRAM, coupled with the gas-phase Master Chemical Mechanism (MCM) within the box model SPACCIM (Wolke *et al.*, 2005), hereafter referred to as CAPRAM–SPARK. The model explicitly represents the formation and equilibrium of iron–chloride complexes ( $\text{FeCl}^{2+}$ ,  $\text{FeCl}_2^+$ ,  $\text{FeCl}_3$ ,  $\text{FeCl}_4^-$ ) based on published thermodynamic and kinetic data [Martell and Smith, 1974; Yatsimirskii, 2012; Stefánsson *et al.*, 2019].

Photolytic decomposition of iron–chloride complexes is implemented to generate Cl radicals over the wavelength range 280–700 nm, with a quantum yield of 1 following Mikkelsen *et al.* [2024].

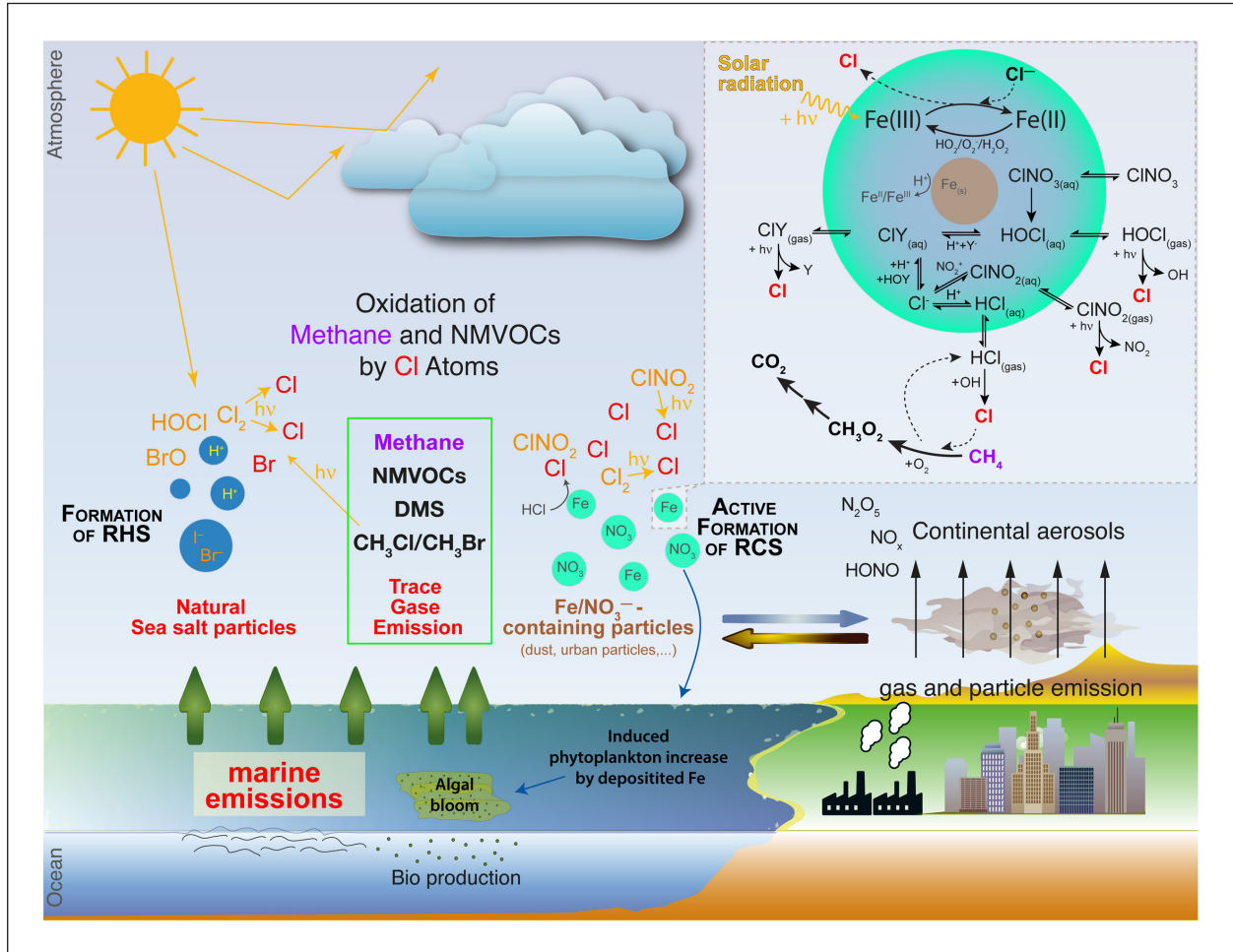


Fig. 1: Atmospheric chemical interaction of methane with reactive halogen species.

To assess the controlling factors of Cl atom formation, a series of sensitivity simulations is performed, systematically varying acidity, changing initial concentration, cloud presence, and photolysis parameters.

These simulations enable a detailed analysis of iron-chloride multiphase chemistry and its role in Cl activation under diverse atmospheric conditions.

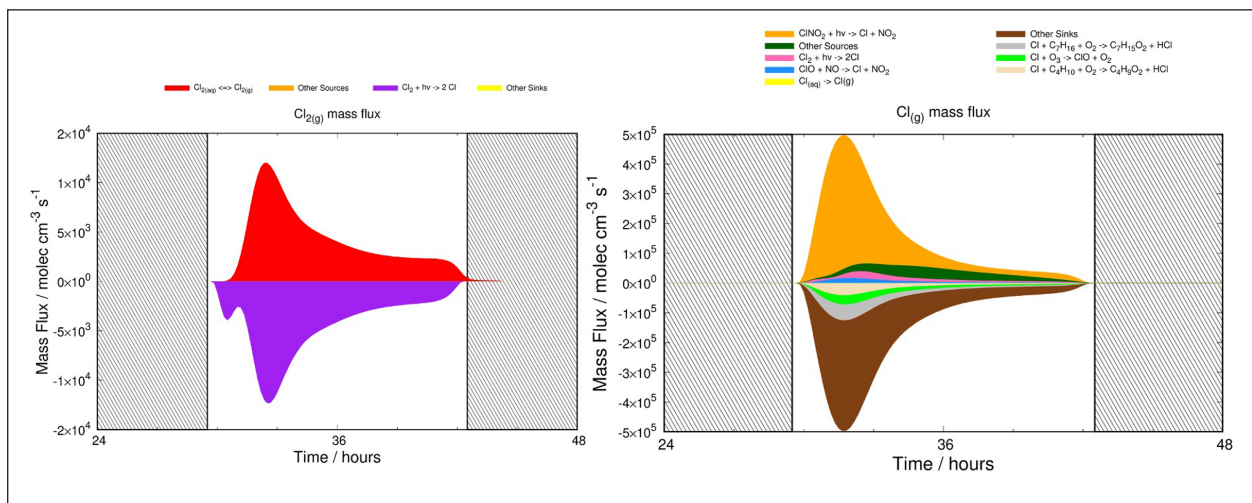


Fig. 2: Sources and sinks of gas-phase reactive Cl<sub>2</sub> and Cl mass flux.

## Results and Discussion

Simulations including the newly implemented iron–chloride complex chemistry show only a minor contribution to total aqueous-phase Cl atoms. Nevertheless, mass flux analysis identifies  $\text{FeCl}^{2+}$  photolysis as the second most important Cl source, after  $\text{HOCl}$  photolysis. The net Cl concentration remains low because newly formed Cl rapidly reacts with  $\text{Fe}^{2+}$ , reforming  $\text{FeCl}^{2+}$ .

Sensitivity studies reveal a strong dependence on aerosol acidity. Lowering acidity from pH1 to pH4 enhances aqueous-phase Cl formation, dominated by increased  $\text{FeCl}^{2+}$  photolysis, leading to ~10% higher  $\text{Cl}_2$  production. The resulting increase in aqueous  $\text{Cl}_2$  and  $\text{Cl}$  promotes enhanced transfer of  $\text{Cl}_2$  and Cl to the gas phase, although the system remains close to phase equilibrium.

In the gas phase, Cl atoms are mainly produced by  $\text{ClNO}_2$  photolysis, with  $\text{Cl}_2$  photolysis as a secondary source (Fig. 2). Despite enhanced Cl activation, the impact on methane oxidation is negligible (<0.1%), as  $\text{CH}_4$  removal remains dominated by OH. Overall, iron–chloride multiphase chemistry significantly enhances Cl activation but has little effect on  $\text{CH}_4$  removal under the studied conditions.

## Outlook

Building on these initial results, future work will focus on extended sensitivity analyses to optimize the CAPRAM-SPARK configuration toward more realistic atmospheric conditions. The simulations will be further validated using available observations to better constrain iron–chloride chemistry and its impact on chlorine activation.

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# An interlaboratory comparison on aerosol particle levoglucosan, mannosan and galactosan quantification by the ACTRIS OrGanic Tracers and Aerosol Constituents - Calibration Centre (OGTAC-CC)

Falk Mothes and Hartmut Herrmann

Es wurde ein Laborvergleich (ILC) zur Quantifizierung der drei häufigsten organischen Tracerverbindungen für die Verbrennung von Biomasse in atmosphärischen Aerosolpartikeln durchgeführt, den Anhydromonosacchariden Levoglucosan, Mannosan und Galactosan. Der vom OrGanic Tracers and Aerosol Constituents - Calibration Centre (OGTAC-CC) innerhalb von ACTRIS durchgeführte ILC basierte auf drei realen  $PM_{2.5}$ -Aerosolfilterproben und zwei wässrigen Standardlösungen, die von den teilnehmenden europäischen Forschungslaboren unter Verwendung ihrer jeweils eigenen Analysenprotokolle chemisch charakterisiert wurden. Die Ergebnisse für die realen UmgebungsfILTERproben zeigten eine gute Übereinstimmung für alle drei Zielverbindungen Levoglucosan, Mannosan und Galactosan mit relativen Standardabweichungen in Bezug auf den Mittelwert von 14%, 22% bzw. 33%. Der Datensatz wurde zusätzlich anhand des Z-Scores bewertet, um die Datenqualität der Labore zu beurteilen. Obwohl verschiedene Analysenprotokolle zum Einsatz kamen, wurden bis auf wenige Ausnahmen alle ILC-Daten als „akzeptabel“ eingestuft. Faktoren mit potenziellen Auswirkungen auf die quantitativen Ergebnisse konnten untersucht werden um belastbare Empfehlungen für zukünftige qualitätsgesicherte Quantifizierungen dieser Gruppe an partikulären organischen Markerverbindungen abzuleiten.

## Introduction

The objective of the present ILC was to evaluate the comparability of the different analytical protocols currently used for the quantification of aerosol particle levoglucosan, mannosan and galactosan. This 1<sup>st</sup> ILC performed by the OrGanic Tracers and Aerosol Constituents - Calibration Centre (OGTAC-CC) within ACTRIS was done in autumn (09-11) 2024 and based on three ambient  $PM_{2.5}$  aerosol filter samples and two aqueous standard solutions to be analysed. 5 future ACTRIS NFs (represented by 4 laboratories) of which the participation was a mandatory QA/QC activity and 4 additional European research laboratories that took part on a voluntary basis should apply their individual analytical protocols (one laboratory applied two different protocols). The comparison of the results with former ILCs by *Yttri et al.* [2015], *Pietrogrande et al.*

[2017] and *Jaffrezo et al.* [2019] back in time between 6 and 10 years at the time of writing enables a review of the developments within the community to assess potential harmonization options ensuring high data quality standards and updating sampling and analytical methods in (EU) standards to acknowledge the scientific developments within this field of atmospheric research.

## Results

The main outcome of the ILC is discussed within this short report here on the obtained results for levoglucosan only, the most common used organic biomass burning tracer in aerosol particles.

Figure 1 shows the results of all 10 laboratories for levoglucosan (in  $\mu\text{g cm}^{-2}$ ) for the 3 different quartz filter samples and the corresponding general mean.

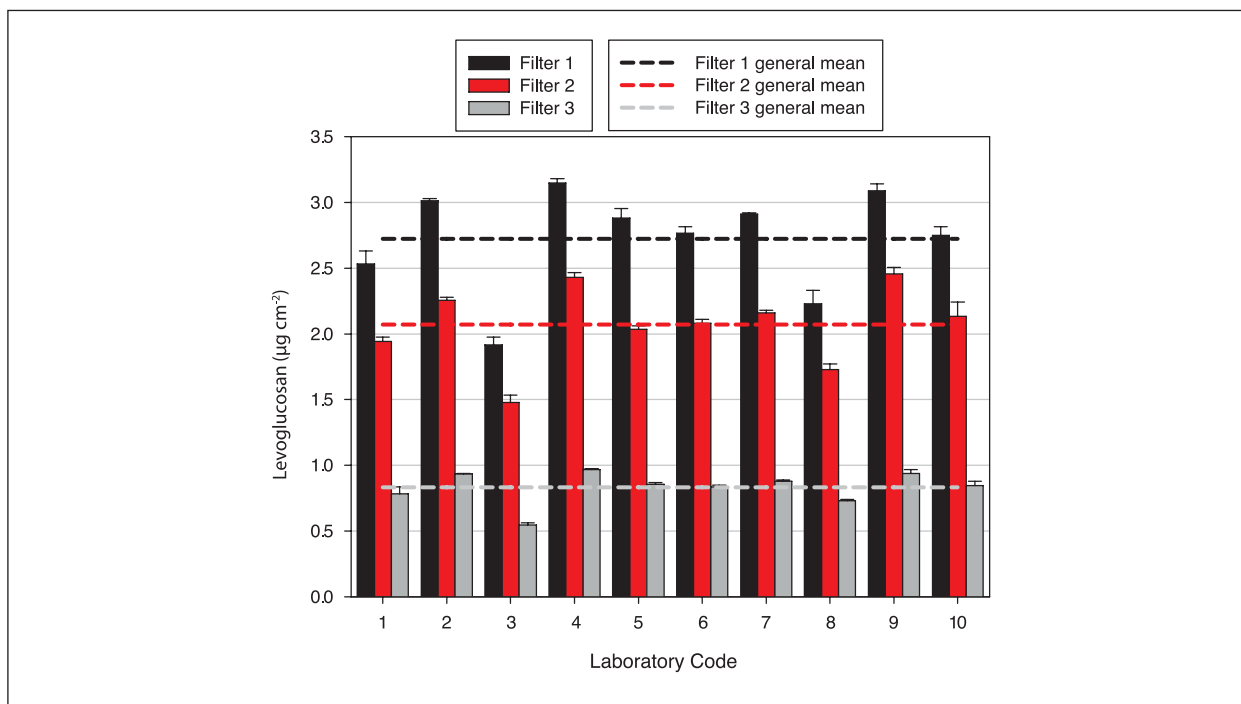


Fig. 1: Results levoglucosan for the three different filter samples obtained by the ten participating laboratories. The general mean of each filter sample is shown in dashed lines and the individual error bars correspond to the  $1\sigma$  standard deviation of the requested triplicate analysis.

The ILC results showed for levoglucosan a very good agreement between all laboratories for the three different filter samples with mass loadings on average between  $0.8$  and  $2.7 \mu\text{g cm}^{-2}$ , although individual sample preparation and different analytical techniques were applied. The obtained standard deviation of the general mean was approximately 15% independent on the amount of levoglucosan in the filter sample. Interestingly, the standard deviation obtained for the aqueous standard solutions was also approximately 15% (8 laboratories provided data, concentration levoglucosan up to  $0.6 \text{ mg L}^{-1}$ ), indicating that the sample preparation steps do not impact too much the

standard deviation of the final results for particulate levoglucosan measurements.

In addition to the general data overview, several method performance tests (Grubb's test for single outlier, the Mandel's h- and k- statistics or the Cochran's test) have been performed to check for individual stragglers and outliers of the provided ILC results. Following these tests, the repeatability and reproducibility standard deviations were calculated (summarized in Tab. 1) and are comparable with results from a former ILC on organic tracers [Jaffrezo *et al.*, 2019], although the filter mass loadings were partly lower in the present ILC.

Tab. 1: General mean and  $1\sigma$  standard deviation, repeatability ( $s_r$ ) and reproducibility ( $s_R$ ) standard deviations for levoglucosan filter samples 1-3.

Statistical property		Filter 1 ( $\mu\text{g cm}^{-2}$ )	Filter 2 ( $\mu\text{g cm}^{-2}$ )	Filter 3 ( $\mu\text{g cm}^{-2}$ )
Levoglucosan				
General mean + $1\sigma$ standard dev.	$\bar{x}$	$2.7 \pm 0.4$	$2.1 \pm 0.3$	$0.8 \pm 0.1$
Repeatability	$S_r$	0.063	0.049	0.023
	$S_r / \bar{x}$	2.3%	2.4%	2.8%
Reproducibility	$S_R$	0.397	0.303	0.125
	$S_R / \bar{x}$	14.6%	14.6%	15.0%

The data quality was finally assessed by the determination of the assigned values for each filter sample following ISO 13528 Annex C, robust analysis: algorithm A and the subsequent calculation of the z-score following ISO 13258 9.4. To point out one case: Although the results for levoglucosan provided by laboratory 3 and 8 were noticeably below the general mean, as can be seen in Fig. 1, the z-score assessment revealed values between 2 and 3, meaning the data is assigned a warning signal but is still acceptable. By definition, participants should be advised to check their measurement procedures following warning signals in case they indicate an emerging or recurrent problem.

## Summary and conclusion

The obtained general standard deviations are between 14 and 33% depending on the target compound, increasing in the order levoglucosan, mannosan, galactosan under consideration of all data provided by the participating laboratories. The QA/QC activity demonstrated that almost all laboratories provided acceptable data for all target compounds applying the z-score assessment.

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## Cooperation

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# Observations of low Antarctic INP concentrations

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**Die in der Antarktis am Boden gemessenen Konzentrationen von eisnukleierenden Partikeln (INPs von engl. ice-nucleating particles) sind die niedrigsten aller bisher global bekannten Werte. Messungen erfolgten an drei verschiedenen Orten im Rahmen von unterschiedlichen Messkampagnen: der deutschen Forschungsstation Neumayer III (NM, zwei Jahre Daten), der belgischen Forschungsstation Princess Elisabeth (PES, Daten von zwei antarktischen Sommern) und der PI-ICE Kampagne auf der spanischen Forschungsstation Juan Carlos, verbunden mit Schiffmessungen westlich der antarktischen Halbinsel. Die INP-Konzentrationen während PI-ICE waren vergleichbar zu Literaturdaten vom südlichen Ozean, und damit bereits niedrig verglichen zu anderen Orten der Erde. Daten von NM und PES waren nochmals niedriger, zeigten keinen Jahresgang (wie sonst gewöhnlich auf Kontinenten beobachtet), und der Anteil an hitzelabilen, also biogenen INPs lag unter der Nachweisgrenze. Außerdem ähnelten sich INP-Konzentrationen von NM und PES. Die Beobachtungen werden darauf zurückgeführt, dass es in der Antarktis kaum Biosphäre gibt, die biogene INPs emittieren könnte.**

## Introduction

Ice-nucleating particles (INPs) are important for the formation of primary ice in mixed-phase clouds. With this, they influence cloud radiative properties and precipitation formation. In the Southern Ocean (SO), large fractions of supercooled liquid water in clouds were observed in satellite data [Choi *et al.*, 2010; Zhang *et al.*, 2018]. This observation is assumed to be linked to a lower abundance of INPs originating from continents in the Southern Hemisphere (SH), compared to the Northern Hemisphere (NH). Up to date, little is known about INP concentrations in the SO, and next to nothing about INP observations on and above Antarctica. This is a grave knowledge-gap, considering that global warming is weaker in the SH

compared to the NH and also weaker than expected based on modeling results. In cooperation with project partners, TROPOS set out to help increasing our understanding of INPs in the SO and particularly on Antarctica. The resulting work, introduced herein, has been published in Wex *et al.* [2025].

## Method

Filter samples were collected for 24 subsequent months (Dec. 2019 to Dec. 2021) at the German Antarctic Neumayer Station III (NM), for two austral seasons (2020/2021 and 2021/2022) at the Belgian Princess Elisabeth Station (PES), as well as during the austral summer PI-ICE field campaign. The latter took place early 2019 both at the Antarctic research

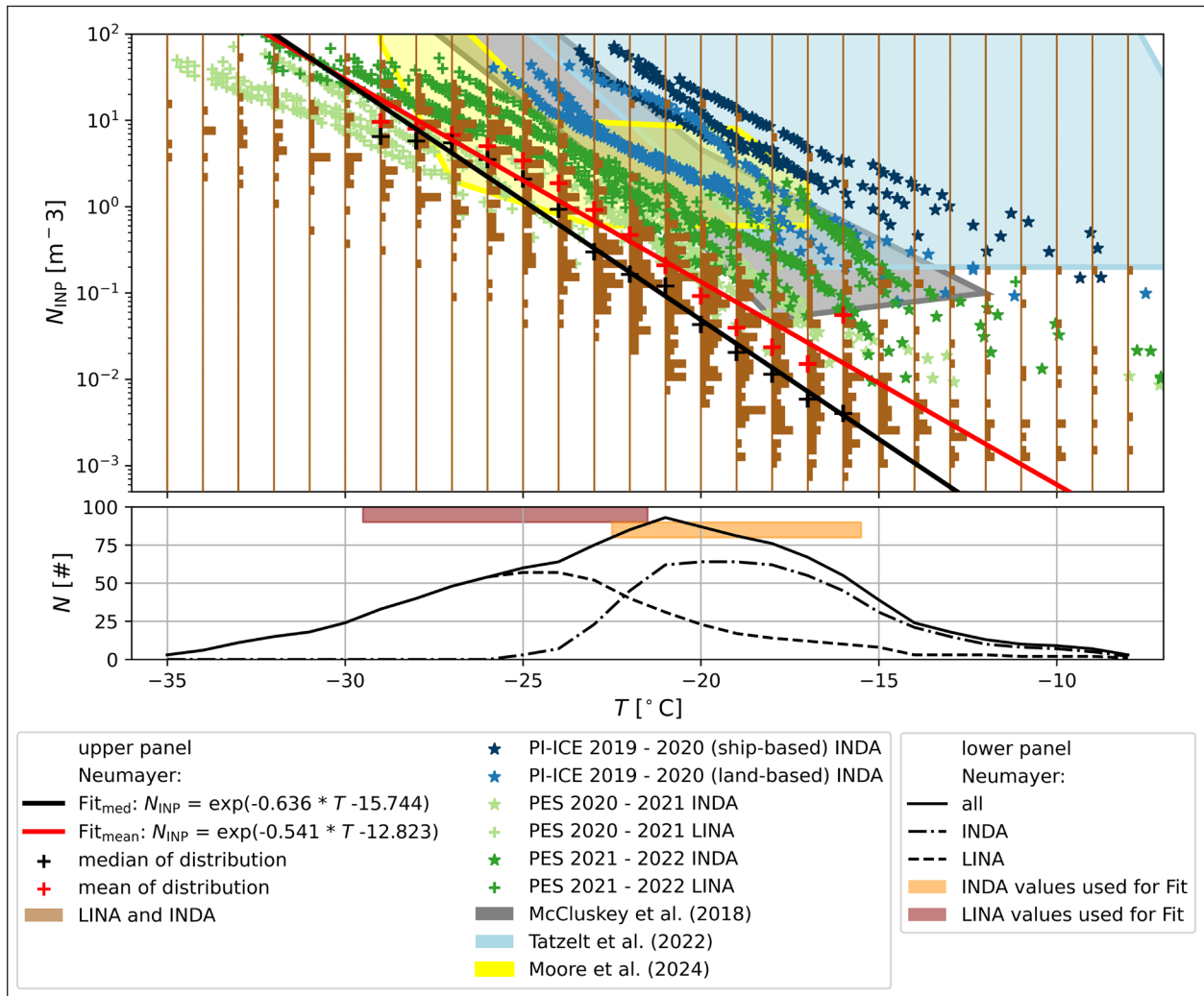


Fig. 1: The upper panel shows spectra of  $N_{\text{INP}}$  for NM (shown as histograms in steps of 1 K), PES and PI-ICE. Also shown are median and mean values for NM, fits through both median and mean values and literature data obtained from measurements in the Southern Ocean. The lower panel shows the number of filters contributing to the NM data set ( $N$ ) at each temperature. The two horizontal bars in the lower panel indicate the temperature ranges for which sampled filters were significantly different from background filters which therefore were used to obtain the fits in the upper panel. The figure was originally published in Wex et al. [2025], licensed under CC BY 4.0 (<http://creativecommons.org/licenses/by/4.0/>).

station Juan Carlos I on Livingston Island as well as west of the Antarctic Peninsula on board the Spanish research vessel RV Hespérides. Filter evaluation was done with the two well-established TROPOS off-line INM measurement methods LINA and INDA [Lacher et al., 2024], yielding both INP concentrations ( $N_{\text{INP}}$ ) and fractions of heat-labile (and hence biogenic) INPs. For further details see Wex et al. [2025].

## Results and Discussion

All spectra of  $N_{\text{INP}}$  obtained for this study are shown in Fig. 1, in comparison to literature data. During PI-ICE,  $N_{\text{INP}}$  are comparable to literature data from the SO [McCluskey et al., 2018; Tatzelt et al., 2022; Moore et al., 2024], i.e., they are already low, compared to other locations on Earth.  $N_{\text{INP}}$  at NM and

PES are lower, still. They also did not show an annual variation, as is typically observed for other continents and even for the Arctic [see e.g., Sze et al., 2023]. The fraction of heat-labile and hence protein-aceous and biogenic INPs was mostly below detection limit. NM data were used to derive simple INP parameterizations (depending on freezing temperature only) as shown in Fig. 1. By comparing INP data from PES to this parameterization, a similarity of  $N_{\text{INP}}$  at both locations was observed, suggesting that similarly low  $N_{\text{INP}}$  may prevail across larger parts of the Antarctic continent.

Overall, our observations of low  $N_{\text{INP}}$  over Antarctica are attributed to the fact that there is hardly any biosphere in Antarctica that could emit biogenic INPs. For more details, see Wex et al. [2025].

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# Tethered balloon measurements of arctic ultrafine aerosol particles during melting season 2024

Mona Kellermann, Thomas Conrath, Theresa Mathes, Joshua Müller, Christian Pilz, Malte Schuchardt, Holger Siebert, Birgit Wehner

**Die Bildung neuer Aerosolpartikel aus der Gasphase ist eine wichtige Quelle für arktisches Aerosol in dieser sonst sehr sauberen Umgebung. Wenn Schnee und Eis schmelzen dann wird dieser Prozess besonders effektiv und kann signifikant zu den vorhandenen Partikelkonzentrationen beitragen. Bei der Frage wo genau diese Prozesse stattfinden und wie die Partikel dann in der Vertikale vermischt werden und zum Beispiel als Wolkenkondensationskeime dienen können gibt es immer noch Lücken. Um diese Lücken weiter zu schließen und dadurch auch die Gründe für die sich schnell erwärmende Arktis besser zu verstehen, wurden vertikale Profile verschiedener meteorologischer und aerosolphysikalischer Parameter mit einem Fesselballonsystem gemessen und analysiert.**

## Introduction

In the otherwise pristine Arctic, new particle formation (NPF) is an important source of aerosol particles during the spring and summer seasons. Arctic aerosol populations exhibit strong seasonal variability, with peaks in ultrafine particle abundances linked to open water and melt conditions [Dall'Osto *et al.*, 2017].

To estimate the direct and indirect effects of aerosol particles on the radiation budget of this rapidly warming climate system, it is crucial to observe the vertical distribution of aerosol particles. Although some ground-based observations exist in this region, there is still a scarcity of data on the vertical distribution of ultrafine particles (UFP) in the Arctic lower troposphere. This vertical information is required to fully understand sources, dynamics, and the potential to act as cloud condensation nuclei (CCN) [Gordon *et al.*, 2017].

Therefore, measurements with the tethered balloon system BELUGA (Balloon-bornE moduLar Utility for profilinG the lower Atmosphere) were conducted during the melting season in 2024 in

Ny-Ålesund, Svalbard. The dataset captures the transition into the melting season over Arctic land, with temperatures steadily rising into positive values and snow cover disappearing. The measured profiles reveal different vertical and temporal changes in ultrafine particle stratification, showing a tendency for UFP concentrations to appear closer to the ground as melting progresses.

## Data and Methods

Between 19 May and 7 June 2024, vertical profiles up to 1200 m were conducted using the tethered balloon system BELUGA in Ny-Ålesund, Svalbard as part of the AIDA campaign (Aerosol variability and Interaction with ambient conditions based on small-scale vertical and horizontal Distribution of Arctic measurements). A Turbulent Meteorological Probe (TMP) was continuously mounted on the tether line to provide meteorological parameters such as temperature, humidity, and wind.

In addition, two interchangeable aerosol measurement systems were operated ~10 m below the TMP. For most flights, the Cubic Aerosol

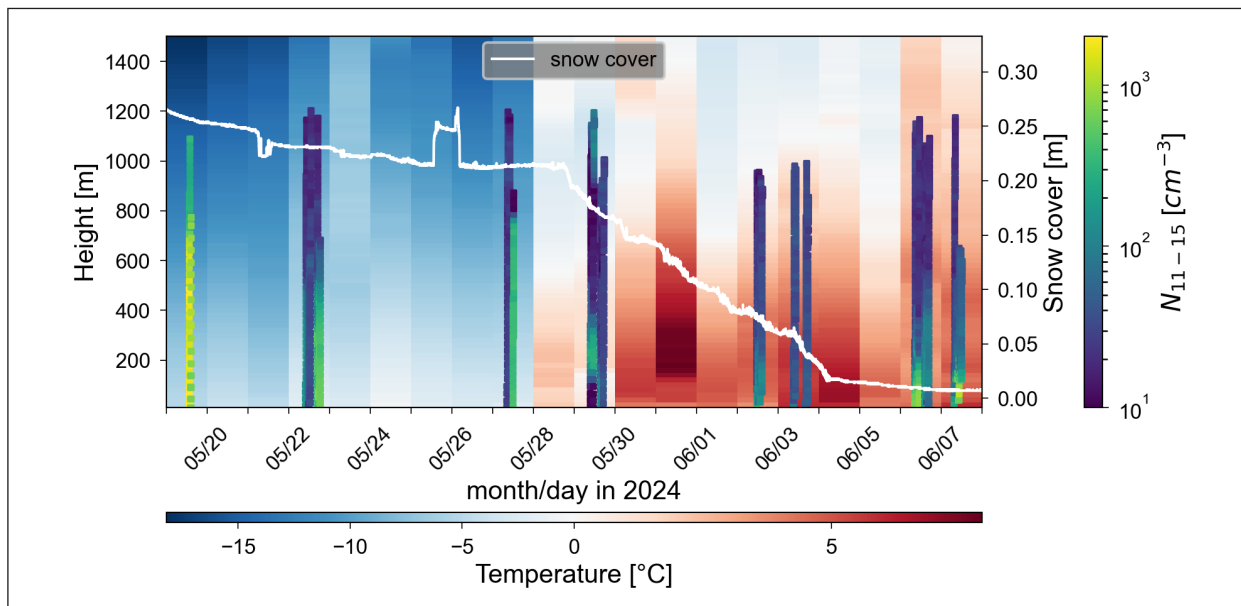


Fig. 1: Overview of the measurement period with temperature from daily radiosonde ascents shown in the background and snow cover at the AWIPEV Observatory indicated in white. Balloon ascents are represented by concentration profiles of 11–15 nm particles ( $N_{11-15}$ ).

Measurement Platform (CAMP) was used [Pilz et al., 2022]. CAMP consists of two Condensation Particle Counters (CPCs) measuring total particle number concentrations above 11 nm and 15 nm, respectively, and a portable optical particle spectrometer (POPS) providing number size distributions from 0.15 to 2.5  $\mu\text{m}$ . By subtracting concentrations from the two CPCs, the particle number concentration in the 11–15 nm size range ( $N_{11-15}$ ) was derived, serving as an estimate of ultrafine particle (UFP) abundance.

As a first field application, a miniaturized Scanning Electrical Mobility Spectrometer (mSEMS) box was deployed during four flights instead of CAMP. The mSEMS provides particle number size distributions from 8 to 350 nm, with scans averaged over 2 minutes together with an additional CPC measuring concentrations above 9 nm. Except for the mSEMS size distribution scans, all data were recorded at 1 Hz temporal resolution, affording high vertical spatial resolution. All measurements were corrected based on instrument calibrations, quality-checked, and adjusted for sampling losses.

Additional long-term ground-based measurements at the Ny-Ålesund research site were used to place the balloon-borne observations into a broader context. Profiles were analyzed with respect to temporal evolution under changing meteorological conditions throughout the campaign and in selected case studies. Qualitative analysis focuses on the vertical distribution of  $N_{11-15}$ , providing insight into aerosol layering in the Arctic lower troposphere during melting conditions.

## Results

Figure 1 shows an overview of the measurement period from late March to early June 2024. Temperature data from daily radiosonde ascents show a clear trend from negative to positive values throughout the period. This trend is accompanied by decreasing snow cover; at the beginning of the campaign the ground was covered by up to  $\sim 20$  cm of snow, which rapidly diminished as temperatures increased. By the end of the measurement period, almost snow-free conditions prevailed, with ground temperatures above  $\sim 5$   $^{\circ}\text{C}$  - typical for the melting onset in this region during May to June.

The  $N_{11-15}$  profiles show a high abundance of ultrafine particles throughout most of the measurement period. In May, profiles exhibit variable layering of  $N_{11-15}$  throughout the measured column. In June, profiles initially show low overall concentrations, followed by a clear enhancement in the lowest 200 m and reduced concentrations aloft. This transition suggests local sources for UFP near the surface with ongoing melt, probably due to increased availability of biological precursor as snow and sea ice vanish. A period with generally low UFP concentrations at the beginning of June coincided with higher concentrations of larger particles, possibly suppressing new particle formation or early growth.

## Data availability

The described dataset is published under <https://doi.pangaea.de/10.1594/PANGAEA.988353>.

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## Cooperation

TU Braunschweig  
AWIPEV

# Remote sensing of mixed-phase clouds, aerosol particles, and their interaction in polar regions

Hannes Griesche, Hannah Sundermann, Martin Radenz, Albert Ansmann, Dietrich Althausen, Holger Baars, Carola Barrientos-Velasco, Hartwig Deneke, Ronny Engelmann, Julian Hofer, Anja Hünerbein, Cristófer Jimenez, Patric Seifert, Ulla Wandinger

**TROPOS ist seit mehreren Jahren mit seiner mobilen Fernerkundungsstation OCEANET-Atmosphäre in den polaren Regionen unterwegs. Aus den entstandenen Datensätzen haben sich wichtige Erkenntnisse für das Verständnis von polaren Mischphasenwolken und Aerosol-Wolken-Wechselwirkungen ergeben. Beispielsweise wurde der Einfluss von Wasserdampf auf den Strahlungsfluss an der Oberfläche bestimmt und der Effekt einer Grenzschichtkopplung von Wolken auf die Wolkeneigenschaften ermittelt. Grundlegende Unterschiede zwischen Arktis und Antarktis wurden beobachtet. Während in der Arktis Wolken in der freien Troposphäre grundsätzlich unter aerosol-belasteten Bedingungen beobachtet wurden, wurden in der Antarktis auch Wolken unter aerosol-limitierten Bedingungen gemessen.**

## Introduction

The polar regions are undergoing rapid changes in the course of recent years. These changes have been obvious in the Arctic and are discussed under the key word Arctic amplification already for more than two decades [Serreze and Francis, 2006]. Yet, they have become more evident in the Antarctic in recent years [Purich and Doddridge, 2023]. Despite major advances in the understanding of the phenomena of amplified polar warming, models still struggle to reproduce the observed changes, especially with respect to potential impacts of aerosol particles [Luo et al., 2025; Schmale et al., 2021].

In 2016, the Leipzig University, the University of Cologne, the University of Bremen, the Alfred Wegener Institut (AWI), and TROPOS initialized the German Transregional Collaborative Research Centre Arctic Amplification: Climate Relevant Atmospheric and Surface Processes and Feedback Mechanisms ((AC)<sup>3</sup>) with the aim to improve the understanding of the changes in the Arctic [Wendisch et al., 2023]. Additionally, TROPOS has conducted long-term remote sensing of clouds and aerosol particles in the polar regions with its mobile platform OCEANET-Atmosphere. During the Arctic expedition MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) in 2019 and 2020 [Shupe et al., 2022], OCEANET-Atmosphere was deployed on the German research icebreaker Polarstern [Engelmann et al., 2021; Griesche et al., 2024]. Subsequently, OCEANET-Atmosphere was shipped to the German

Antarctic research station Neumayer III [70.67°S, 8.27°W, 42 m a s l.] for the Continuous Observations of Aerosol-Cloud Interaction (COALA) campaign [Radenz et al., 2024]. During each deployment, OCEANET-Atmosphere comprised a similar setup (e.g., a multiwavelength polarization Raman lidar Polly<sup>XT</sup>, a microwave radiometer HATPRO, a sun and lunar photometer, and a Parsivel<sup>2</sup> disdrometer) with only small changes in the instrumentation. For COALA, a cloud radar Mira-35 and a scanning Doppler lidar LITRA-S were added to the OCEANET-Atmosphere observatory. During MOSAiC, these observations were covered by external partners. Besides ground-based observations, TROPOS also utilizes satellite remote sensing to study the polar cloud and aerosol system and has carried out radiation closure studies based on the MOSAiC observations within a BMFTR-funded project [Barrientos et al., 2025a]. Here, we summarize the major findings obtained by ground-based and satellite observations during MOSAiC and COALA.

## Aerosol and cloud process studies in the Arctic

Arctic low-level mixed-phase cloud properties were found to be highly dependent on the surface coupling state of the cloud, especially at cloud-top temperatures above -10 °C and from spring to autumn [Griesche et al., 2025]. At these cloud-top temperatures and between April and July, the fraction of ice-containing clouds in surface-coupled situations

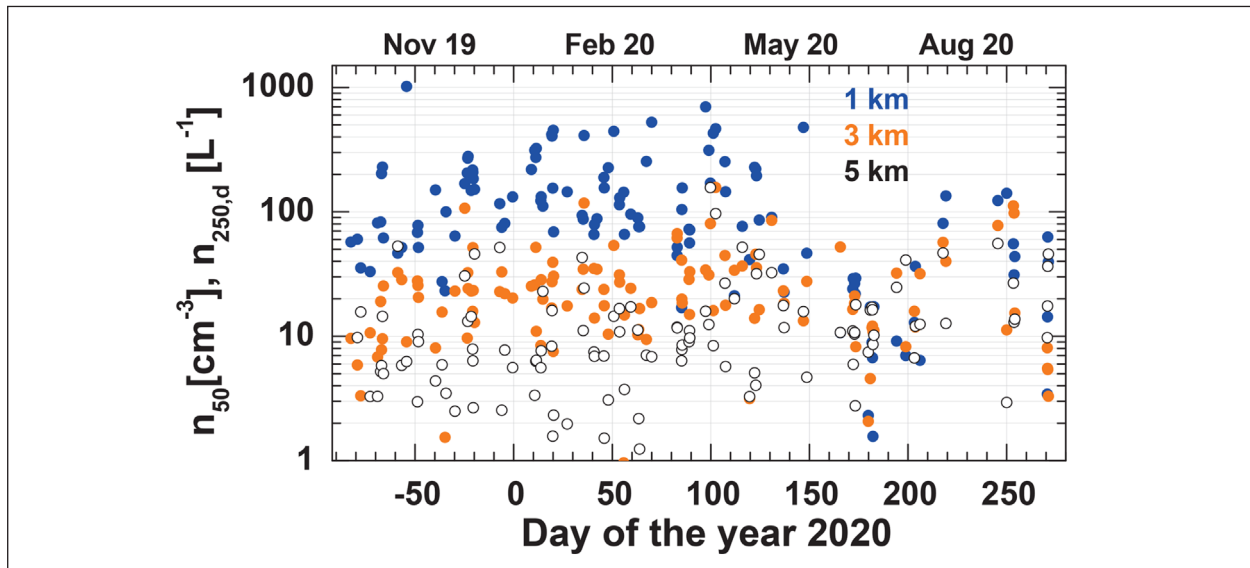


Fig. 1: Particle number concentration  $n_{50,dry}$  during MOSAiC obtained from lidar observations at cloud-free conditions for the height levels of 1 km (blue circles), 3 km (orange circles), and 5 km (white circles). Data gaps, especially during the summer months, indicate long phases with low clouds and fog.  $n_{50,dry}$  can be regarded as a proxy for the reservoir of activatable CCN. The same values, shown in the figure for  $n_{50,dry}$ , can be obtained for  $n_{250,d,dry}$  (dust fraction of  $n_{250,dry}$ , now in number per liter) by applying the respective extinction-to- $n_{250,dry}$  conversion factor and by assuming a dust fraction of 7.5%.  $n_{250,d,dry}$  may indicate the reservoir of most favorable INPs. Figure from Jimenez et al. [2025].

was 2–3 times higher compared to decoupled cases. In August and September, a larger fraction of decoupled ice-containing clouds was observed at  $T > -10$  °C. Hence, the factor of coupled-vs-decoupled ice-containing clouds was reduced to 1.3. By means of INP measurements at the surface, sea-ice concentration, the distance to the ice edge, and the travel time along back-trajectories the observed phenomena could likely be attributed to the presence of ice nucleating particles (INPs) active above  $-15$  °C at the surface. In Jimenez et al. [2025], the dual-field-of-view polarization lidar method was applied to derive liquid-water cloud microphysical properties. It was shown that continuous formation of water droplets by aerosol particle activation is a key for the longevity of mixed-phase clouds. Figure 1 shows the annual cycle of aerosol number concentrations and deduced cloud condensation nuclei (CCN) and INP estimations, during MOSAiC for different sizes and at different heights from the lidar observations as presented in Jimenez et al. [2025]. The influence of wildfire smoke on Arctic cirrus formation during MOSAiC was investigated in Ansmann et al. [2025a] and Ansmann et al. [2025b]. The smoke pollution in the upper troposphere was observed to be considerably enhanced for more than 6 months and several cirrus systems were observed in this region at cloud-top temperatures between  $-60$  °C and  $-70$  °C. By means of combined ground-based remote sensing [Ansmann et al., 2025a] and simulations [Ansmann et al., 2025b] it was shown that, even though being inefficient INPs,

aged smoke particles dominated the ice formation in the observed cirrus via heterogeneous ice formation.

Mixed-phase clouds that form during Arctic marine cold air outbreaks exhibit characteristic structures, initially forming as roll clouds or cloud streets parallel to the wind, and eventually breaking up into a cumuliform cloud field. They can be easily identified in satellite imagery. Ongoing research focuses on analysing how these cloud structures evolve during cold air outbreaks with different intensities using observations of the Moderate-resolution Imaging Spectroradiometer (MODIS) satellite. This work extends the airborne measurements presented in Klingebiel et al. [2025a] and Klingebiel et al. [2025b], places these field campaigns into a broader context on both temporal and spatial scales, and continues the close collaboration with (AC)<sup>3</sup> partners.

Clouds and water vapour widely control the surface radiation budget of the Arctic. In this regard, a TROPOS-led analysis of profiles of water vapor mixing ratio, based on the Polly<sup>XT</sup> measurements from MOSAiC, revealed a linear relationship between integrated water vapor and the broadband thermal-infrared irradiance at the surface [Seidel et al., 2025]. The observed relationship was found to be dependent on the water vapor-weighted mean temperature (representative temperature of the water vapor distribution) and was confirmed by 53 independent cases. The observed radiation budget during MOSAiC was

compared to radiative transfer simulations based on ground-based and satellite remote sensing, with generally good agreement [Barrientos-Velasco *et al.*, 2025b]. These simulations revealed a cloud radiative effect at the top-of-the-atmosphere of  $-5.2 \text{ W m}^{-2}$  and at the surface of  $25.0 \text{ W m}^{-2}$ . The conducted studies showed that cloud processes in the free Arctic troposphere are likely constantly happening under polluted conditions. Anthropogenic smoke and aerosol particles are omnipresent above the boundary layer. A fact which, until now, seems to be different in the Antarctic.

### Aerosol-cloud interaction and mixed-phase cloud studies in the Antarctic

In contrast to the Arctic, mixed-phase clouds in the Antarctic are driven by lower aerosol concentrations. Radenz *et al.* [2024] presented observations of aerosol and clouds by means of ground-based remote sensing over the Ekström Ice Shelf. They discussed a case of a free-tropospheric mixed-phase cloud layer formed in an aerosol-limited environment where both, concentration of CCN and INP, as well as derived numbers of cloud droplets and ice crystals, were on the order of a few tens per  $\text{ccm}$  or  $\text{m}^3$ , respectively. Water vapor profiles derived from the measurements in Antarctica reveal a strong impact of warm and moist air intrusions on cloud and precipitation formation, causing the strongest snowfall events. Comparison of observed water vapor mixing ratio with the European Centre for Medium-Range Weather

Forecasts reanalysis ERA5 shows a dry bias of the model in the lowest kilometer, strongly depending on the surface parameterization. Detailed investigation of the OCEANET-Atmosphere dataset is ongoing, e.g., by connecting the remote-sensing to aerosol surface in-situ observations. Furthermore, the Cloudnet dataset that was started during COALA has been continued by AWI since 2024, in collaboration with TROPOS. This continued dataset helps to provide the context to balloon-borne observations done by the Extreme Environments Research Lab of the École polytechnique fédérale de Lausanne in the summer seasons of 2024/25 and 2025/2026. Joint projects for bringing together profiling in-situ observations and remote sensing are ongoing as well.

The different studies discussed here suggest that the longevity of free-tropospheric Arctic mixed-phase clouds is usually not limited by the supply of cloud condensation nuclei and ice nucleating particles, as the respective reservoirs were always found to be well filled. In contrast, in Antarctica, clouds were observed under aerosol-limited conditions, and surface in-situ observations also show extremely low concentrations of CCN and INP [e.g., Wex *et al.*, 2025]. Yet, stratospheric aerosol, likely from volcanic emissions of Hunga Tonga–Hunga Ha’apai, was constantly observed by the ground-based remote sensing and contributed the largest share to the total optical depth during COALA [Radenz *et al.*, 2024].

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Multiple national and international project partners

# Detailed cloud microphysical simulations of ice formation pathways in artificial seeding experiments (PolarCAP)

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**Das DFG geförderte PolarCAP-Projekt untersucht in Zusammenarbeit mit dem CLOULAB-Team der ETH Zürich unter anderem die Eisbildung in Mischphasenwolken bei Temperaturen zwischen 0 und -10 °C. Während zweier Winterperioden (2022-2024) wurden in der Nähe von Eriswil, Schweiz bodengebundene Fernerkundungsbeobachtungen mit kontrollierten Wolkenimpfexperimenten kombiniert. Dabei wurden Silberiodid-Aerosole mittels unbemannter Luftfahrzeuge (Drohnen) in die leicht unterkühlten Flüssigwasserwolken eingebracht, welche als Eiskeime dienen. Für die Modellierung der Eisbildung wurde das Spektral-Bin-Mikrophysikmodell SPECS, gekoppelt an das numerische Wettervorhersagemodell COSMO, um Lagrangesche Partikelverfolgung und einen künstlichen Partikelquellterm erweitert. Eine neu implementierte, speziell für Silberiodid entwickelte Immersionsgefrierparametrisierung zeigte eine deutlich erhöhte Eiskernierungseffizienz im Vergleich zu standardmäßigen staubbasierten Schemata und erzielte eine verbesserte Übereinstimmung mit In-situ-Messungen. Sensitivitätsexperimente wurden für zwei verschiedene Gitterweiten (100 m und 400 m), sowie unterschiedlicher Eiskristallwachstumsannahmen (kugelförmig, säulenförmig) durchgeführt. Die Experimente ergaben Abhängigkeiten der Eiskristallentwicklung sowohl von der Modellauflösungen als auch von der angenommenen Eiskristallform, was die Bedeutung akkurater mikrophysikalischer Darstellungen in Simulationen von Mischphasenwolken deutlich macht.**

## Introduction

Advancing our understanding of complex microphysical processes within mixed-phase clouds is fundamental to improve weather predictions and climate simulations. In collaboration with the CLOUDLAB project at ETH Zurich, the PolarCAP project investigates the initialisation and evolution of the ice phase at slight supercooling temperatures between 0 and -10°C. In this temperature range, on the one hand aerosol particles are required as ice nucleating particles (INP), while on the other hand ice multiplication and secondary ice formation processes play key roles for the cloud evolution and precipitation formation. The DFG-funded project PolarCAP is a joint collaboration of the Departments of Atmospheric Modelling (MOD) and of Remote Sensing (RSD) of TROPOS. In the course of PolarCAP, the mobile

remote sensing platform LACROS (Leipzig Aerosol and Cloud Remote Observations System) has been deployed next to the CLOUDLAB equipment to a pre-alpine site near Eriswil, Switzerland, during the two winters between 2022 and 2024. CLOUDLAB conducted the seeding of supercooled liquid cloud layers with silver iodide (AgI) particles using unattended aerial vehicles (UAVs) and collected a basic set of ground-based remote sensing observations approx. 3 km downwind. The LACROS site added an extensive set of continuous ground-based remote sensing observations to evaluate the outcome of the seeding experiments on a large scale. Besides the support of CLOUDLAB activities [Marcolli *et al.*, 2016; Henneberger *et al.*, 2023; Ramelli *et al.*, 2024; Omanovic *et al.*, 2024a; Omanovic *et al.*, 2024b; Miller *et al.*, 2024], PolarCAP concentrated specifically on studies of the regional variability of INP

[Ohneiser et al., 2025a], on the interaction between the frequently occurring supercooled stratus cloud and precipitation [Ohneiser et al., 2025b], on the characterisation of precipitation measurement techniques [Gaudek et al., 2025], and on the detection of secondary ice production and coexisting hydrometeor types using scanning Doppler cloud radar [Teisseire et al., 2025].

## Methods

The modelling contribution to PolarCAP built on the spectral-bin microphysics model SPECS, coupled to the numerical weather prediction model COSMO (Consortium for Small-scale Modeling)-SPECS, which was extended with Lagrangian tracking and an artificial particle source term to mimic the controlled cloud seeding experiments of CLOUDLAB. A significantly more efficient immersion freezing parameterisation [Omanovic et al., 2024a], specifically designed for silver iodide (AgI) particles was included into the model, based on an exponential fit to laboratory measurements [Marcolli et al., 2016]. We confirm that the default parameterisation [DeMott, 1995], which is based on in-situ measurements of natural dust aerosols, requires unrealistically high flare particle emission rates to achieve sufficient ice nucleation at temperatures above  $-10^{\circ}\text{C}$ , in comparison to the field measurements. The AgI-based scheme, on the other hand, can be operated with a much more realistic flare emission rate of around  $10^6 \text{ m}^{-3} \text{ s}^{-1}$ , which is sufficiently consistent with the observations made during the CLOUDLAB campaign, thereby reducing the flare particle emission rate by five orders of magnitude compared to the default parameterisation [Henneberger et al., 2023; Ramelli et al., 2024; Miller et al., 2024].

## Results

We conducted a small variety of COSMO-SPECS model runs, with two different horizontal grid spacings of 400 and 100 m. In addition, the habit of the primary ice growth regime was varied between spherical crystals and columns. Three model runs of the following configuration: (A) 400 m horizontal grid spacing and spherical ice crystals growth, (B) 400 m grid spacing and columnar ice crystals growth, and (C) 100 m grid spacing and columnar ice crystals growth. Figure 1 shows the comparison of ice crystal size evolution along the plume path, identified by the cloud tracking tool tobac [Heikenfeld et al., 2019]. At each time step, the size-resolved ice water content is integrated over all grid cells within the tobac segmentation mask, thereby capturing the total ice mass produced within mixed-phase plume. The population of ice particles grows rapidly from  $10 \mu\text{m}$  to  $100 \mu\text{m}$  within 5 minutes. Shortly after buildup, the ice crystals increase their terminal velocity and start to precipitate. In Fig. 1A to 1B, the models response to the choice of the ice shape becomes visible. For columnar crystals, the larger axis ratio has the effect of increasing the major diameter of the particles, which increases the surface area and consequently decreasing their terminal velocity. Columnar ice crystal (Fig. 1B and 1C) grow up to sizes of  $500 \mu\text{m}$ . The effect of grid resolution becomes visible when comparing Fig. 1B to 1C, where the mean crystal size of 1C is approximately larger by a factor of two compared to 1B.

The study demonstrates that the spectral-bin microphysics module SPECS coupled to COSMO is capable of reproducing real-world cloud seeding experiments. The implementation of the AgI-specific ice nucleation scheme enabled a comparison to the

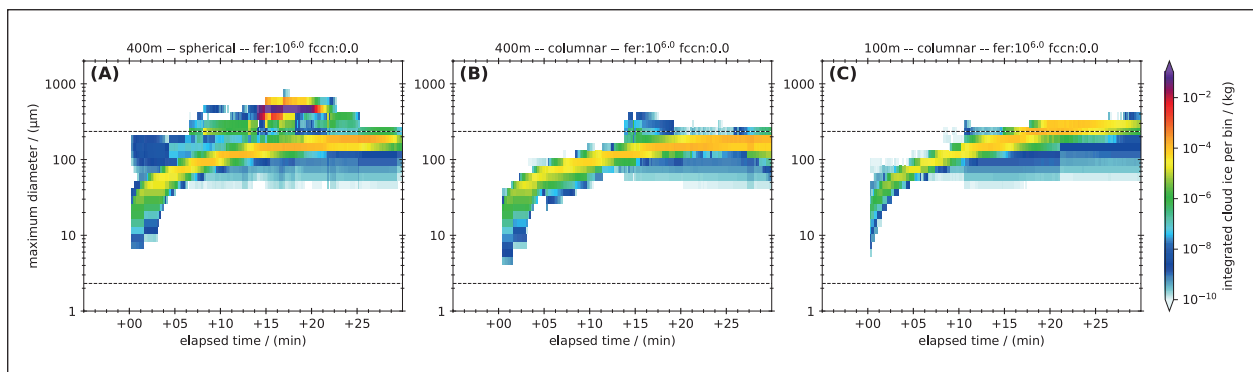


Fig. 1: Comparison of the integrated frozen water content along the track of frozen particles. Three COSMO-SPECS model runs are presented: (A)  $d_{xy} = 400 \text{ m}$ /spherical crystals, (B)  $d_{xy} = 400 \text{ m}$ /columnar crystals, and (C)  $d_{xy} = 100 \text{ m}$ /columnar crystals. The x-direction represents the elapsed time since start of the seeding and in y-direction the diameter of frozen particles. The colour values show the cloud ice in kg integrated over the spatial extend of the ice plume (i.e., the segmentation mask computed by tobac). The dashed horizontal thresholds at  $2.5 \mu\text{m}$  and  $250 \mu\text{m}$  divide the frozen particle size distribution into aerosols, ice crystals, and snow.

standard aerosol parameterisation. The identified strong enhancement of ice nucleation rates via the AgI parameterisation and the corresponding improved agreement to the in-situ measurements of INP and ice crystal concentration demonstrates the relevance of applying accurate aerosol information in simulations

of aerosol-ice activity of slightly supercooled clouds. The strong impact of applied ice crystal shapes and grid spacing on the cloud evolution requires accurate representation and tracking in order to reproduce the characteristics of ice formation in slightly supercooled cloud systems appropriately.

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## Cooperation

CLOUDLAB project team at ETH Zürich, Switzerland

# Regionalizing ICON–HAM-lite for process-level aerosol studies

Bernd Heinold, Jason Müller, Anne Kubin, Fabian Senf, Ina Tegen

**Eine regionale Ausschnitts(LAM)-Version des atmosphärischen Aerosolmodells ICON–HAM-lite wurde entwickelt, um hochaufgelöste Aerosolsimulationen auf Prozessskala zu ermöglichen. Sie ergänzt die globale Version des Modells, erlaubt flexible Sensitivitäts- und Ensembleexperimente und unterstützt die effiziente Untersuchung von Wechselwirkungen zwischen Aerosolen, Wolken und Strahlung. Am Beispiel der australischen „Black-Summer-Waldbrände“ 2019–2020 konnte gezeigt werden, dass durch pyro-konvektiven Eintrag sowohl Rauch als auch Wüstenstaub zuverlässig simuliert und deren vertikale Verteilung erfasst werden kann.**

## Introduction

The representation of multiscale atmospheric processes, including aerosol–climate interactions, remains a central challenge in climate modelling. Traditional Earth system models operate at horizontal resolutions of about 100 km and rely on parameterizations for convection, while convection-resolving models at kilometre-scale resolution substantially improve the representation of deep convection, precipitation extremes, and aerosol transport [Prein *et al.*, 2015; Schär *et al.*, 2020; Stevens *et al.*, 2019]. The storm-resolving configuration of the ICON Earth system model has recently been coupled to the reduced-complexity aerosol module HAM-lite for global kilometre-scale interactive aerosol–climate simulations [Weiss *et al.*, 2025]. As a key achievement, a limited-area mode (LAM) version of ICON–HAM-lite has been developed. Its capabilities are demonstrated for desert dust and wildfire smoke during the 2019–2020 Australian wildfire event.

## Method

The ICOSahedral Nonhydrostatic (ICON) Earth system model has been advanced for storm-resolving applications [Hohenegger *et al.*, 2023]. Within this framework, the reduced-complexity aerosol module HAM-lite was implemented for global kilometre-scale aerosol–climate simulations by Weiss *et al.* [2025]. HAM-lite is derived from the comprehensive HAM module [Stier *et al.*, 2005]. It simplifies HAM's full aerosol microphysics by representing aerosols as log-normal modes with predefined sizes and compositions. This reduces computational cost while retaining key aerosol–radiation and aerosol–cloud interactions. The default configuration includes two pure modes for

dust and sea salt and two internally mixed modes for sulfuric and carbonaceous aerosols.

Building on the global model setup, a LAM version of ICON–HAM-lite was developed for regional simulations at 5–1 km resolution. Aerosol tracers were extended with a domain index and integrated into the ICON routines for initial and lateral boundary conditions, allowing consistent initialization and updates with meteorological tracers. Pre-processing tools generate aerosol boundary fields, emissions, and surface properties from global datasets. To better represent wildfire smoke injection, satellite-derived fire radiative power was scaled and incorporated as a surface sensible heat flux [cf. Muth *et al.*, 2025].

The 2019–2020 Australian wildfires were simulated to show the flexibility and capability of the new LAM configuration. The simulations use a 2.5 km-domain (R2B10) over 132°E–160°E and 19°S–42°S, covering 25–31 December 2019. Sea surface temperature and sea ice were prescribed from Atmospheric Model Intercomparison Project (AMIP) data, while atmospheric and land initial and lateral boundary conditions were provided by ECMWF analysis. Biomass burning emissions were taken from daily satellite-based Global Fire Assimilation System (GFAS) data.

## Results and Conclusion

The 2019–2020 austral summer, Australia's Black Summer, featured unprecedented wildfires in southeastern Australia. Fire activity peaked 29 December–4 January, with deep pyro-convective towers lofting smoke aerosols up to 14–16 km [Ohneiser *et al.*, 2020]. During this period, 0.3–1.1 Tg of smoke was injected and advected rapidly eastward across southern mid- and high latitudes [Peterson *et*

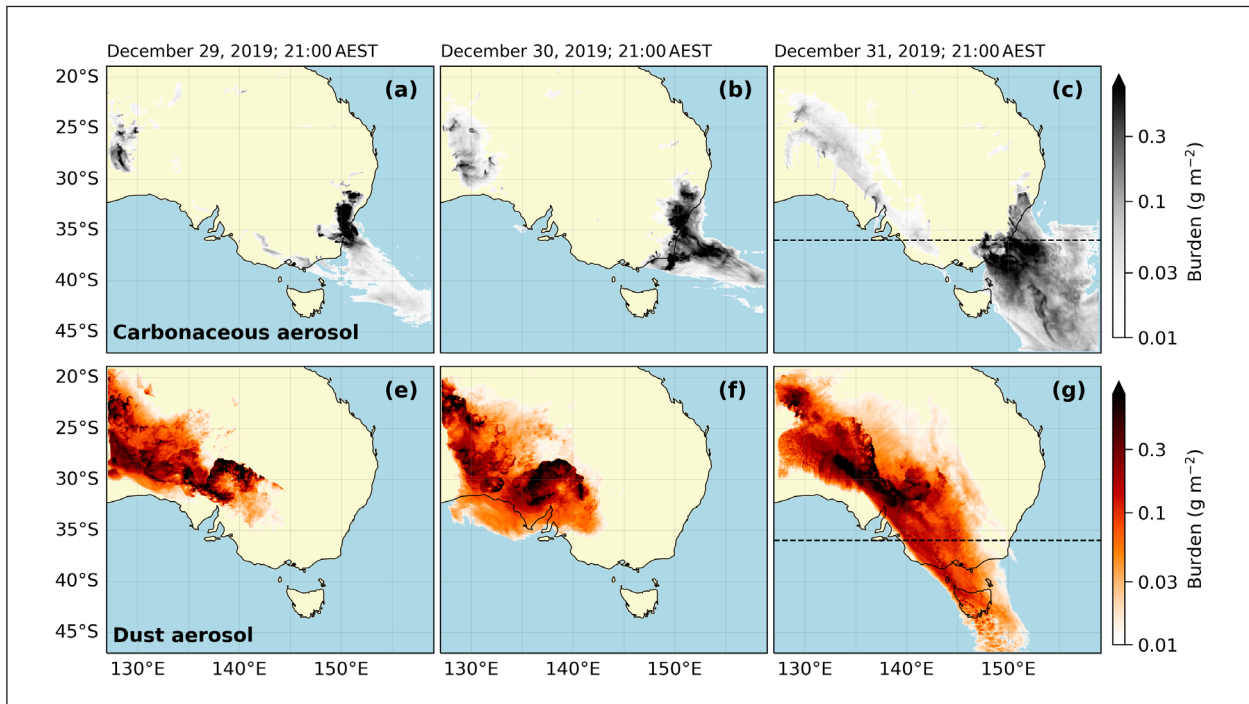


Fig. 1: Maps of column burdens of (a–c) carbonaceous aerosol and (d–f) desert dust over southeastern Australia and the southwestern Pacific Ocean on 29–31 December 2019, as simulated with ICON–HAM-lite LAM. The dashed line in panels (c) and (f) marks the location of the zonal cross section shown in Fig. 2.

al., 2021]. The extensive, long-lived smoke plumes significantly influenced the radiation budget and the atmospheric dynamics in the southern hemisphere [Heinold et al., 2022; Senf et al., 2023]. Simultaneously, intense desert dust was emitted over central Australia by frontal passages and moist convection and transported southeastward. Figure 1 shows the modelled burdens of carbonaceous aerosol and dust over southeastern Australia and adjacent oceans (29–31 December 2019). Fire-induced buoyant updrafts loft dense smoke plumes extending far from the source, while desert dust from central Australia forms a distinct southeastward-advected plume. The model reproduces the observed large-scale smoke distribution in good agreement with satellite retrievals [Peterson et al., 2021], capturing the intense plumes over land and the Tasman Sea.

Fig. 2 shows a zonal cross section along  $35\pm 5^\circ\text{S}$  on 31 December 2019 of modelled desert dust (colored) and carbonaceous aerosol (grayscale) concentrations. Elevated smoke layers appear above 10 km and extend toward the tropopause at 14 km, with concentrations reaching up to  $16\ \mu\text{g m}^{-3}$  when averaged over the  $5^\circ$  latitude band. Dust remains largely below 6 km, mean concentrations peaking at  $4\ \mu\text{g m}^{-3}$ , though some is transported to the heights of the smoke plume. This vertical contrast reflects different injection mechanisms: pyro-convective

buoyancy for smoke versus mechanical lifting for dust. High-altitude transport of smoke extends its atmospheric lifetime and amplifies its radiative impact, while dust plays a significant but regionally limited role. The concurrent transport of dust and smoke creates a complex aerosol layering, which merits further investigation.

The case study shows that the LAM version of ICON–HAM-lite provides a flexible, computationally efficient tool for process-level aerosol studies, particularly for natural primary aerosols. Complementing the global model, it enables rapid sensitivity tests, ensemble simulations, and interactive aerosol experiments, with high-resolution (1–5 km), capturing fine-scale processes beyond the reach of traditional global or full chemistry–transport models. Future extensions, such as additional prognostic modes for nitrate or secondary organic aerosols, would improve fidelity in pollution-dominated regions. Its resolution aligns with in-situ and remote sensing observations (e.g., ESA’s EarthCARE satellite), facilitating model evaluation and interpretation. Scientifically, the LAM allows quantification of region-specific aerosol–cloud–radiation interactions under convective and mixed-phase conditions, with potential case studies including wild-fire smoke–dust mixtures in West Africa and low-level mixed-phase clouds in polar regions.

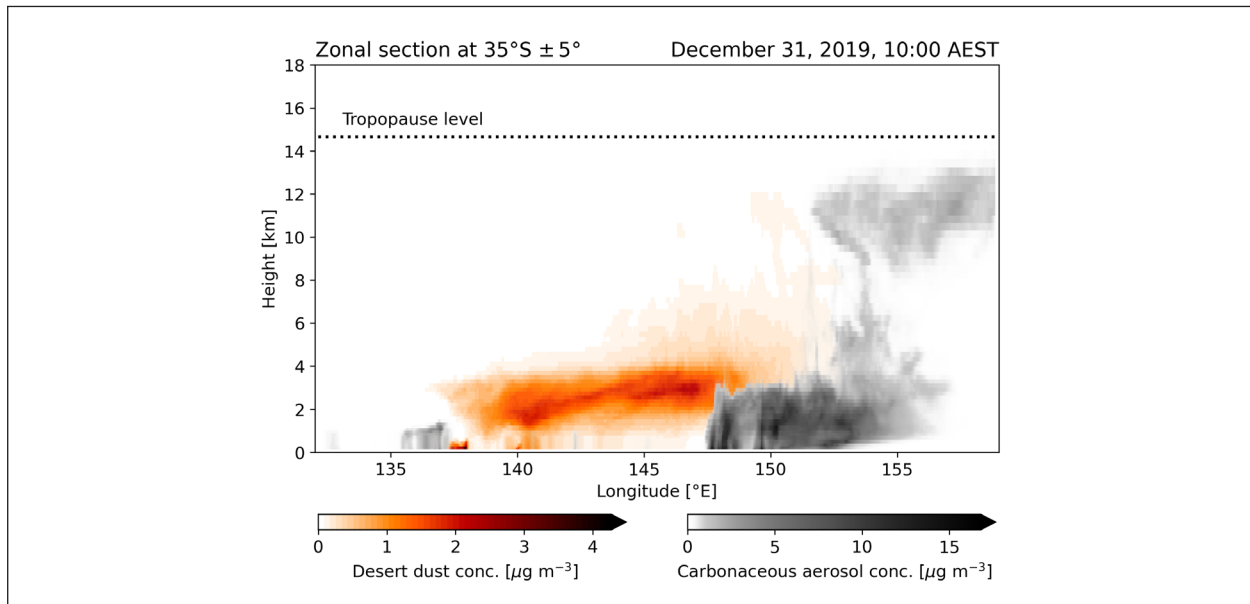


Fig. 2: Zonal cross section of aerosol concentrations along  $35\pm 5^\circ\text{S}$  on 31 December 2019, averaged over the  $5^\circ$  latitude band, showing the vertical and longitudinal distribution of desert dust (colored shading) and bushfire-related carbonaceous aerosol (grayscale). The horizontal dashed line denotes the approximate tropopause height.

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# Optical Lab for Lidar Applications (OLALA)

Moritz Haarig, Esha Semwal, Thomas Oppermann, Markus Hartmann, Dietrich Althausen, Ronny Engelmann, Heike Wex, Andreas Macke

Das optische Labor für Lidaranwendungen (Optical Lab for Lidar Applications – OLALA) hat sich zum Ziel gesetzt, die Streueigenschaften von Mineralstaubpartikeln in der exakten Rückstreuung zu verstehen. Jene Partikel stellen durch ihre unregelmäßige Form eine große Herausforderung für die Ableitung mikrophysikalischer Größen aus Fernerkundungsmessungen dar. Dafür wird ein neues Streulabor am TROPOS aufgebaut, in dem gröbenselektierte Staubpartikel mit einem Laserstrahl vermessen werden. Die Herausforderung hierbei besteht in der Beobachtung der exakten Rückstreuung ( $180^\circ$ ), was zu einigen experimentellen Schwierigkeiten geführt hat. Im Sommer 2025 konnten die ersten erfolgreichen Messungen bei einer Laserwellenlänge von 532 nm erfolgen. Aufbauend auf unseren Erfahrungen erweitern wir momentan das Labor um zwei weitere Wellenlängen (355 und 1064 nm), damit wir an die atmosphärischen Beobachtungen unserer Lidargeräte anknüpfen können. Gleichzeitig arbeiten wir an einer Verbesserung der Beschreibung unregelmäßig geformter Partikel in optischen Modellen. Insbesondere die Oberflächenrauheit ist in nur wenigen Modellen enthalten, ist aber auf mikroskopischen Abbildungen von Staubkörnern deutlich zu erkennen. Hierfür arbeiten wir mit Masanori Saito von der Universität von Wyoming, USA, zusammen, bei dem Thomas Oppermann einen dreimonatigen Forschungsaufenthalt verbrachte. Erste Ergebnisse der Rückstreuung an oberflächenaufgerauten, unregelmäßigen Hexaedern stimmen gut mit den Resultaten aus unserem Streulabor überein. Diese Übereinstimmung zeigt das große Potential der Leibniz Nachwuchsgruppe OLALA (2023 – 2028) zur dauerhaften Etablierung eines weltweit einzigartigen Lidarstreulabors.

## Introduction

Mineral dust is the most abundant aerosol type (by mass) on Earth emitted from the large deserts like the Sahara. Mineral dust as a mostly natural aerosol needs to be separated from anthropogenic pollution and smoke to assess the aerosol-related climate effects by mankind. The irregular shape of mineral dust particles enables the separation from other spherical aerosol types such as pollution or tropospheric biomass-burning smoke. However, the complex shape challenges its description in optical models because the simple assumption of a spherical particle leads to large discrepancies between the simulations and observations. Various non-spherical models have been proposed in literature reaching from simple spheroids [Dubovik *et al.*, 2006] to irregular hexahedra [Saito *et al.*, 2021] and irregularly shaped particles [Gasteiger *et al.*, 2011]. However, they lack a good dataset for validation and constraints. Often, the results are compared to lidar field observations [Saito and Yang, 2021], where neither the size distribution nor the refractive index or shape characteristic are well-known. Laboratory

studies at the interface between optical modelling and remote sensing are strongly needed to fill the gap.

The Optical Lab for Lidar Applications (OLALA) is a Leibniz Junior Research Group, which was granted to Dr. Moritz Haarig by the Leibniz Association for a duration of 5 years (2023 – 2028). It proposes to fill the gap by combining laboratory efforts with novel model approaches to improve our fundamental understanding of the optical properties of mineral dust needed for global observations with active remote sensing from ground and space.

## The new scattering lab at TROPOS

In 2023, we started to plan and construct a new scattering laboratory at TROPOS to achieve the  $180^\circ$  backscattering. A sketch of the laboratory is provided in Fig. 1. We use existing infrastructure and expertise from the Leipzig Aerosol Cloud Interaction Simulator (LACIS) and from the construction of PollyXT lidars at TROPOS. Aiming at the exact backscattering, we were facing several challenges to detect the weak particle signal in the strong background noise. Step by step, we improved the detectors, the beam

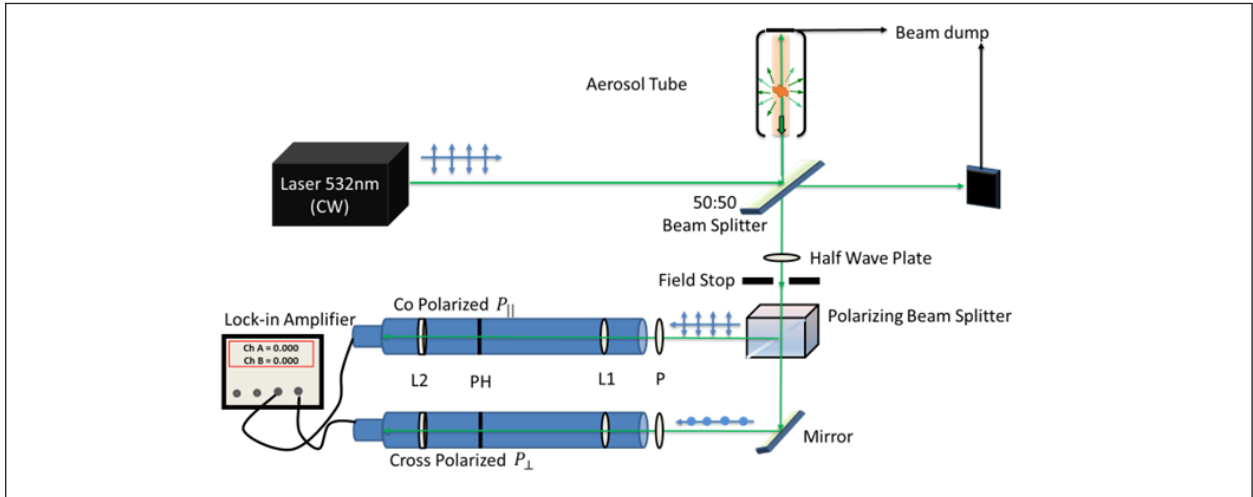


Fig. 1: Sketch of the optical part of the OLALA laboratory setup (Semwal et al., 2026). A 50:50 beam splitter directs the laser light into the aerosol tube and enables the detection of the backscattered light at 180°. The polarizing beam splitter separates the two polarization components and directs it to the respective channels.

dumps, the calibration unit, and signal detection by the lock-in amplifier. In summer of 2025, we were able to perform the first successful measurements with our setup at 532 nm [Semwal et al., 2026]. Since then, we conducted experiments with mono-modal size distributions of Arizona Test Dust (ATD), sodium chloride (NaCl), Ammonium sulfate, polystyrene latex (PSL) beads and Saxonian soil dust. The careful size

selection leading to the mono-modal size distributions is a novelty of our laboratory which enables us to better constrain the optical models (Fig. 2).

The efforts are ongoing to expand the OLALA setup to include observations at 1064 nm (currently ongoing) and 355 nm (planned for 2026). Once we will have finalized the triple-wavelength experimental setup, we will characterize dust samples from various

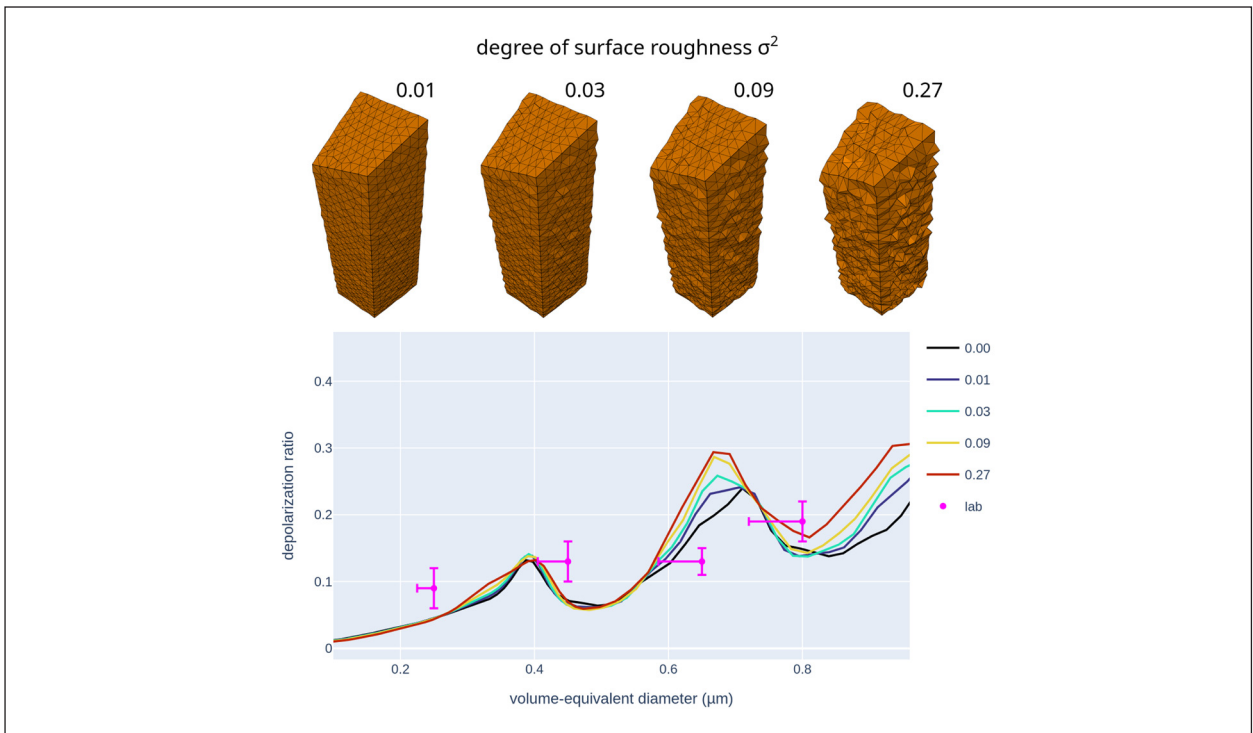


Fig. 2: Top: Surface roughness added to a single irregular hexahedron. Bottom: The size-resolved laboratory measurements (magenta dots) of ATD compared to the modelling results using the single irregular hexahedron with various degrees of surface roughness as shown above [preliminary results, Oppermann et al., 2026]

desserts like the Sahara, Negev (Israel), Aralkum (Uzbekistan) and Simpson Desert (Australia).

### Improvements in the optical models

Parallel to the laboratory endeavor, we are working on improved particle shape models. From an intense literature study, we know, that natural mineral dust particles are non-spherical, asymmetric and have a rough surface. Current models have treated the non-sphericity, but most of the proposed particles are still symmetric and almost all have smooth surfaces. Therefore, we took the irregular hexahedra proposed by *Saito et al.* [2021] which consist of an ensemble of 20 irregular, deformed cubes (hexahedra) which are not symmetric. In summer of 2025, Thomas Oppermann spent a three-month secondment at the University of Wyoming, USA, to work together with Masanori Saito on the addition of surface roughness to the irregular hexahedra model [Oppermann et al., 2026]. The newly generated roughened particles are shown in Fig. 2a. Here, they are based on just the first out of the 20 particles belonging to the ensemble. Nevertheless, they can already nicely reproduce the laboratory observations for size selected Arizona Test Dust (ATD) as shown in the preliminary results in Fig. 2b. These results are promising and show the great potential of OLALA in

combining laboratory observations and model developments for an improved understanding of the scattering properties of irregularly shaped mineral dust particles.

### Outlook

TROPOS runs several lidar field stations around the global dust belt with stations in Dushanbe (Tajikistan), Limassol (Cyprus) and Mindelo (Cabo Verde), which are organized in the TROPOS-led PollyNET. Furthermore, TROPOS is strongly engaged in the EarthCARE satellite mission, which provides global lidar observations of mineral dust. The improved understanding of the scattering properties of mineral dust gained in the OLALA project will certainly improve the retrieval algorithms for the ground-based and spaceborne lidar observations, e.g., the estimation of fine and coarse mode dust contributions and its related radiative effects. Our strong involvement in the algorithm development for lidar retrievals will pave the way to include the findings of the OLALA project.

The strength of the OLALA project lies in the combination of novel laboratory measurements with model developments to the goal of an improved understanding of mineral dust in atmospheric measurements. It is work in progress, but the first laboratory and modelling results are encouraging.

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### Cooperation

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University of Lyon, France  
Technical University Darmstadt, Germany  
University of Lille, France

# Long-term lidar observations in Dushanbe, Tajikistan

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**TROPOS hat in den Jahren 2015 und 2016 die allerersten Lidarmessungen im zentralasiatischen Tadschikistan in Zusammenarbeit mit der Tadschikischen Nationalen Akademie der Wissenschaften durchgeführt. Aufgrund der äußerst erkenntnisreichen Messungen wurde 2019 eine permanente Messstation in Dushanbe, Tadschikistan, als Teil der europäischen Forschungsinfrastruktur ACTRIS errichtet und liefert seitdem wertvolle Daten zum Aerosoltransport und zur Aerosol-Wolken-Wechselwirkung in einer stark vom Klimawandel betroffenen Region. Des Weiteren ermöglicht dieser Außenposten des TROPOS einen wertvollen Beitrag zur Validierung von Satellitenmessungen im ansonsten spärlich mit Messgeräten ausgestatteten Zentralasien. Die langjährige, gute Zusammenarbeit mit den Kollegen in Tadschikistan sichert die Aufrechterhaltung der Lidarstation in Dushanbe.**

## Introduction

Tajikistan lies in the center of the northern hemispheric dust belt and is surrounded by major dust sources. Central Asia and especially Tajikistan are highly affected by climate change. Aerosol observations in Central Asia are sparse but highly important to understand regional and global transport of mineral dust and other prevalent aerosol types, such as continental pollution or smoke, and their effects on radiation budget and cloud formation. First-ever lidar observations in Tajikistan were initiated by TROPOS in collaboration with the S.U. Umarov Physical-Technical Institute of the National Academy of Sciences of Tajikistan. From March 2015 to August 2016, a PollyXT multiwavelength polarization Raman lidar [Engelmann *et al.*, 2016] as part of PollyNET [Baars *et al.*, 2016; PollyNET, 2025] was installed in the Tajik capital of Dushanbe in the framework of an 18-month measurement campaign [Central Asian Dust Experiment; Hofer *et al.*, 2017]. The results with regard to aerosol optical, microphysical, and cloud-relevant parameters were presented and discussed in Hofer *et al.* [2020a,b, 2024].

## PollyXT lidar station at Dushanbe, Tajikistan, as an ACTRIS outpost

As a consequence of the important results and the need for long-term observations, a containerized PollyXT lidar with dual-field-of-view capability was installed at Dushanbe for permanent observations in 2019 [Engelmann *et al.*, 2019] in the framework of ACTRIS [Aerosol, Clouds and Trace Gases Research Infrastructure; Laj *et al.*, 2024]. First exemplary results of recent research activities using the new and still growing data set from the ACTRIS aerosol profiling station in Dushanbe are presented in the following.

## Relating cloud and aerosol properties from long-term lidar observations

The dual-field-of-view polarization method [Jimenez *et al.*, 2020a,b] allows the retrieval of microphysical properties of liquid-water clouds (effective radius, cloud droplet number concentration (CDNC)) at high temporal resolution. Together with the retrieval of cloud-condensation-nuclei concentration (CCNC) estimates using the POLIPHON method [Polarization Lidar Photometer Networking; e.g., Ansmann *et al.*,

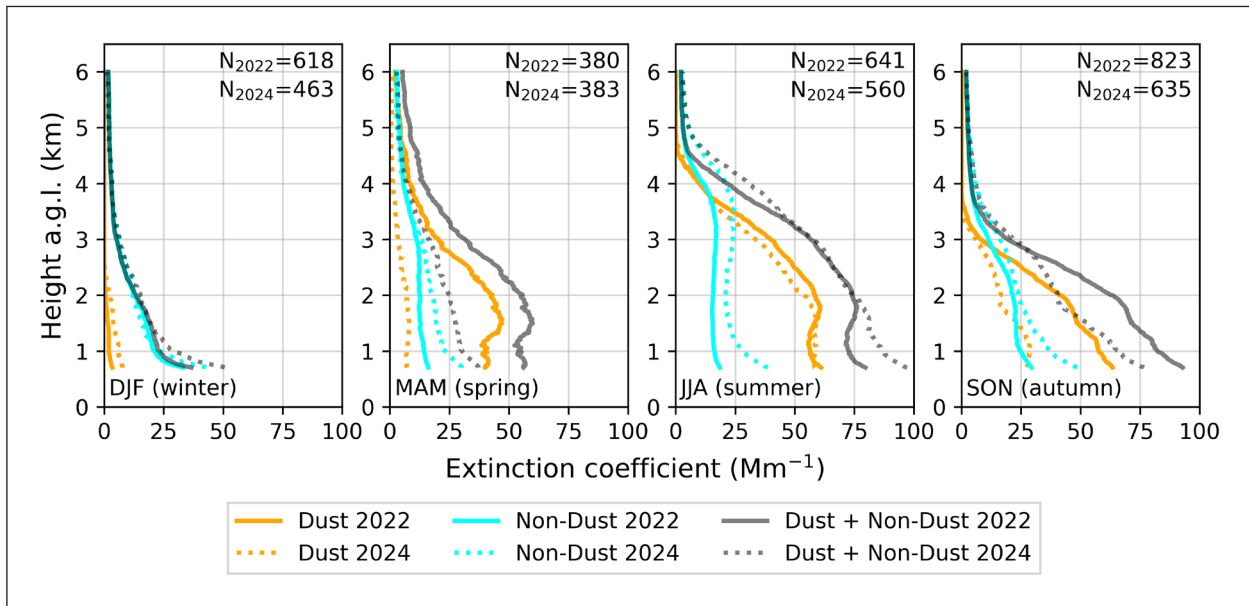


Fig. 1: Seasonal median vertical profiles of the dust (orange), non-dust (cyan), and total particle extinction coefficient (black) in Dushanbe for the winter (DJF; a), spring (MAM; b), summer (JJA; c), and autumn season (SON; d) of the years 2022 (solid lines) and 2024 (dashed lines). The dust and non-dust fractions were separated with the POLIPHON method. The number of vertical profiles used per year and season is indicated by  $N$ .

2019], this setup enables aerosol-cloud-interaction studies like presented in Jimenez [2021] and Lipken et al. [2024].

Continuous, long-term measurements from 2019 to 2023 were used to investigate the aerosol and cloud microphysical properties and their relationships. Based on the criterion of a time gap of at least 1 h between two cloud observations, more than 1500 liquid-water cloud layers were defined in the study period. It was found that the CCNC peaks in winter due to domestic heating [Hofer et al., 2020a], while at the same time, the CDNC is generally lower. This indicates that the often-occurring polluted mineral dust might play a crucial role in cloud formation over Dushanbe. Furthermore, a positive but plateauing correlation between CDNC and CCNC was found indicating that Tajikistan might represent a dynamics-limited (i.e., depending on updrafts) but not aerosol-limited regime [Jimenez, 2021].

### Extended seasonal statistics of aerosol properties

While the data from the 18-month campaign in 2015/16 were used to infer first seasonally resolved statistics about aerosol load and type in Dushanbe, the continuous observations since 2019 allow the analysis of trends and interannual variations. For instance, the seasonal median profiles of the dust, non-dust, and total particle extinction coefficient for the seasons of the years 2022 (Fig. 1a–d) and 2024 (Fig. 1e–g) reveal that particularly spring (Fig. 1f) and

autumn of 2024 (Fig. 1h) were significantly less dusty compared to the same seasons of the year 2022 (Fig. 1a and d, respectively). The variations of the non-dust (i.e., continental pollution) contribution, on the other hand, are smaller. Such differences in dust load are attributed to different weather patterns, but this needs to be further investigated.

### EarthCARE calibration and validation efforts and product development

As one of the few ground-truthing stations in Central Asia, the ACTRIS outpost in Dushanbe is of vital importance for EarthCARE/ATLID [Earth Cloud, Aerosol and Radiation Explorer/Atmospheric Lidar; Wehr et al., 2023] validation and the development of novel products. An example of those activities is presented in Fig. 2. On 12 September 2025, the PollyXT lidar in Dushanbe observed a scene of mixed dust including a lofted layer at about 4–5.5 km a.g.l. (Fig. 2a,b). Lidar-measured profiles of aerosol optical properties from ground and space during a very close EarthCARE overpass (Fig. 2d,e) are shown in Fig. 2ci–cv. The closest overpass distance to the ground station was 37 km and a generally good agreement between the ground-based and spaceborne lidar observables is found. The EarthCARE/ATLID products (Fig. 2f,g) show that the Hindukush mountain range in Afghanistan and the Zarafshan mountain range in Tajikistan served as natural border and trapped aerosol up to heights of 6–7 km a.s.l. mostly typed as dust, smoke, and their mixtures. A

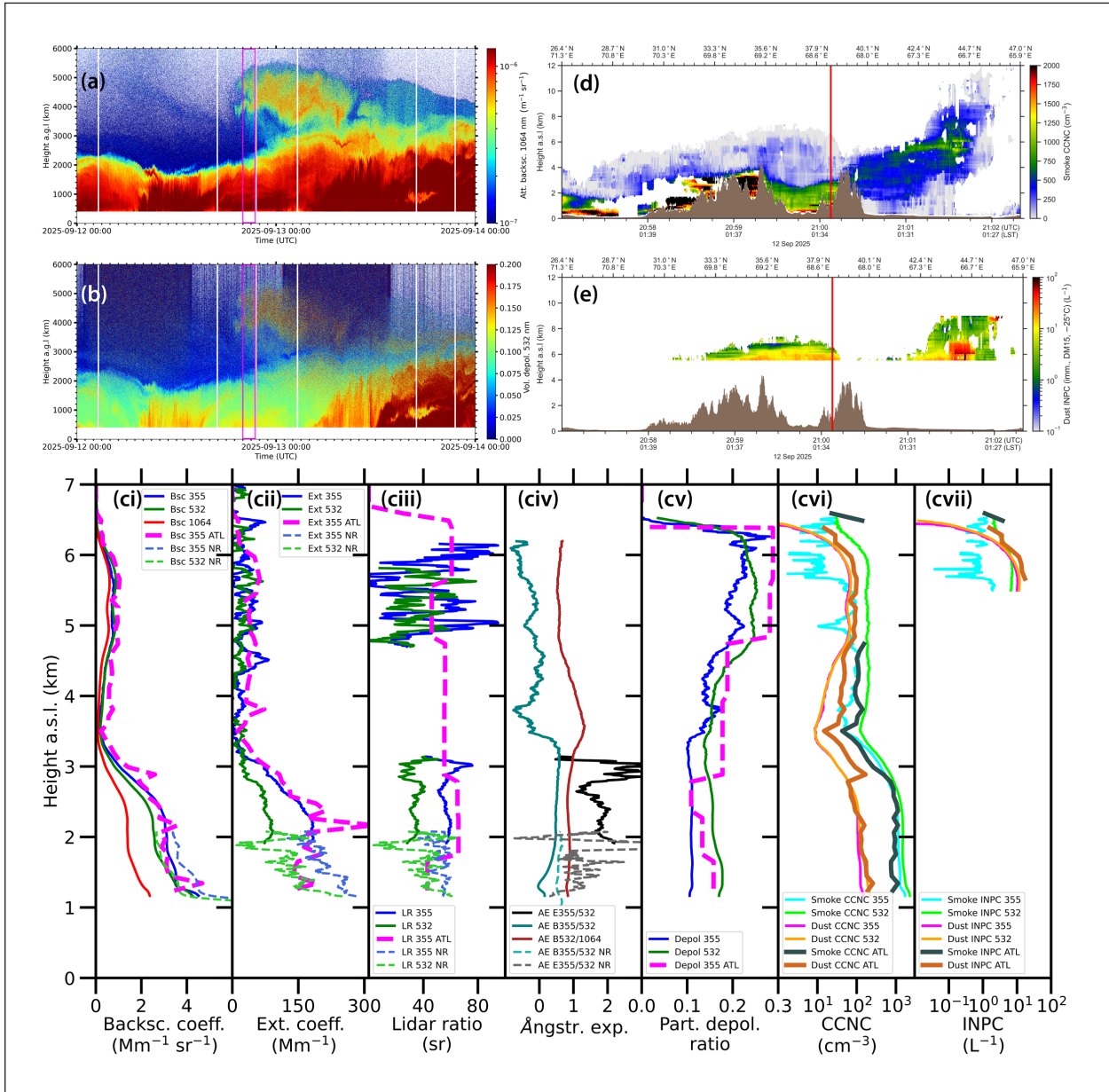


Fig. 2: Time-height plot of attenuated backscatter at 1064 nm (a) and volume depolarization ratio at 532 nm (b) measured by PollyXT at Dushanbe, Tajikistan, on 12–13 Sep. 2025, aerosol optical properties (ci–cvii) from PollyXT averaged during 12 Sep. 2025, 20:00–21:30 UTC (indicated with magenta rectangles in (a) and (b)) and from the EarthCARE/ATLID extinction, backscatter, and depolarization product (A-EBD; Donovan et al., 2024; baseline BA, low resolution) at 2025-09-12 21:00:07634991232 (dashed magenta), and dust and smoke CCNC and INPC estimates from POLIPHON using 355- and 532-nm optical properties and conversion factors, respectively. Parametrizations are used to retrieve immersion freezing INPC estimates. Uncertainties range from 10% (Bsc), 50% (CCNC), to a factor of 3 (INPC). Time-height plots of POLIPHON estimates of smoke CCNC (d) and dust INPC (e) retrieved using EarthCARE products for parts of the Frame 07343B. The surface elevation is depicted in brown. The closest profile to the reference ground station (see also (ci–cvii)) is indicated as vertical red line.

novel experimental product for EarthCARE/ATLID using POLIPHON, which was developed at TROPOS, was applied to separate dust and smoke fractions and to retrieve the corresponding cloud-relevant aerosol properties such as CCNC (Fig. 2g,cvi) and ice-nucleating particle concentration (INPC) estimates (Fig. 2h,cvii) from both EarthCARE/ATLID and PollyXT. Fair agreement was found, but the EarthCARE/ATLID particle depolarization ratio tends to

be slightly higher than the one measured by PollyXT, leading to partial discrepancies in the retrieved CCNC and INPC estimates (Fig. 2cvi,cvii). The EarthCARE/ATLID depolarization bias is known and still under investigation [see Bley et al., 2026]. Nevertheless, proof-of-concept for these novel products has been shown and thus will enable future global aerosol-cloud-interaction studies using EarthCARE/ATLID observations.

## Conclusion

The ACTRIS outpost in Central Asia, the only one in this key region of Earth's climate, was used for first long-term trend analysis, process studies, and as a test bed for product development as well as validation of spaceborne observations. Additionally, the station enables knowledge transfer and bridge building with Central Asian institutions.

Furthermore, these activities led to two scientific conferences organized by TROPOS focusing

specifically on the topic of Central Asian dust which took place once in Dushanbe (2019) and Nukus, Uzbekistan (2024) [Central Asian Dust Conference; e.g., *Althausen et al.*, 2020; *CADUC*, 2026].

A new project funded by the German Federal Ministry of Research, Technology and Space will start in 2026 to investigate the spatial aerosol distribution over the mountainous regions of Tajikistan and to further intensify our collaboration with the National Academy of Sciences of Tajikistan.

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# Characterizing UTLS aerosol with the high-power Raman and fluorescence lidar MARTHA

Benedikt Gast, Cristofer Jimenez, Albert Ansmann, Moritz Haarig, Ronny Engelmann, Holger Baars, Ulla Wandinger

**Das leistungsstarke Raman- und Fluoreszenz-Lidar MARTHA kann Aerosolpartikel von der Troposphäre bis hin zur unteren Stratosphäre erkennen und charakterisieren. Selbst in herausfordernden Situationen mit geringen Partikelkonzentrationen in der oberen Troposphäre und unteren Stratosphäre können Waldbrandrauch und vulkanisches Sulfat durch ihre unterschiedlichen Fluoreszenzeigenschaften nun eindeutig unterschieden werden. Im Sommer 2025 konnten so zahlreiche stratosphärische Rauchsichten von starken kanadischen Waldbränden über Leipzig beobachtet werden.**

## Introduction

The largest uncertainties in assessing and predicting climate change arise from aerosol particles and their interactions with clouds. Due to its high vertical and temporal resolution, lidar remote sensing is well suited to characterizing the vertical distribution of aerosol particles in the atmosphere. Most of the lidar-based aerosol studies focus on the (lower) troposphere, as the major fraction of aerosol load is found there. The upper troposphere and lower stratosphere (UTLS) are somewhat disregarded. This is partly because accurate aerosol detection and typing with lidar can be challenging in the UTLS region, especially in the case of low aerosol loads. In particular, the distinction between wildfire smoke and volcanic sulfate usually requires extinction-related aerosol properties, which are difficult to obtain properly at cirrus level and low aerosol optical depth. One option to tackle this problem is the usage of high-power lasers and large telescopes to increase the signal-to-noise ratio. Furthermore, the recently evolving fluorescence lidar technique can help to resolve UTLS typing problems by adding an additional intensive quantity – the fluorescence capacity, which was introduced by Reichardt [2014].

Once achieved, a robust aerosol typing in the UTLS can enhance the understanding of cirrus cloud formation. While background sulfate favors homogeneous ice nucleation, smoke particles can provide an

important ice-nucleating particle source for heterogeneous ice nucleation.

## Instrumentation and method

Both approaches discussed in the introduction are unified in the Multiwavelength Atmospheric Raman Lidar for Temperature, Humidity and Aerosol Profiling (MARTHA) – a high-power Raman lidar with fluorescence capabilities. Due to its high laser power of up to 89 W and the large main mirror with a diameter of 80 cm, the MARTHA lidar is well suited for stratospheric aerosol observations. The laser-induced aerosol fluorescence is detected with a broadband channel in a wavelength range from 444 to 488 nm. Similarly to Veselovskii *et al.* [2020], the fluorescence backscatter coefficient is derived from the fluorescence and nitrogen Raman backscatter signals. Technical details are described in Gast *et al.* [2025]. As an intensive property for aerosol typing, the fluorescence capacity  $G_F$  is calculated as the ratio of the fluorescence backscatter coefficient to the particle backscatter coefficient at 532 nm.

## Results and discussion

### Improved detection of thin aerosol layers.

Besides the capabilities of the fluorescence lidar technique to improve the aerosol typing [Veselovskii *et al.*, 2022], it can even enhance the detection of optically

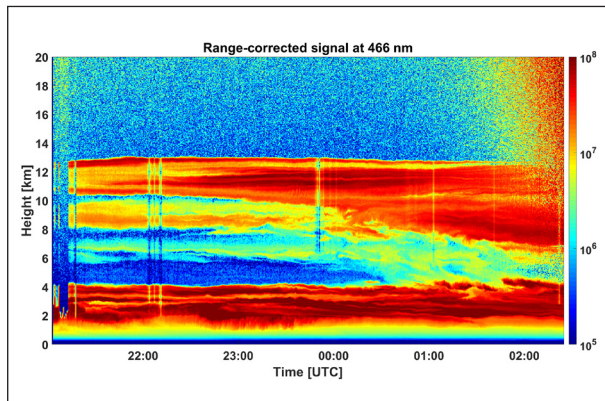


Fig. 1: Height-time distribution of the range-corrected fluorescence signal at 466 nm measured at Leipzig on 3-4 June 2025.

thin aerosol layers, especially in the UTLS region. In several measurement cases with an apparently low aerosol load in spring and summer of 2023, the information from the fluorescence channel clearly revealed the presence of smoke layers from Canadian wildfires that were not recognizable in the traditional elastic-backscatter signals. As the fluorescence emission is limited to aerosol particles only (air molecules and hydrometeors are excluded from this process), such a dedicated “particle” channel is valuable in situations with low particle concentrations and enables an unambiguous differentiation between aerosol particles and hydrometeors [Gast et al., 2025].

**Discrimination between smoke and volcanic sulfate.** While smoke typically exhibits high fluorescence capacities ( $G_F > 2 \times 10^{-4}$ ) [Veselovskii et al., 2022; Gast et al., 2025], volcanic sulfate is expected to show very low fluorescence, but up to now, observational evidence is rare [Hedelt et al., 2025]. In late winter and spring of 2025, optically rather thin layers of volcanic sulfate (aerosol-optical depth (AOD)  $< 0.02$ ) could be observed at Leipzig from the tropopause up to 25 km height. For the first time, the fluorescence of stratospheric sulfate was characterized. The sulfate aerosol showed very low fluorescence capacities of  $G_F \sim 1 \times 10^{-5}$ . These results demonstrate, that wildfire smoke and volcanic sulfate can be clearly discriminated by means of fluorescence lidar [Gast et al., 2026].

**The 2025 wildfire season.** 2025 was another year with exceptionally strong wildfire emissions in North America and Europe [CAMS, 2025]. At the end of May and beginning of June, strong wildfires in Canada triggered several pyrocumulonimbus (pyroCb) events, injecting large amounts of wildfire smoke up to the lower stratosphere. A high AOD near the fires of larger than 3 at 355 nm and the following long-range

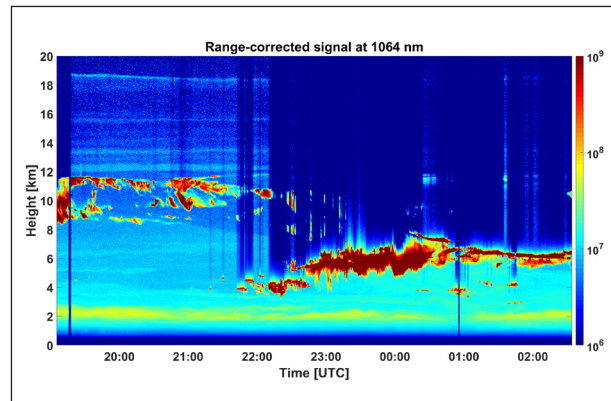


Fig. 2: Height-time distribution of the range-corrected lidar signal at 1064 nm measured at Leipzig on 5-6 July 2025.

transport of the smoke plume over the Atlantic Ocean could be observed by the Earth Cloud, Aerosol and Radiation Explorer (EarthCARE) satellite [Haarig et al., 2025]. Further results from EarthCARE are also described in a dedicated long article in this report.

When the first large smoke plume reached Europe in early June, a high smoke load was also measured with MARTHA at Leipzig. The AOD at 355 nm reached values of up to 2 at maximum. On the night of 3-4 June, large parts of the troposphere were covered by smoke layers, as can be seen from the strong fluorescence signals in Fig. 1. While at that time, the highest smoke layers were found at altitudes up to 14 km, the height of the stratospheric smoke layers observed at Leipzig gradually increased over the course of the summer. In early July, the highest smoke layer was located at around 19 km (see Fig. 2). Later in autumn, the smoke appeared to be vertically more diluted, being observed as rather homogeneous layer reaching from the tropopause up to 19-20 km altitude.

In general, smoke layers directly above the tropopause were observed quite frequently throughout the whole wildfire season. At the lower boundary of these smoke layers, often the formation of cirrus clouds was observed.

## Conclusion and outlook

The high-power Raman and fluorescence lidar MARTHA has proven its ability to detect and characterize aerosol particles throughout the troposphere and up to the lower stratosphere. Due to their different fluorescence properties, wildfire smoke and volcanic sulfate can be unambiguously discriminated, even in challenging low-concentration situations in the UTLS region. The relevance of these new technical capabilities became evident in the wildfire season of 2025, when pyroCb events triggered by huge

Canadian wildfires injected large amounts of wildfire smoke into the lower stratosphere. At Leipzig, the formation of cirrus clouds was frequently observed at the lower boundary of smoke layers directly below

the tropopause. As a next step, the microphysical properties of such cirrus clouds will be investigated in future using lidar-radar synergy to enhance the understanding of corresponding aerosol-cloud interactions.

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# Long time organic aerosol characterisation and source identification at Melpitz

Samira Atabakhsh, Laurent Poulain, Mira Pöhlker, Hartmut Herrmann

**Obwohl die europäischen Luftqualitätsvorschriften die Luftreinheit in Städten erheblich verbessert haben, bestehen nach wie vor große Wissenslücken über die Veränderungen der Aerosolquellen, da konventionelle chemische Tracer nur begrenzt einsetzbar sind. Die Online-Aerosolmassenspektrometrie überwindet dieses Problem, indem sie organische Quellen mit hoher zeitauflösender Qualität auflöst. Eine zehnjährige Messreihe mit einem Aerosolmassenspektrometer in Melpitz (2012–2022) zeigt eine starke Saisonabhängigkeit und ausgeprägte Ost-West-Kontraste bei anthropogenen organischen Aerosolen. Die PM1-Trendanalyse zeigt einen signifikanten Rückgang, der hauptsächlich auf winterliche Reduktionen und stärkere Verbesserungen in östlichen Luftmassen zurückzuführen ist.**

## Introduction

Atmospheric aerosol particles, quantified as particulate matter (PM), play a central role in climate forcing [IPCC, 2021] and significantly influence air quality, ecosystems, and human health ([Fowler *et al.*, 2009]). Their chemical variability reflects diverse emission sources, atmospheric processing, and meteorological conditions. In 2021 alone, exposure to fine PM levels exceeding the WHO guideline of  $5 \mu\text{g m}^{-3}$  was linked to 293,000 premature deaths across Europe [EEA, 2023]. This highlights the necessity of long-term measurements that capture not only PM composition but also changes in the contributing aerosol sources; an aspect that is still insufficiently characterized in Central Europe. The online aerosol mass spectrometers like the Aerosol Mass Spectrometer (AMS, DeCarlo *et al.* [2006]; [Jayne *et al.*, 2000] or the Aerosol Chemical Speciation Monitor (ACSM, Ng *et al.* [2011]) provide non-refractory aerosol chemical composition at high time resolution, which by using positive matrix factorization analysis on the organic fraction [F. Canonaco *et al.*, 2013; Francesco Canonaco *et al.*, 2021; Ulbrich *et al.*, 2009] make it possible to identify the main sources of the organic aerosol (OA) fraction of the particles. Therefore, based on a decade of ACSM measurements, the trend in the aerosol chemical composition and OA sources was investigated at the TROPOS research station Melpitz.

## Method

Long-term aerosol physico-chemical properties measurements are conducted at the TROPOS rural background station Melpitz ( $51.5255^\circ\text{N}$ ,  $12.9277^\circ\text{E}$ ; 86 m a.s.l.), located about 50 km northeast of Leipzig, Germany. Operating since 1992 by TROPOS [Spindler *et al.*, 2004; Spindler *et al.*, 2013] and integrated into the European Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) as well as the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (EMEP), the site is representative for Central European background conditions, and its typically influenced by southwesterly maritime air masses as well as, by dry continental inflow from the easterly wind associated with long-range transport (LRT) of particles (e.g. Spindler *et al.* [2010]).

From September 2012 to August 2022, non-refractory  $\text{PM}_{10}$  (NR- $\text{PM}_{10}$ ) components (e.g., organics, sulfate, nitrate, ammonium, and non-sea-salt chloride) were measured with an Aerosol Chemical Speciation Monitor (ACSM; Aerodyne Inc., USA, [Ng *et al.*, 2011]) at 30-minute time resolution, yielding 76 % data coverage. Measurements were completed with equivalent Black Carbon (eBC) derived from a multi-angle absorption photometer (MAAP, model 5012, Thermo Fischer Scientific, Petzold and Schönlinner [2004]) converted from  $\text{PM}_{10}$  to  $\text{PM}_{10}$  using a 0.9

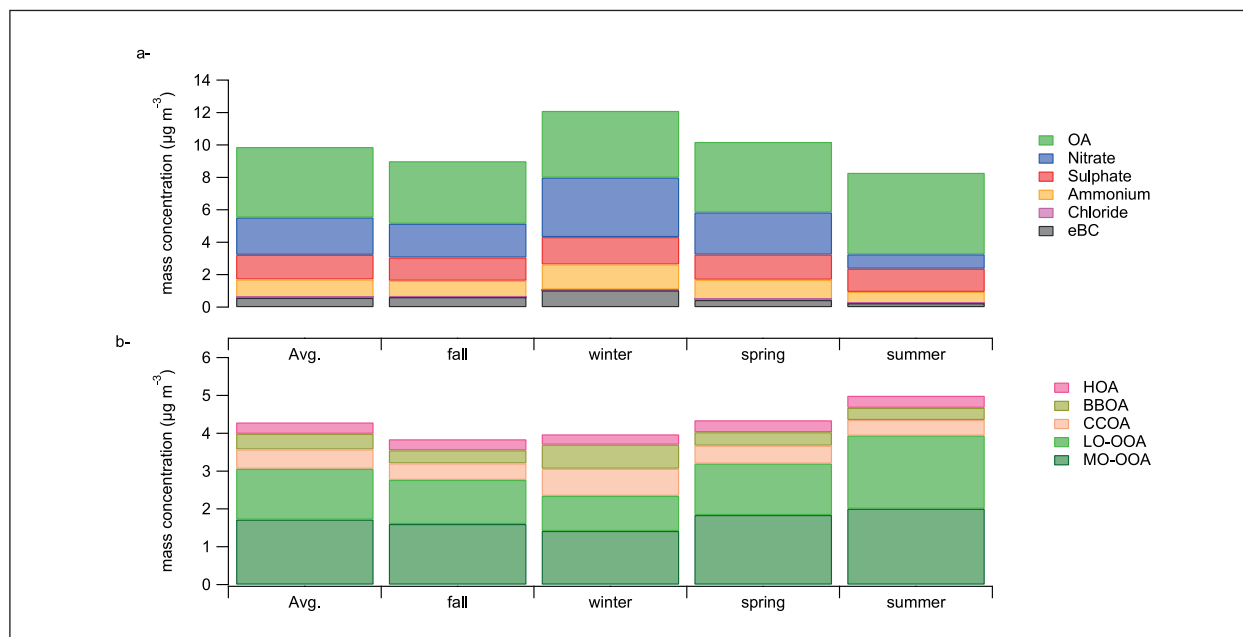


Fig. 1: Decadal averages mass concentration of (a) PM<sub>1</sub> chemical composition and (b) PMF-resolved OA sources.

scaling factor [L. Poulain et al., 2020], and particle number size distribution using a dual mobility particle size spectrometer (TROPOS type T-SMPS, Birmili et al. [1999]). All of the instruments were sampled through a common PM<sub>10</sub> inlet with controlled humidity ([Tuch et al., 2009]).

Additionally, Levoglucosan mass concentration, an atmospheric tracer for biomass burning emissions, was obtained from daily PM<sub>10</sub> quartz filters following the analytical method from Iinuma et al. [2009]. Trace gases and meteorological parameters were also available.

Source apportionment analysis of the OA was performed over the entire time period using yearly rolling PMF [Samira Atabakhsh et al., 2025; S. Atabakhsh et al., 2023; Francesco Canonaco et al., 2021] but using the same initialization parameters. All yearly results were then combined to obtain the final results. Additionally, eBC(PM<sub>1</sub>) contributions to POA factors were estimated via multilinear regression [Laborde et al., 2013; Laurent Poulain et al., 2021].

To connect these observations to regional transport, air mass origins were determined from wind direction and 96-h HYSPLIT trajectories [Draxler and Hess, 2004], while the Eastern-Western air mass classification was made following the approach developed for the station by Spindler et al. [2010]. Finally, PM<sub>1</sub> chemical composition and OA trends were quantified using the 3 pre-whitening (3PW) method developed by Collaud Coen et al. [2020].

## Result and discussion

The decade-long measurements at Melpitz showed an average PM<sub>1</sub> concentration of  $9.79 \mu\text{g m}^{-3}$ , with clear seasonality (Fig. 1), a winter maximum, and a summer minimum, consistent with previous studies using online or offline approaches made at Melpitz (e.g. Crippa et al. [2014]; Spindler et al. [2010]). Overall, OA dominated the PM<sub>1</sub> composition (44%), followed by nitrate (24%), sulfate (15%), ammonium (11%), and eBC(PM<sub>1</sub>) (6%), while chloride was negligible. The large OA fraction agrees with observations from other European rural background stations [Bressi et al., 2021].

Seasonal and interannual variability was substantial, particularly in winter, when PM<sub>1</sub> ranged from  $6.9 \mu\text{g m}^{-3}$  (2019–20) to  $16 \mu\text{g m}^{-3}$  (2016–17). Winter concentrations correlated with lower temperatures and reduced boundary-layer mixing. Nitrate showed the largest variability among inorganics, enhanced in spring by agricultural activities and in winter by ammonium nitrate formation. Summer nitrate concentrations decreased, mainly due to the semi-volatility properties of ammonium nitrate. Overall, western air masses carried more nitrate, while eastern air masses brought higher eBC(PM<sub>1</sub>) and OA, consistent with LRT from more polluted regions. OA peaked in summer due to enhanced secondary formation and contributed more under the influence of Eastern air masses.

Trend analysis (Fig. 2) revealed a significant decline in total PM<sub>1</sub> ( $-4.59 \text{ \% y}^{-1}$ , or  $-0.04 \mu\text{g m}^{-3} \text{ y}^{-1}$ ),

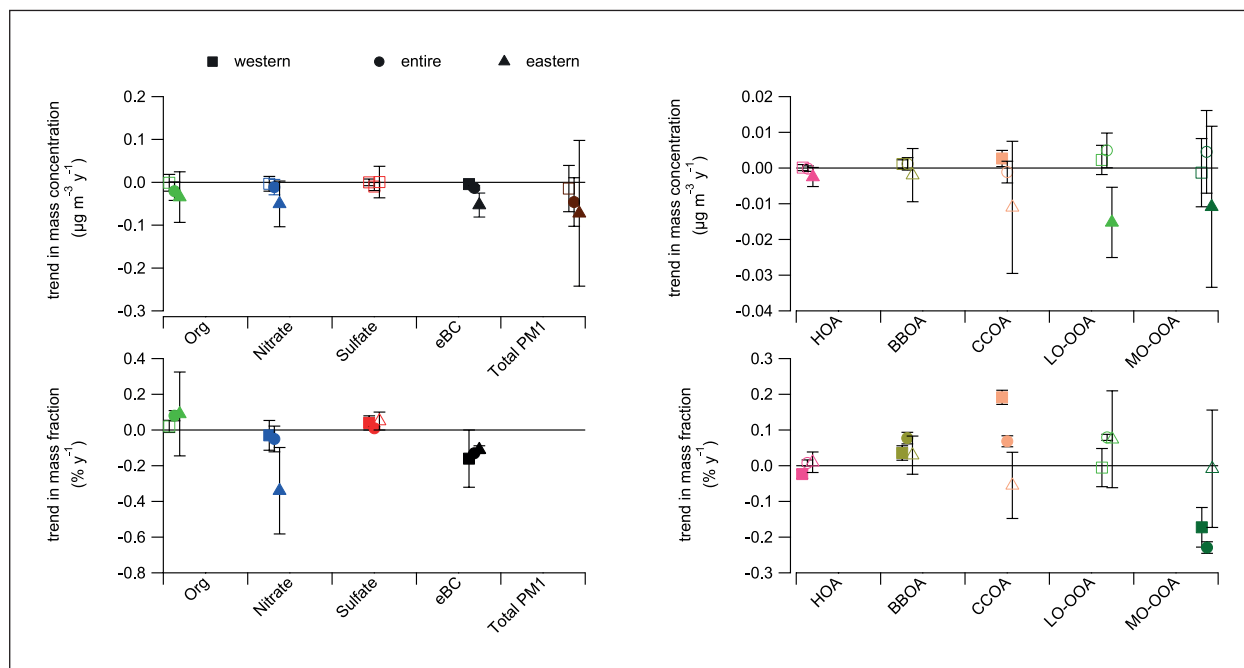


Fig. 2: Decadal 3PW trend results for Melpitz station showing long-term changes in mass concentration (top) and mass contribution (bottom) for (a) PM<sub>1</sub> chemical components and (b) PMF-resolved OA sources. Colored symbols denote statistically significant trends, while grey markers indicate non-significant trends. Trend slopes are shown for Western (■), entire dataset (●), and Eastern (▲) air masses, with vertical bars representing upper and lower confidence limits.

driven mainly by decreases in fall ( $-0.11 \mu\text{g m}^{-3} \text{y}^{-1}$ ) and winter ( $-0.12 \mu\text{g m}^{-3} \text{y}^{-1}$ ). Eastern air masses showed a stronger improvement with a decline of  $-28 \text{ \% y}^{-1}$  than Western ones, narrowing the historical pollution gap between the two air mass classes [Spindler et al., 2010]. Nitrate displayed a slight but significant negative trend, mostly within Eastern air masses, likely linked to  $\text{NO}_x$  emissions controls. Sulfate exhibited mixed seasonal trends—declining in fall and winter but increasing in summer, possibly reflecting enhanced secondary aerosol formation. eBC(PM<sub>1</sub>) showed a consistent decreasing trend across most seasons (overall  $-1.3 \text{ \% y}^{-1}$ ), reflecting reductions in combustion emissions. OA also slightly reduced on an annual basis ( $-2.05 \text{ \% y}^{-1}$ ), driven by winter declines, though its contribution increased in some seasons due to changes in PM<sub>1</sub> composition.

Source apportionment identified five OA factors: hydrocarbon-like OA (HOA, 7 % of total OA), biomass burning OA (BBOA, 10 % of OA), coal combustion OA (CCOA, 12 % of OA), low-oxidized oxygenated OA (LO-OOA, 31 % of OA), and more-oxidized oxygenated OA (MO-OOA, 40 % of OA). Secondary OA (LO-OOA + MO-OOA) dominated throughout the decade, especially in summer and under Eastern air masses, indicating strong photochemical and regional aging influences. Primary sources (BBOA and CCOA) increased markedly in winter (each contributed 24%

to OA) and were consistently higher under Eastern air flows, confirming their link to transported residential heating and coal-combustion emissions, respectively (Fig. 1). Trend analysis showed that primary factors generally intensified in contribution, even when absolute concentrations remained stable, suggesting shifts in regional heating practices and energy use (Fig. 2). In contrast, LO-OOA and MO-OOA showed season-dependent trends, with winter decreases and occasional warm-season enhancements, reflecting the sensitivity of secondary formation pathways to meteorology and precursor availability.

Our results emphasize that air quality regulation not only affects urban air quality but also affects background sites via long-range transport of atmospheric air masses. These results are relevant not only for air quality purposes but can also be used to improve the prediction of aerosols' physical properties, such as light absorption and scattering, as well as hygroscopicity, on a long-term basis. Including such a trend variation in aerosol modeling could also contribute to improving our knowledge of long-term variation in aerosol particle properties and ultimately contribute to the improvement of climate modeling.

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### Cooperation

MeteoSwiss  
University of Modena Reggio Emilia

# Microphysical properties of refractory black carbon aerosols for different air masses at a central European background site

Yifan Yang, Thomas Müller, Laurent Poulain, Samira Atabakhsh, Jens Voigtländer, Shubhi Arora, Mira L. Pöhlker

Schwarzer Kohlenstoff (Black Carbon, BC) ist ein bedeutender, lichtabsorbierender Bestandteil des atmosphärischen Aerosols, der das Klima beeinflusst. Untersuchungen zu den physikalischen Eigenschaften von BC in verschiedenen Luftmassen fanden im Sommer und Winter (2021) an der ACTRIS-Station Melpitz in Deutschland statt. Das an dieser Station gemessene Aerosol wird als repräsentativ für europäisches Hintergrundaerosol angesehen. Es zeigte sich, dass die Partikel im Sommer kleinere BC-Kerne und geringere Konzentrationen aufwiesen als im Winter. Durch photochemische Prozesse kam es tagsüber zu einer verstärkten Beschichtung der BC-Kerne. Weiterhin wurden in weit transportierten Luftmassen stärker beschichtete BC-Kerne beobachtet als in lokal beeinflussten Luftmassen. Im Winter wurden höhere BC-Massenkonzentrationen und größere Kerndurchmesser in Luftmassen aus östlicher Richtung im Vergleich zu solchen aus westlicher Richtung festgestellt. Emissionen aus Hausfeuerung beeinflussten die BC-Eigenschaften erheblich und führten zu größeren Kerndurchmessern sowie dickeren Beschichtungen. Ein verbessertes Verständnis dieser BC-Eigenschaften ermöglicht eine genauere Darstellung der optischen Eigenschaften von Aerosolen in Klimasimulationen.

## Introduction

Black carbon (BC), which is predominantly produced by the incomplete combustion of fossil fuels and biomass burning, is the most strongly absorbing atmospheric aerosol. Therefore, it exerts a substantial influence on the Earth's climate system [Bond *et al.*, 2013]. Current estimates of its direct radiative forcing vary widely from +0.1 to +1.0 W m<sup>-2</sup>, highlighting persistent challenges in accurately representing aerosol absorption in climate models [Wang *et al.*, 2016]. These uncertainties can be attributed to our limited understanding of the size distribution, mixing state, morphology, spatiotemporal distribution, lifetime, and absorption properties of BC, all of which require more representative and long-term measurements [Liu *et al.*, 2020]. Although numerous field studies have explored the mixing state of BC in Europe, the majority of this research has focused on short periods of pollution or single seasons. To address this gap and improve our understanding of the long-term variability in BC physical characteristics, we conducted detailed measurements of refractory black carbon (rBC) at the Central European

background site Melpitz during two contrasting periods, summer (August 2021) and winter (December 2021).

## Method

Backward trajectory analysis and wind direction patterns were used to identify different air mass characteristics at Melpitz during both seasons. The microphysical properties of refractory black carbon (rBC) within these air masses were characterised using a Single Particle Soot Photometer (SP2, Droplet Measurement Technologies, Longmont, CO, USA). The mass median diameter (MMD), derived from measured rBC mass size distributions, represented the average rBC particle size within a time window. Size-resolved coating thickness (CT) was also calculated to assess the rBC mixing state. In addition, an Aerosol Chemical Speciation Monitor (ACSM, Aerodyne Research, MA, USA; Ng *et al.*, 2011) was used to quantify the bulk chemical composition of non-refractory PM<sub>1</sub> species, including organic aerosol (OA), nitrate, sulfate, ammonium, and non-sea-salt chloride.

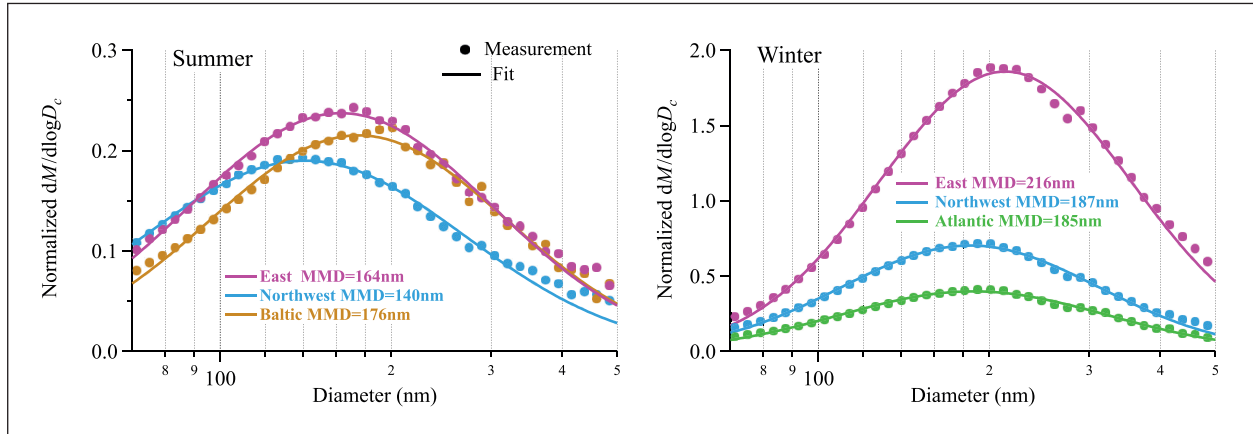


Fig. 1: Mass size distribution of rBC for each air mass in summer and winter. The circles show measurements, and the solid line represents the lognormal fit.

## Results and Discussion

Three characteristic air masses were identified in both seasons: two common air masses associated with east and northwest transport, and one season-specific air mass originating from the Baltic Sea in summer and from the Atlantic Ocean in winter. As shown in Fig. 1, in summer, rBC exhibited a similar mass concentration ( $\sim 0.16 \mu\text{g m}^{-3}$ ) among all air masses, with the smallest mass median diameter (MMD) of rBC observed in the long transportation from the northwest (140nm). While in winter, the highest rBC concentration ( $1.23 \pm 0.60 \mu\text{g m}^{-3}$ ) and largest MMD ( $\sim 216 \text{ nm}$ ) were found in easterly air masses, whereas the lowest concentration ( $0.23 \pm 0.12 \mu\text{g m}^{-3}$ ) and smallest MMD ( $\sim 185 \text{ nm}$ ) occurred in the western air mass from the Atlantic Ocean.

Figure 2 displays the diurnal variation of size-resolved coating thickness for the entire data set for

the two seasons. Within a season, the different air masses exhibited similar diurnal patterns. In summer, higher fractions of thickly coated rBC (CT $>50\text{nm}$ ) were observed in the afternoon, suggesting the contribution of photochemical processes to the mixing state of rBC. In contrast, winter showed high fractions of thickly coated rBC throughout most of the day, except between 15:00 and 21:00. The lower values are related to the lower emissions from residential heating due to the higher temperature in the daytime and the increased traffic during rush hour in the afternoon. Moreover, in the long-range transported air masses from the west were associated with higher ambient temperatures than the easterly-influenced air mass, potentially leading to less residential heating emissions. As a result, smaller core sizes and thinner CT were observed in these long-transported air masses.

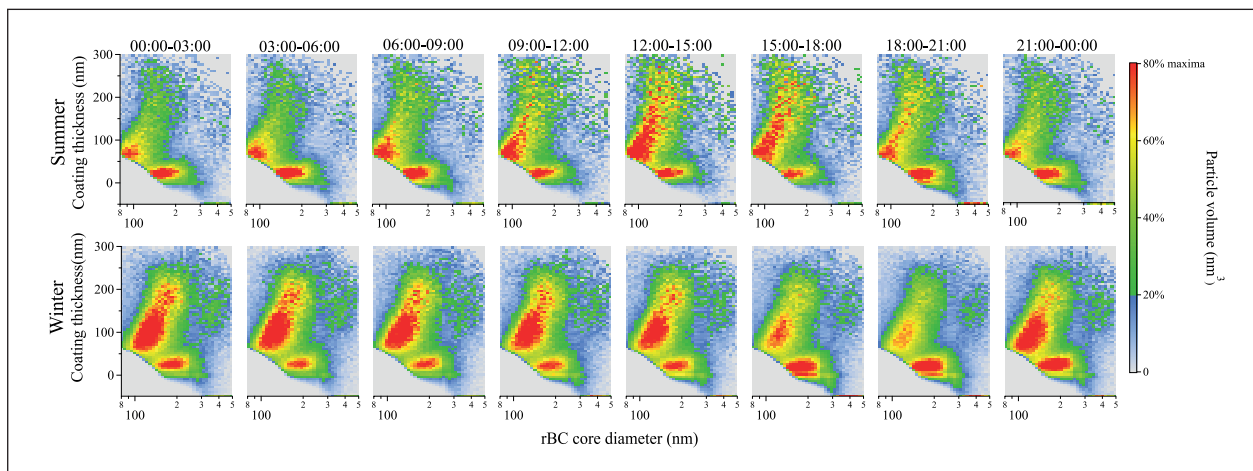


Fig. 2: Diurnal variation of size-resolved coating thickness and mass fraction of each type of rBC in the ambient sample. The panels for each season, from left to right, represent time intervals of 00:00–03:00, 03:00–06:00, 06:00–09:00, 09:00–12:00, 12:00–15:00, 15:00–18:00, 18:00–21:00, and 21:00–00:00. The color scale represents the total particle volume, with red set at 80% of the maximum value

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# The effect of bark beetle infestation on BVOC emissions, ozone and secondary organic aerosol

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**Vegetation emittiert fortwährend biogene flüchtige organische Verbindungen. Äußere Einflüsse und Stressfaktoren wie Lufttemperatur und Insektenbefall können die Emissionen einzelner Pflanzen beeinflussen und verändern. Dürreperioden in den vergangenen Jahrzehnten haben zu einer verminderten Resilienz von Koniferen geführt, welche daraufhin besonders anfällig für biotische Stressoren waren. In Mittel- und Nordeuropa sind und waren große Teile der Fichtenwälder von starkem Borkenkäferbefall (*Ips typographus*) betroffen. Die Verletzung des Baumes durch die Bohraktivität des Käfers führt zu erhöhter Harzproduktion, welches zu einem Anstieg der Emissionen flüchtiger organischer Verbindungen führt. Zur Simulation dieses Prozesses wurde eine Parametrisierung für stressbedingte biogene Emissionen entwickelt und in das Chemietransportmodell COSMO-MUSCAT integriert. In einer Simulationsstudie für das Jahr 2021 wurde gezeigt, dass die stressbedingten Emissionen zu einer Erhöhung der sekundären organischen Aerosolmasse führen und somit Auswirkungen auf die Luftqualität haben.**

## Introduction

Biogenic Volatile Organic Compounds (BVOC) are emitted constantly from vegetation and contribute about 90 % to the VOC inventory worldwide [Guenther *et al.* 1995]. BVOC are a plant communication tool in order to react to environmental changes and stressors. In the past decades the spruce bark beetle became an increasing threat to coniferous forests in middle and northern Europe. For reproduction purposes, the beetles bore holes into the stem of trees. Trees try to repel this attack by releasing large amounts of resin, which is a major source of stored BVOC [Zhao *et al.* 2011, Eller *et al.* 2013]. Bark beetle infested spruces emit up to 700 times more BVOC than healthy trees [Jaakkola *et al.* 2023]. BVOC are known as precursors of secondary organic aerosol (SOA), which further affects air quality and cloud formation processes. BVOC are also interacting in ozone formation and can together with anthropogenic VOC (AVOC) contribute to an increase in ozone in the context of high NO<sub>x</sub> concentrations.

## Methods

The biogenic emission module of the chemical transport model COSMO-MUSCAT (Consortium for small scale modelling – Multiscale Aerosol Transport model) [Wolke *et al.* 2012] parametrises BVOC emissions based on emission potentials of 138 plant functional types, which includes 116 single tree species [Luttkus *et al.* 2022]. This detailed emission module was extended by stem emissions and stress-induced emissions. The parametrisation of the stress related BVOC emissions is based on the seasonal cycle of the exponential population growth of spruce bark beetles. Start and end of infestation are retrieved from the analysis of infestation data provided by the phenological model PHENIPS (Phenological Model of *Ips typographus*) [Baier *et al.* 2007]. In 2021, 46 % of the spruce trees within Germany showed significant defoliation, much of which can be attributed to drought and bark beetle infestation [BMELH, 2022]. However, the exact extent of bark beetle infestation within spruce forests remains unclear, thus 46 % were

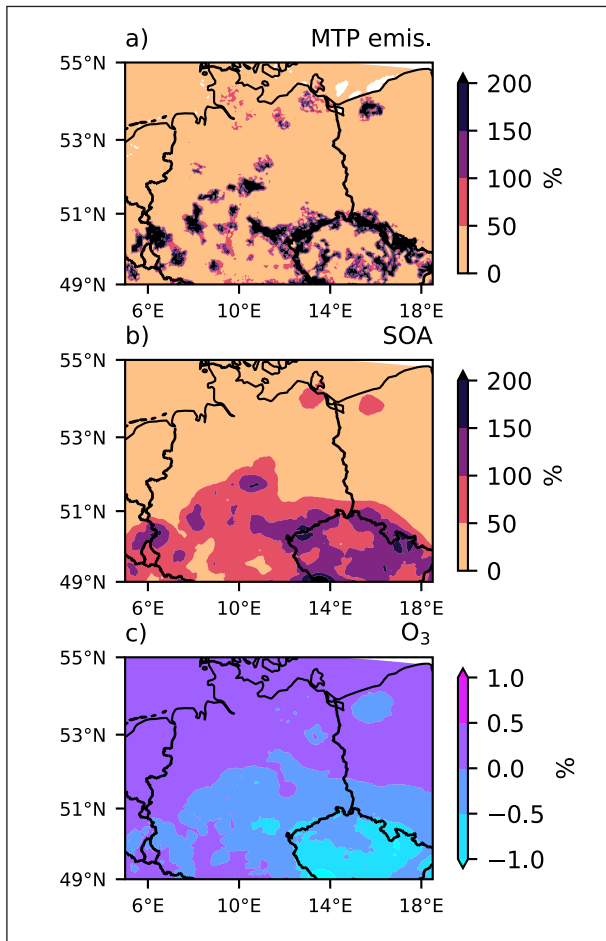


Fig. 1: Relative change under bark beetle stress within Germany centred domain for the seasonal average May to August 2021 for a) monoterpene emissions b) SOA concentration and c) ozone concentration.

assumed as an initial value for bark beetle stress. The applied standardised emission rates for  $\alpha$ -pinene, limonene and sesquiterpenes for healthy and bark beetle infested stem emissions are adopted from the findings by Jaakkola et al. [2023].

The newly developed parametrisation was integrated in COSMO-MUSCAT with the necessary adaptations for the standardised emission rates for *Picea abies* (Norway spruce). Simulated were a reference and a stress scenario for the growing season May to August 2021.

### Results and Discussion

Bark beetle stress especially increases monoterpene emissions (Fig. 1a) from storage structures of the tree. The tree species specific parametrisation enables to relate the effect to areas with abundant spruce trees. Thus, also effects on SOA are predominantly observed in those areas (Fig. 1b). The domain average SOA concentration for the growing period increases by 36 % due to bark beetle stress, and thus also PM<sub>2.5</sub> concentration increases (not shown here). SOA formation follows a strong diurnal cycle, with highest concentrations observed throughout the night. Major contributions to total SOA come from products from reactions of  $O_3$  and  $NO_3$  with lumped  $\alpha$ - and  $\beta$ -pinene (API). With the increased BVOC emissions due to bark beetle stress also the SOA composition is affected. Figure 2 shows the change in the contribution to SOA of the reaction products from the oxidation of relevant BVOC by OH,  $O_3$  and  $NO_3$  between stress and reference scenario. With the stress

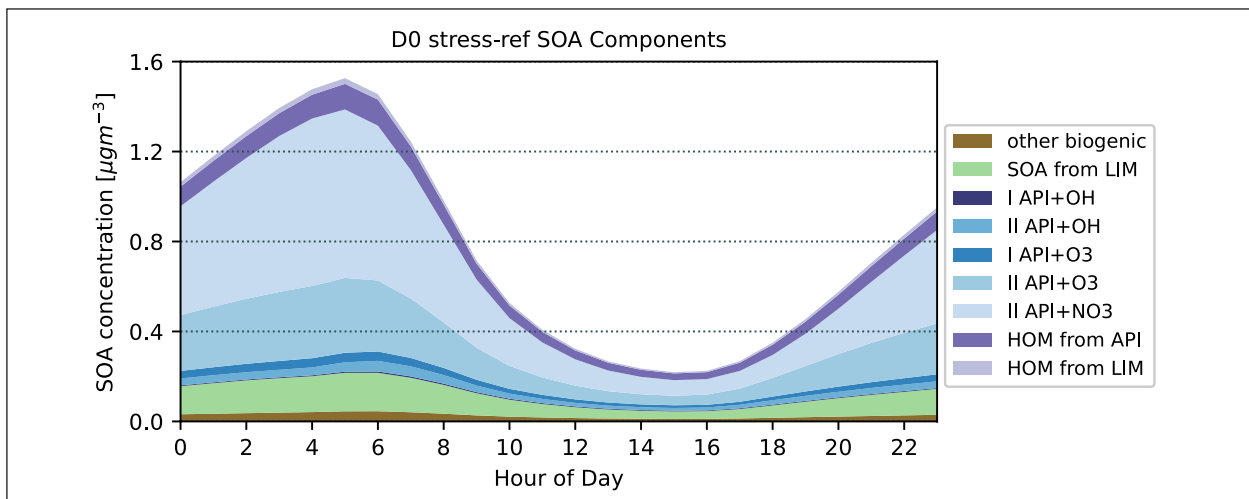


Fig. 2: Difference in the SOA composition between stress and reference scenario on seasonal and domain average [ $\mu g m^{-3}$ ]. Other biogenic comprises SOA products from isoprene, sesquiterpenes and biogenic aromatics, whereby the largest change comes from increased sesquiterpene contribution. The change in the contribution of SOA from limonene oxidation with OH,  $O_3$  and  $NO_3$  are summarised under LIM. The changes in the contribution from lumped  $\alpha$ - and  $\beta$ -pinene products (API) are differentiated between two volatility classes. The denotation I and II represent low and semi volatile, respectively. The change in the contribution from highly oxygenated molecules (HOM) is differentiated for products resulting from API and LIM.

parametrisation SOA formation from API products increases significantly, with a stronger effect during night. This is dominated by the semi volatile products from the oxidation by  $O_3$  and  $NO_3$  (II API+ $NO_3$  and II API+ $O_3$ ). The stress-related elevated limonene (LIM) emissions are as well reflected in the increased SOA production. Furthermore, the contribution of highly oxygenated molecules (HOM) increases, which are extremely low volatile oxidation products.

The effect on the ozone concentration on seasonal average is less pronounced on a regional scale (Fig.1c) with a tendency toward slightly decreasing concentration. However, comparisons of hourly and local concentrations show, that in single

spruce-rich areas during night a decrease in ozone concentration up to 8 % is possible.

SOA affects the amount of cloud condensation nuclei. Thus, increased monoterpene emissions caused by bark beetle infestation may have an impact on cloud formation and cloud radiative properties. With this the study contributes to a better understanding of the biosphere-atmosphere linkage. Stress-induced BVOC emissions are of increasing interest with ongoing changes in the climate system especially in the context of drought and heat events, and should be further considered in field and modeling studies.

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# Impact of wood combustion on air quality in Saxony: Field campaigns and first results

Nabil Deabji, Dominik van Pinxteren, Laurent Poulain, Jens Voigtländer, Hartmut Herrmann

**Im Rahmen des Projekts „Einfluss der Holzfeuerung auf die Luftqualität der Stadt Radeburg“ werden für das Sächsische Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG) die Auswirkungen des zunehmenden Einsatzes von Kleinf Feuerungsanlagen auf die Luftqualität in Sachsen untersucht. Der Fokus liegt auf der PM-Belastung durch primäre Partikelemissionen aus der Holzverbrennung und sekundärer Partikelbildung aus Vorläufergasen. Seit Oktober 2023 werden an einem temporären Messstandort in Radeburg umfassende Messungen durchgeführt, darunter kontinuierliche Spurengasmessungen, tägliche PM<sub>10</sub>-Filterprobenahme, VOC-Messungen sowie der Einsatz eines Sensornetzwerks. Zwei jeweils zweiwöchige Intensivmesskampagnen mit hochauflösenden Instrumenten ergänzen die Langzeitmessungen. Erste Ergebnisse zeigen deutliche Erhöhungen der Holzverbrennungsmarker während der Heizperiode und charakteristische Tagesgänge der Schadstoffkonzentrationen. Die Ergebnisse sollen Empfehlungen für Maßnahmen zur Reduktion der Luftbelastung durch Holzfeuerung unter städtischen Bedingungen liefern.**

## Introduction

The increasing use of wood burning for domestic heating in Saxony raises concerns about the impacts on local air quality [van Pinxteren *et al.*, 2023]. Wood combustion emits significant amounts of particulate matter (PM), including health-relevant components such as polycyclic aromatic hydrocarbons (PAHs) and black carbon [Simoneit *et al.*, 2002]. Primary particle emissions are accompanied by volatile organic compounds (VOCs) that contribute to secondary organic aerosol (SOA) formation during atmospheric aging. Additionally, improper fuel use, such as burning plastic waste, may further deteriorate air quality [Grahame *et al.*, 2014]. TROPOS is investigating these impacts for the Saxon State Office for Environment, Agriculture and Geology (LfULG) through the project “Impact of wood combustion on air quality in Saxony”. The project aims to comprehensively characterize PM pollution and its sources in a location with a high density of wood-burning installations, quantify the contribution of wood combustion to local air pollutant concentrations, and provide recommendations for pollution mitigation measures and future air quality monitoring strategies.

## Methods

Radeburg, a municipality northwest of Dresden with a wood-burning installation density exceeding

300 per km<sup>2</sup>, was selected as the measurement location. A temporary measurement station was established in October 2023 and has been operating through two heating periods (2024/25 and 2025/26). The measurement program includes continuous monitoring of trace gases (NO<sub>x</sub>, SO<sub>2</sub>, CO), equivalent black carbon (eBC, Aethalometer AE33), and meteorological parameters. At its core it contains daily PM<sub>10</sub> filter sampling using a Digital high-volume collector with comprehensive offline chemical characterization. VOC measurements (C<sub>2</sub>-C<sub>12</sub>, online TD-GC-FID) provide hourly data essential for modeling secondary particle formation, as shown in Figure 1.

Two-week intensive campaigns conducted at the end of January/beginning of February in 2025 in both heating periods deploy high time-resolution instruments including an Aerosol Chemical Speciation Monitor (ACSM) for PM composition, proton transfer reaction mass spectrometry for VOC analysis, and mobility particle size spectrometer (MPSS) for size distribution measurements. During these periods, filter sampling temporal resolution increases from 24 to 8 hours to capture diurnal variations. A network of eight battery-powered RAMP sensors measures PM<sub>2.5</sub>, CO, NO, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub> at distributed locations throughout Radeburg. Mobile backpack measurements using optical particle sizers and aethalometers during intensive campaigns provide spatial concentration patterns for particle size distribution and eBC.

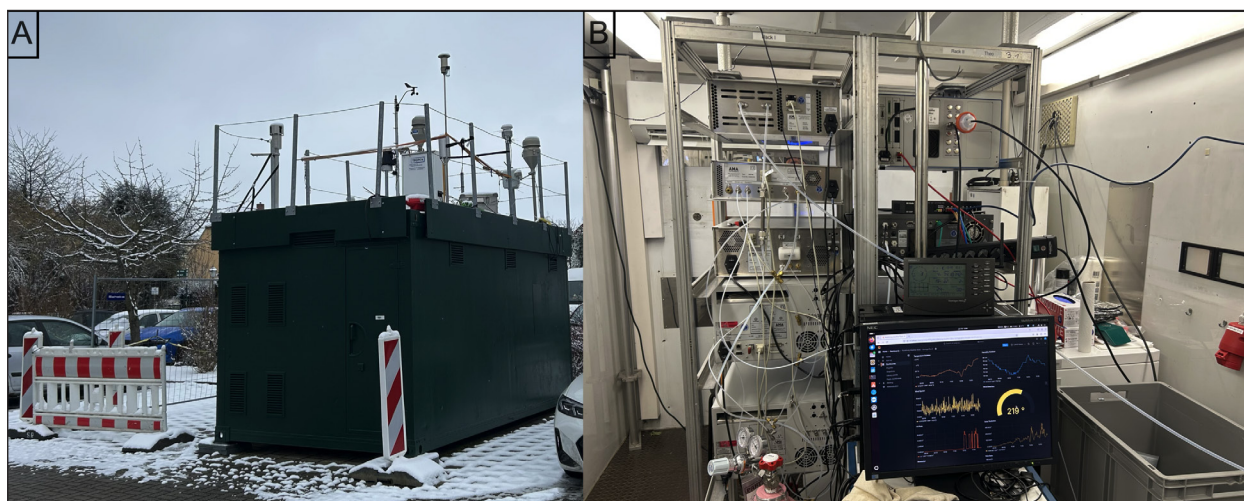


Fig. 1: Measurement infrastructure in Radeburg: (A) Container station equipped with multiple aerosol and gas inlets on roof platform; (B) Interior showing continuous monitoring instruments for trace gases, VOCs, and particulate matter, operational throughout two heating seasons (October 2024 – April 2025).

PM<sub>10</sub> filters undergo comprehensive chemical characterization including gravimetric mass, elemental and organic carbon (EC/OC), inorganic ions, wood combustion tracers (levoglucosan, mannosan, galactosan), PAHs, nitro-PAHs, hopanes (fossil fuel markers), methoxyphenols (lignin degradation products), and plastic combustion markers (triphenylbenzene, quaterphenyl). Oxidative potential measurements quantify health-relevant particle properties [Deabji et al., 2025].

### First results

**Seasonal and diurnal patterns.** Continuous measurements from October 2024 to April 2025 revealed pronounced seasonal variations in PM concentrations. Winter months, particularly February and March, exhibited PM<sub>10</sub> concentrations 2–3 times higher than autumn or spring periods, with mean values exceeding 20 µg m<sup>-3</sup>. Equivalent black carbon (eBC) concentrations followed a similar seasonality, reaching ~2 µg m<sup>-3</sup> during peak heating periods. Diurnal profiles showed characteristic evening and nighttime peaks for all PM size fractions, coinciding with residential heating activity. Source apportionment of eBC using the aethalometer model distinguished fossil fuel combustion (BC<sub>ff</sub>, morning peaks) from biomass burning (BC<sub>bb</sub>, evening/nighttime dominance), confirming wood combustion as the dominant driver of nocturnal pollution episodes.

**Biomass burning dominance during intensive campaign.** The January–February 2025 intensive measurement period captured substantial wood combustion impacts on air quality. PM<sub>10</sub> mass

concentrations averaged 31 µg m<sup>-3</sup> with a range of 12–61 µg m<sup>-3</sup>, with several episodes exceeding the EU daily limit of 50 µg m<sup>-3</sup>. Chemical analysis of 8-hour filter samples revealed OC as the dominant fraction with an average of 6.9 µg m<sup>-3</sup>. Levoglucosan concentrations reached high levels with up to 1100 ng m<sup>-3</sup>. Tracer-based quantification indicated that biomass burning contributed approximately 60% of measured OC and 50–55% of PM<sub>10</sub> mass during the intensive period. Secondary organic carbon accounted for ~56% of total OC, highlighting the importance of atmospheric processing. High-molecular-weight PAHs, including benzo[a]pyrene (up to 0.9 ng m<sup>-3</sup>) and the wood combustion marker retene, co-varied strongly with levoglucosan, demonstrating that residential heating emissions contribute both particulate mass and toxic organic pollutants in line with former findings [Poulain et al., 2011].

Figure 2 illustrates a pronounced influence of biomass burning on the observed aerosol composition during the intensive campaign. Levoglucosan concentrations show strong temporal variability, with pronounced peaks that coincide with elevated benzo(a)pyrene (BaP) levels, indicating a common combustion-related origin. Periods with the highest levoglucosan concentrations (up to ~1100 ng m<sup>-3</sup>) are consistently associated with enhanced BaP (up to ~7 ng m<sup>-3</sup>), supporting the dominance of residential biomass burning as a major source of carcinogenic PAHs during these episodes. Moreover, levoglucosan levels increase markedly during colder conditions, with the highest concentrations occurring at near-zero or negative temperatures, reflecting intensified domestic heating demand.

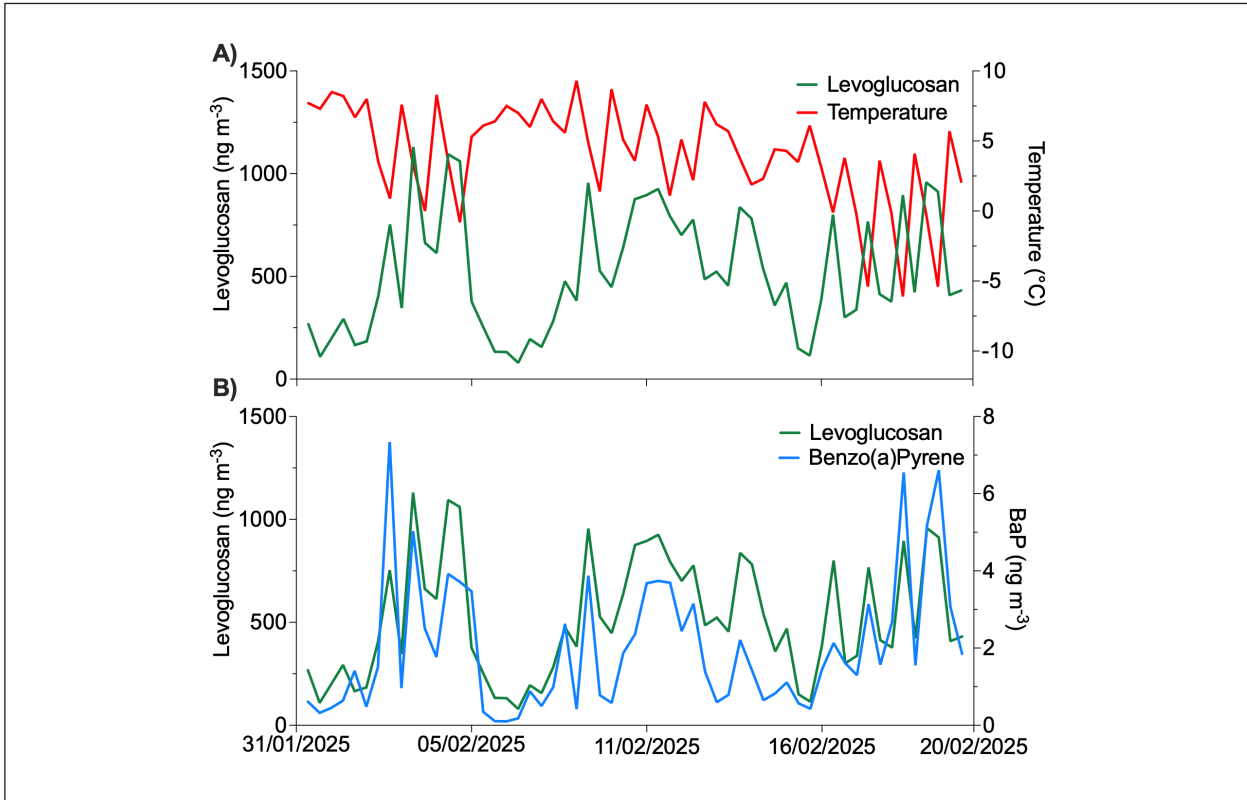


Fig. 2: (A) Time series of levoglucosan concentrations (green, left axis) and ambient air temperature (red, right axis) during the intensive measurement period, illustrating the relationship between biomass burning tracer levels and meteorological conditions; (B) Time series of levoglucosan (green, left axis) and benzo(a)pyrene concentrations (blue, right axis), highlighting the co-variation between biomass burning tracers and combustion-related polycyclic aromatic hydrocarbons.

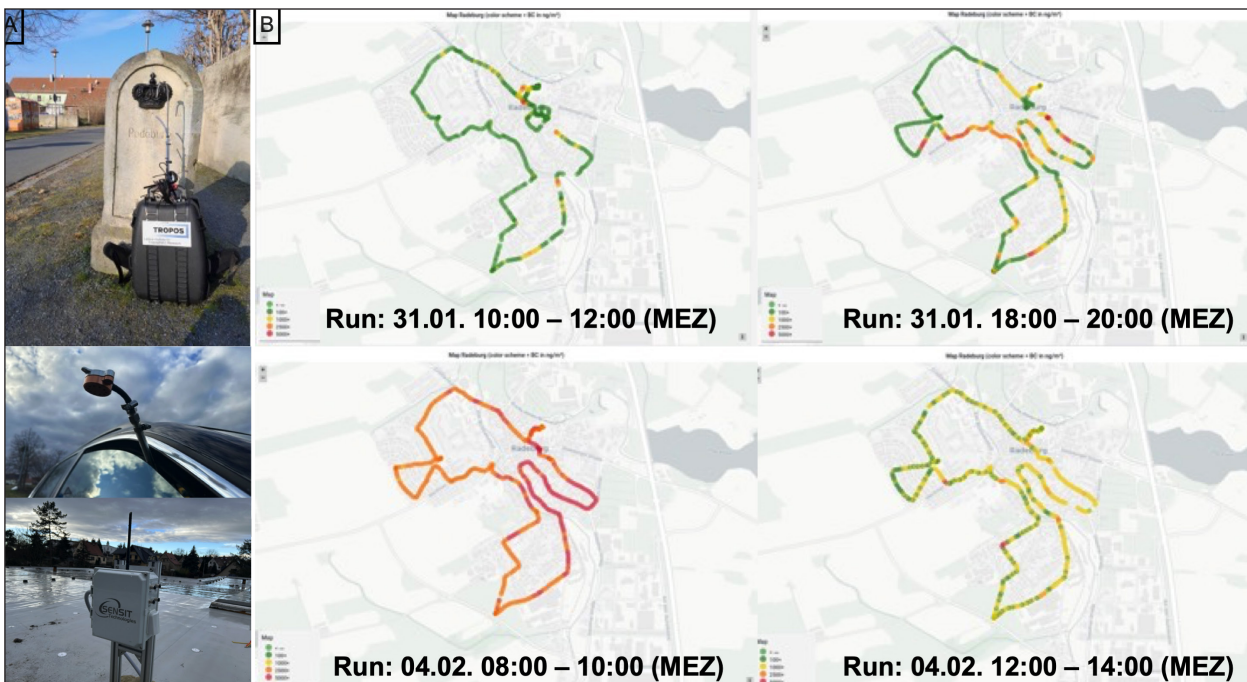


Fig. 3: Spatial pollution characterization: (A) Complementary measurement systems deployed during intensive campaign; (B) Backpack measurements reveal high eBC concentrations ( $>5 \mu\text{g m}^{-3}$ ) in residential heating hotspots during morning and evening periods, with substantial reduction during midday due to improved mixing. Maps show representative runs under temperature inversion conditions.

The combined co-variation of levoglucosan with both BaP and temperature provides robust evidence that biomass burning was a key driver of particulate pollution during the campaign, particularly under wintertime conditions.

**Mobile measurement across Radeburg.** To characterize small-scale spatial variability in air pollution, complementary measurement approaches were deployed during the intensive campaign, including mobile backpack measurements, stationary RAMP low-cost sensors distributed across the town, and mobile filter sampling for levoglucosan analysis at selected hotspots (Fig. 3A). Mobile backpack measurements conducted over six days (31 January – 8 February 2025) comprised 26 runs totaling more than 50 hours of high-resolution measurements along a ~7 km route through residential neighborhoods. These measurements captured equivalent black carbon (eBC), ultrafine particles (10–300 nm), and PM<sub>2.5</sub> concentrations with meter-scale spatial resolution. Under high-pressure weather conditions with morning temperature inversions typical of the measurement period, eBC concentrations reached values exceeding 5 µg m<sup>-3</sup>, with pronounced spatiotemporal differences across the town (Fig. 3B). Concentrations were consistently highest during morning (08:00–10:00) and evening (18:00–20:00) periods when residential heating activity was most intense and atmospheric mixing was suppressed by stable boundary layer conditions. Midday runs showed substantially lower concentrations due to improved vertical mixing and reduced heating demand. Clear spatial patterns emerged, with certain street segments and

neighborhoods consistently exhibiting elevated black carbon levels corresponding to areas with high wood stove density, while other areas remained comparatively cleaner even during peak heating hours. These high-resolution spatial measurements confirm that local emission sources create substantial exposure gradients within Radeburg, with residents in wood-heating hotspots experiencing significantly higher pollutant concentrations than those in less-affected neighborhoods. These findings corroborate the persistent spatial gradients observed in the RAMP sensor network, where sensors 1173/1174 consistently recorded elevated PM<sub>2.5</sub> concentrations compared to sensors 1052/1055, confirming that neighborhood-scale emission differences create reproducible pollution hotspots.

### Outlook

The project is ongoing, and the present results represent an intermediate status of the Radeburg field campaign. Further analyses are currently in progress, including an extended evaluation of the chemical composition of PM<sub>10</sub>, source apportionment using receptor modelling, and the integration of spatially resolved measurements from the sensor network and mobile observations. In addition, a second measurement phase is planned, including a dedicated intensive campaign, which will provide enhanced temporal resolution and complementary datasets. These forthcoming activities will allow for a more comprehensive assessment of seasonal variability, source contributions, and the impact of residential biomass burning on local air quality.

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# Chemical composition and sources of size-resolved particles in Leipzig over 25 years

Vanessa Engelhardt, Dominik van Pinxteren, Khanneh Wadinga Fomba, Laurent Poulain, Hartmut Herrmann

**Die langzeitliche Entwicklung größen aufgelöster Aerosolpartikel im Großraum Leipzig wurde durch ACD TROPOS und Kooperationspartner anhand von Messkampagnen in 1999/00, 2013/15 und 2023/24 untersucht. Starke Emissionsminderungen bei Verkehr, Kohleverbrennung und Industrie reduzierten ultrafeine und feine Partikelmasse um bis zu 85 %, während grobe, nicht abgasbedingte Anteile aus Straßenstaub und Abrieb zunahmen. Sekundäre Inhaltsstoffe verlagerten sich teilweise vom Akkumulations- in den ultrafeinen Bereich, Biomasseverbrennung bleibt im Winter sehr relevant, während neu auftretender Belastung aus östlichen Luftmassen episodisch von kriegsassozierten Ferntransporten aus der Ukraine erhöht wird.**

## Introduction

Particulate matter (PM) remains one of the most critical air pollutants affecting human health and climate in Europe [Pisoni *et al.*, 2025]. Despite substantial emission reductions, cities in Germany continue to exceed WHO Air Quality Guidelines, highlighting the need to understand how PM composition and sources evolve across particle sizes and environments. A recent size-resolved PM campaign in Leipzig (Saxony) in 2023/24, at a traffic site (LMI), an urban background site (TRO), and a rural background site (MEL), characterizes present-day aerosol concentrations, chemical composition, and sources. An assessment of 25-year changes in PM mass, composition, and source contributions, is then enabled by comparing the results from the recent campaign alongside two previous campaigns from 1999/00 [Herrmann *et al.*, 2006] and 2013/15 [van Pinxteren *et al.*, 2016] at the same three sites, thereby documenting how emission controls, atmospheric chemistry, and regional transport have reshaped air quality in Leipzig on a regional scale, over a multi-decadal timescale.

## Methods and sites

Particle samples were collected using Berner cascade impactors (75 L min<sup>-1</sup>, 24 h) covering five size ranges, from 0.05 to 10 µm aerodynamic diameter. Sampling was conducted over approximately 20 days per season, aiming at conditions of westerly (clean Atlantic) and easterly (more polluted continental) flow regimes. Samples were analysed for OC/EC, major and trace inorganic ions, trace metals and a suite of molecular markers (n-alkanes, hopanes,

PAHs, sugars, among others). For the last two periods, 2013/15 and 2023/24, source apportionment also relied on Positive Matrix Factorization (PMF) applied separately to each size fraction, complemented by crustal material reconstruction, carbon preference index calculations, and the Lenschow increment method to distinguish local, urban, and regional contribution.

## Results and discussion

Current size-resolved PM in Leipzig in Fig. 1 shows high mass concentration from fine mode PM for winter at all three sites, with the 0.42–1.2 µm range contributing the largest mass (about 5, 4.3, and 3.6 µg m<sup>-3</sup> at LMI, TRO, and MEL), and fine particles accounting for roughly 54–72 % of total PM across the urban to rural gradient. In summer, the distribution shifts towards coarse particles, with the largest stage reaching about 3.6 µg m<sup>-3</sup> at LMI compared to 2.8 µg m<sup>-3</sup> for the fine stage, reflecting enhanced road dust and soil resuspension under dry and warmer conditions.

Over 25 years, ultrafine and fine particle (0.05–1.2 µm) mass concentration shown in Fig. 2 decreased strongly between 1999/00 and 2013/15 (by roughly 60–85 % depending on size), and the fine particles continued to decline more slowly thereafter, while mainly coarse fractions have increased since 2013/15, particularly at MEL, indicating a shift from combustion to non-exhaust and dust-related PM.

A comparison of the PM sources between the period 2013/15 and 2023/24 in Fig. 3 confirms that exhaust traffic, which dominated in 1999/00, has become marginal and is no longer resolved as

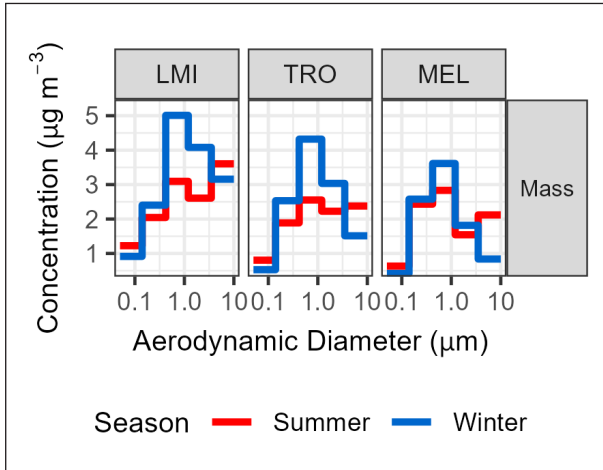


Fig. 1: Median size-resolved particle mass concentration during the summer and winter campaigns for the period 2023/24 at the three measurement sites (LMI, TRO and MEL).

a distinct factor in 2023/24, whereas non-exhaust traffic (tire and brake wear plus resuspension) now accounts for roughly half or more of traffic-related fine PM at urban sites LMI and TRO. Winter biomass burning remains a persistent contributor (often around 10–20 % of fine winter mass) [van Pinxteren et al., 2023], most pronounced under westerly conditions and traced by levoglucosan and PAHs.

Secondary particles have undergone a structural shift: fine-mode ammonium nitrate has roughly halved at traffic and urban sites, yet ultrafine secondary mass has increased by a factor of about 2 to 3, now contributing on the order of 20-35 % of submicron winter particles and implying a transition towards smaller particle sizes with potentially stronger health

relevance despite lower PM<sub>2.5</sub> mass. In summer, secondary inorganic and organic aerosol particles still dominates fine mass (around 60–80 %), closely tied to photochemistry and precursor availability, while non-combustion and biogenic sources such as soil/crustal dust play an increasingly visible but still minor role in the overall PM mass budget.

PM contributions from the East have decreased as reported by [Atabakhsh et al., 2025] for ultrafine PM, and also fine particles. The present results show, a new PM source for 2023/24, observable both seasons (winter and summer), with air masses backward trajectories reflecting a long-range transport origin mainly from the East, and with a chemical profile indicating war-related emissions, contributing on the order of 1 to 3 µg m<sup>-3</sup> across sizes, but mainly in the coarse size range. This profile represents an emerging transboundary source with hitherto unknown health implications.

### Conclusions and Implications

Over the past 25 years, Leipzig has shifted from a combustion-dominated PM regime to one increasingly shaped by secondary formation, mechanical abrasion, and other diffuse sources. Fine-particle concentrations have dropped by up to about 80-85%, but slower reductions since 2013/15 together with rising coarse fractions indicate that conventional exhaust controls in traffic and industries are not longer sufficient. Further air-quality gains will depend on coordinated control of ammonia and other secondary particle precursors, targeted management of non-exhaust emissions (tyres, brakes, road dust,

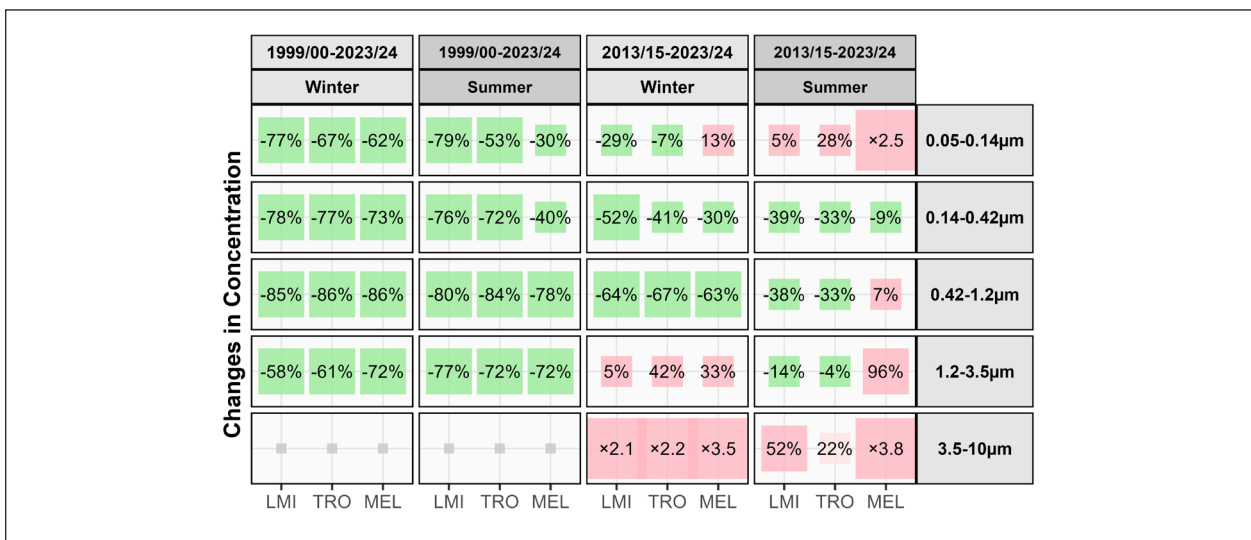


Fig. 2: statistically significant particle mass concentration changes in percentage % at LMI, TRO and MEL between 1999/00 and 2023/24 as well as between 2013/15 and 2023/24 for all size ranges and seasons. The square size represents the approximate magnitude of the change, the color represents the respective direction of the change (green = decrease, red = increase,  $p < 0.05$ ).

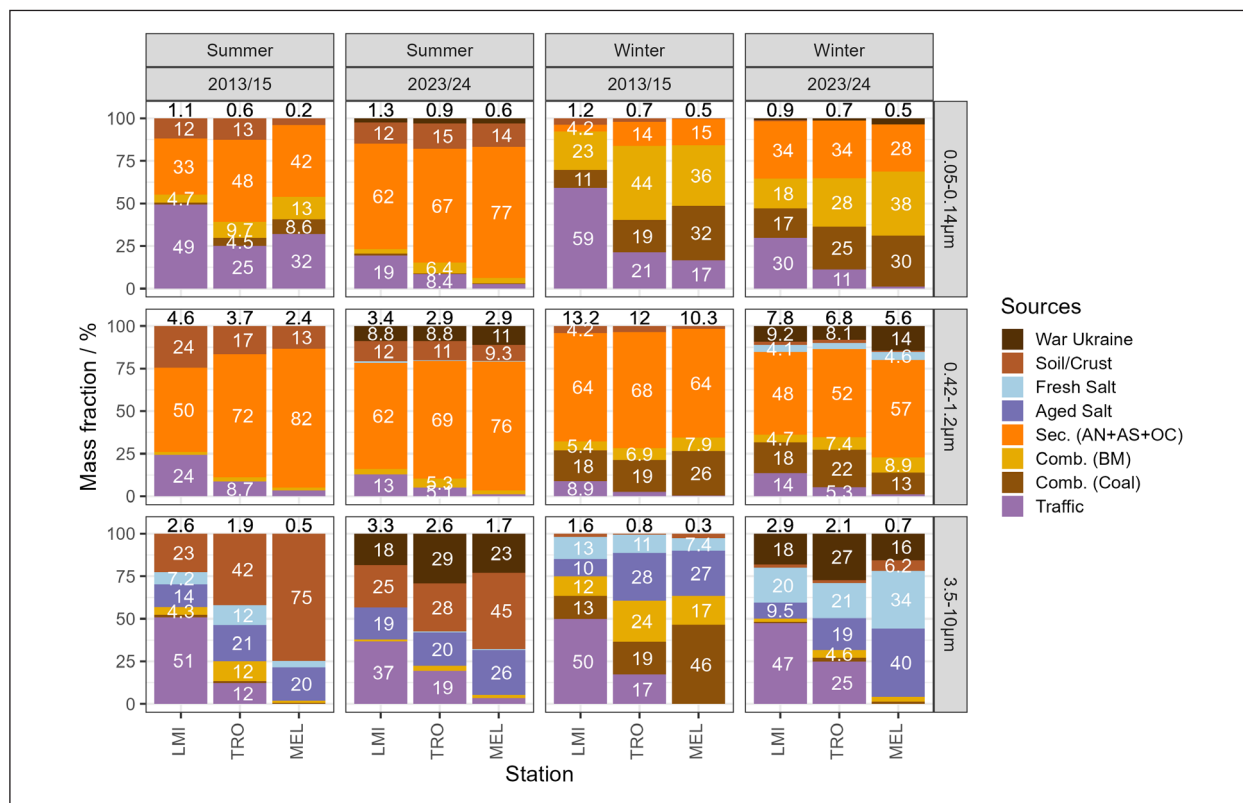


Fig. 3: Size-resolved PMF source contributions (% of stage mass) in harmonized source groups for 2013/15 and 2023/24 across particle sizes 0.05–0.14  $\mu\text{m}$  (Berners stage 1), 0.42–1.2  $\mu\text{m}$  (Berners stage 3) and 3.5–10  $\mu\text{m}$  (Berners stage 5) and categories.

drought-related soil dust), and stricter standards and enforcement for residential biomass burning. Maintaining long-term, size-resolved chemical monitoring

is essential to guide adaptive air-quality policy in a regime where secondary and non-combustion sources dominate.

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## Cooperation

LfULG

# LoCo-PM: Application and benefit of dense cost-efficient air quality networks for air quality modelling

Roland Schrödner, Honey Alas, Anna Sührig, Michael Weger, Jens Voigtländer

**Ein Netzwerk aus kostengünstigen Feinstaubsensoren wurde in Leipzig rund um ein amtliche Luftgütemessstation betrieben um den Mehrwert neuartiger Sensorik zu untersuchen. Alle Sensoren wurden kalibriert und mit Referenzinstrumenten verglichen. Zwischen den verschiedenen Standorten konnten Unterschiede im mittleren Tagesgang und Spitzenkonzentrationen festgestellt werden. Während der Messkampagne wurde die Rauchwolke eines Kellerbrandes an mehreren Standorten beobachtet. Dieses Ereignis wurde für einen Vergleich mit einem hochauflösenden urbanen Transportmodell herangezogen.**

## Introduction

22 cost-efficient (aka 'low-cost') commercially available particulate matter (PM) measurement devices were used in a diverse urban area in Leipzig, Germany. The instruments measure mostly PM<sub>2.5</sub>, some additionally PM<sub>10</sub>, and are equipped with methods for quality assurance such as sample air conditioning to a defined temperature and regular internal zero-point calibration. From July 2022 to September 2023, the measurement network was applied. It covers roughly 2x2 km<sup>2</sup> and holds different urban characteristics (e.g., residential areas, important main roads, city parks). At the centre of the network is an official air quality monitoring station located directly at a main road (Lützner Straße).

To investigate the variability across the instruments, all instruments were calibrated against reference measurements in the laboratory and in outside air. Also, the dependence of the agreement between reference and sensor PM<sub>2.5</sub> measurements on aerosol and meteorological conditions (e.g., temperature, secondary organic aerosol (SOA), humidity) was investigated. The measurement campaign was accompanied by regular mobile measurements [using backpacks, Alas *et al.*, 2018; Voigtländer *et al.*, 2021] of PM<sub>2.5</sub> and black carbon within the network.

## Evaluation

Before calibration, the cost-efficient instruments tend to underestimate reference measurements in the

lab by ~30 % and they show a considerable spread amongst each other. After calibration, they perform generally quite well, particularly for higher PM loads > 10 µg m<sup>-3</sup>. However, in ambient air the instruments still tend towards an underestimation of ~10-30 % compared to reference methods. The built-in sample air heating successfully avoids a dependence on relative humidity, partly on the expense of losing some of the volatile mass (e.g., SOA, nitrate).

Differences between different locations in the observation area could be observed in, e.g., the diurnal cycle but also peak and mean concentrations (Fig. 1). Due to the high time resolution (10 s raw data), short peak events such as New Year's fireworks or summer barbecues can be detected and compared to 'background' conditions at other stations in the network.

## High-resolution modelling

On 31 August 2023, a fire occurred within the measurement network close to the monitoring station Leipzig Lützner Straße (~50 m upwind of the station). The smoke plume emerged at ~18:08 from a cellar window (according to newspaper article), i.e., at ground level, and reached different stations in the network. Although the wind direction was northwesterly, the sites directly southeast of the fire location did not receive a measurable signal. Instead, first the instrument at the location of the monitoring station observed PM<sub>2.5</sub> concentrations of several 100 up to more than 1000 µg m<sup>-3</sup> (with an hourly average PM<sub>10</sub>

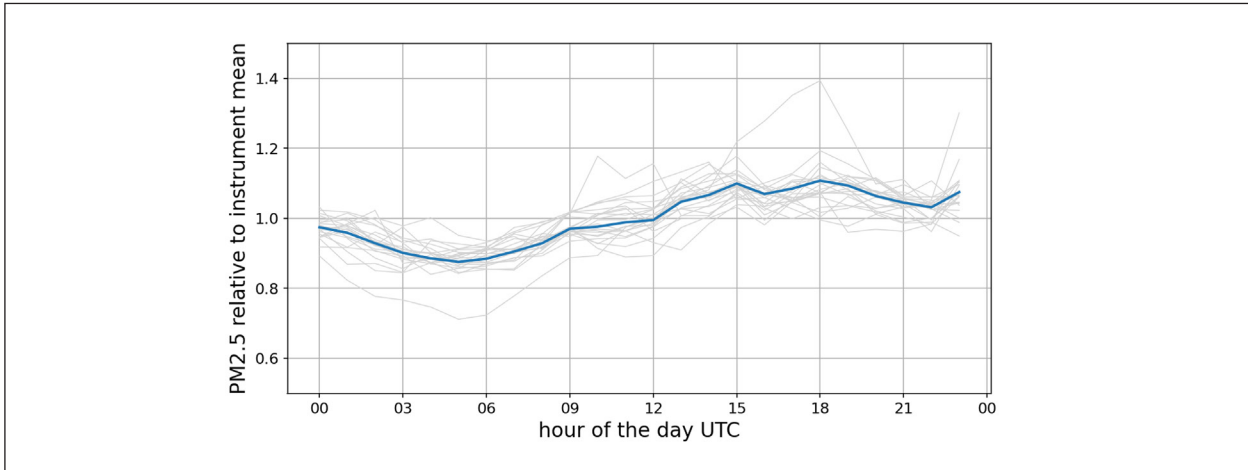


Fig. 1: PM<sub>2.5</sub> average relative diurnal cycle (blue: average over all instruments, grey: individual instruments) during winter 2022/2023 (Oct-Mar). Elevated concentrations in the late afternoon and evening can be seen as well as a pronounced minimum at around 06 UTC (07:00 local time). The increased concentration (offset) at 23 UTC is mainly due to the contribution of the New Year's fireworks.

concentration of  $120 \mu\text{g m}^{-3}$  observed by the monitoring station). About 10 minutes later, two stations further to east than indicated by the wind direction measured a sudden increase in PM<sub>2.5</sub> concentrations of  $10 - 20 \mu\text{g m}^{-3}$ , whereas the easternmost station received the plume a few minutes earlier than the other station. The smoke plume transport was investigated using the high-resolution dispersion model CAIRDIO [Weger et al., 2021; 2022]. The model was applied with a horizontal 10 m and a vertical resolution of 3 m close to the ground. It takes into account

the 3D structure of the buildings in the domain and can therefore represent air-flow canalization effects by street canyons. At the location of the fire, Lützner Straße is about  $\sim 15$  m wide and aligned by  $\sim 20$  m tall buildings and stretches out in east-west direction. Two simulations were carried out. In the first simulation, a point source was placed at the estimated location of the fire near the ground (1.5 m height), resulting in emissions mainly occurring within the Lützner Straße street canyon. In the second simulation, the respective point source was slightly shifted to the south

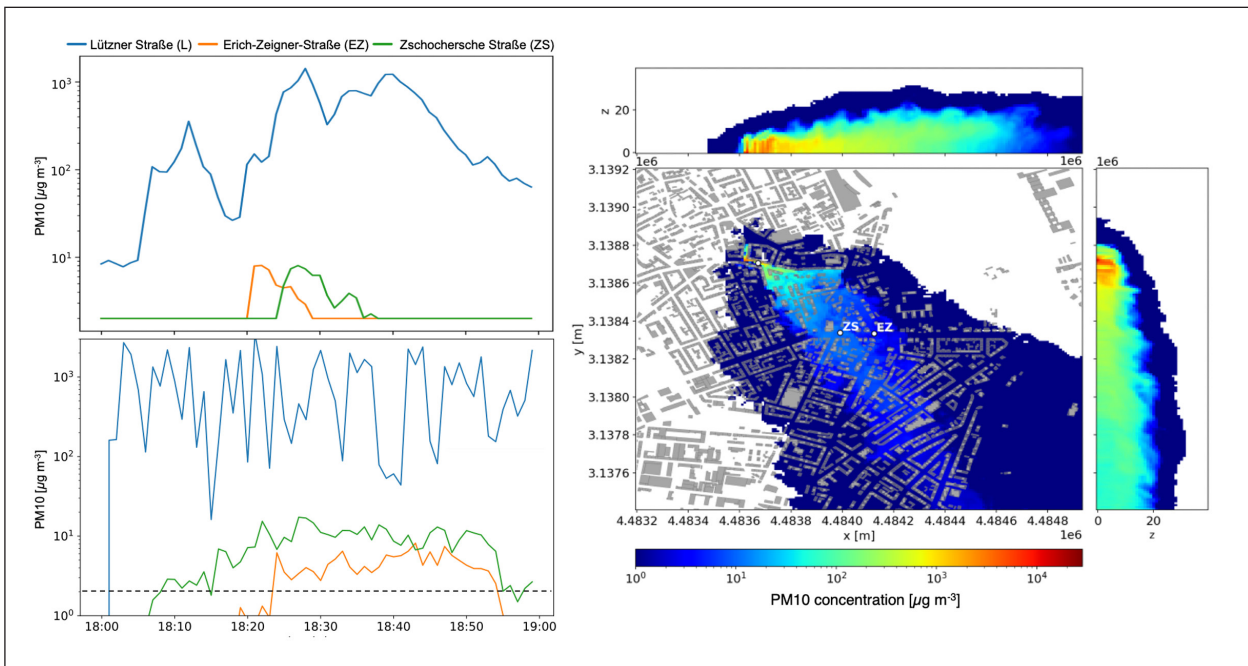


Fig. 2: Left: Time series at three measurement locations as measured (top) and simulated with CAIRDIO (bottom). Right: Simulation result at 18:31 showing the PM<sub>10</sub> concentration in the lowermost model layer and the zonal and meridional sum as curtain plot resulting from the dispersion of the correctly placed point source (first simulation).

(~10 m) within a backyard, so that the free dispersion with the prevailing wind direction (north-westerly) was not blocked by the buildings flanking Lützner Straße.

The low emission height resulted in an initially eastward dispersion along Lützner Straße in the first simulation with the correct location of the point source (Fig. 2). Just after encountering the first cross-section (~350 m from the fire location), the smoke plume turned southwards and was eventually lifted above the building roof tops. This dispersion pattern in the model could reproduce the 10–15 min time shift and the concentration difference between the nearest site and the two sites further to the east. In the second simulation with the wrong fire location, the plume was lifted too quickly and could not reach the monitoring station and only one of the other two stations. The modelling exercise demonstrated the canalization effect of the street canyon. Further, it proved the general capability of CAIRDIO to simulate high-resolution tracer transport by taking into account realistic building (i.e., obstacle) structures.

## Summary

The applied cost-efficient instruments applied in a dense network have the potential to be used in monitoring of air quality limit values, i.e., to indicate the exceedance of limit values in certain locations and therefore could provide a method to evaluate the placement of administrative high-quality monitoring stations and to identify (not yet monitored) air quality hotspots. The high time resolution and stable measurements allow for conclusions in relative terms, i.e., the propagation of short local peaks and temporally and spatially varying diurnal and weekly cycles (e.g., between main roads and city parks or between seasons). Such data is valuable for the development and evaluation of air quality models in general (e.g., diurnal cycles of emissions). Further, a high-resolution urban dispersion model was applied and validated using the measurement network.

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## Cooperation

Dr. Födisch Umweltmesstechnik AG, Markranstädt, Germany

# In situ and laboratory investigation of indoor air pollution using low-cost sensors: assessment of performance and source monitoring with participatory engagement

Andrea Cuesta-Mosquera, Jan-David Förster, Sebastian Düsing, Jens Voigtländer, Mira Pöhlker

**Luftschadstoffe in Innenräumen können gefährliche Konzentrationen erreichen, doch eine flächen-deckende Überwachung der Luftqualität in Innenräumen wird durch die Kosten und die Komplexität herkömmlicher Messgeräte eingeschränkt. Kostengünstige Sensoren bieten eine erschwingliche Alternative, erfordern jedoch aufgrund ihrer variablen Leistungsfähigkeit eine sorgfältige Charakterisierung. Im Rahmen des EDIAQI-Projekts hat TROPOS handelsübliche LCS-Sensoren durch Laborvergleichsmessungen evaluiert und AQBIE entwickelt, ein tragbares und benutzerfreundliches Multisensor-Messgerät für Luftschadstoffe in Innenräumen. AQBIE wurde unter Einbeziehung der Öffentlichkeit entwickelt und verfügt über interaktive Funktionen, mit denen Haushalte neben Luftqualitätsmessungen auch Aktivitäten in Innenräumen melden können. Laborergebnisse zeigten eine akzeptable Präzision, aber eine variable Genauigkeit im Vergleich zu Referenzgeräten, was die Notwendigkeit einer Kalibrierung unterstreicht. AQBIE demonstrierte eine konsistente Erkennung der Dynamik der Innenraumverschmutzung und untermauerte damit sein Potenzial für die kontinuierliche Überwachung, Expositionsbewertung und datengestützte Minderungsstrategien.**

## Introduction

Indoor air pollutants can reach hazardous levels and exceed outdoor concentrations, posing risks to human health [Manisalidis *et al.*, 2020]. However, understanding indoor air pollution (IAP) remains limited due to the diversity of emission sources and the complex dynamics of indoor pollutants [Saraga *et al.*, 2023]. Effective IAP monitoring requires reliable, interactive instrumentation and community participation to enable meaningful integration of pollution data, sources, and human activities. Conventional research- and policy-grade instruments are costly and operationally demanding, limiting widespread IAP characterization. Low-cost sensors (LCS) offer an affordable, low-complexity alternative, but their performance is variable and subject to uncertainty from environmental influences, manufacturing artefacts, and cross-sensitivities [Ródenas García *et al.*, 2022]. As a result, rigorous characterization is essential to ensure the reliability of LCS data.

Within the framework of the Evidence-driven indoor air quality improvement (EDIAQI) project, TROPOS has been working on the characterization and application of LCS to improve reliability and advance understanding of indoor dynamics and exposure to air pollution. This work was made through (i) laboratory characterization of commercial sensors and (ii) the development of an interactive IAP monitor.

## Characterization of low-cost sensors

The performance of several commercially available LCS from EDIAQI provider partners was characterized under controlled conditions (chamber and laboratory experiments) and in real-world settings (offices). The unit-to-unit variabilities, deviations from reference-grade instruments, and sensitivity to environmental parameters were assessed. The devices measured particulate matter (PM<sub>10</sub>, PM<sub>2.5</sub>), gases (CO, CO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>), temperature, relative humidity, and atmospheric pressure. Various IAP sources

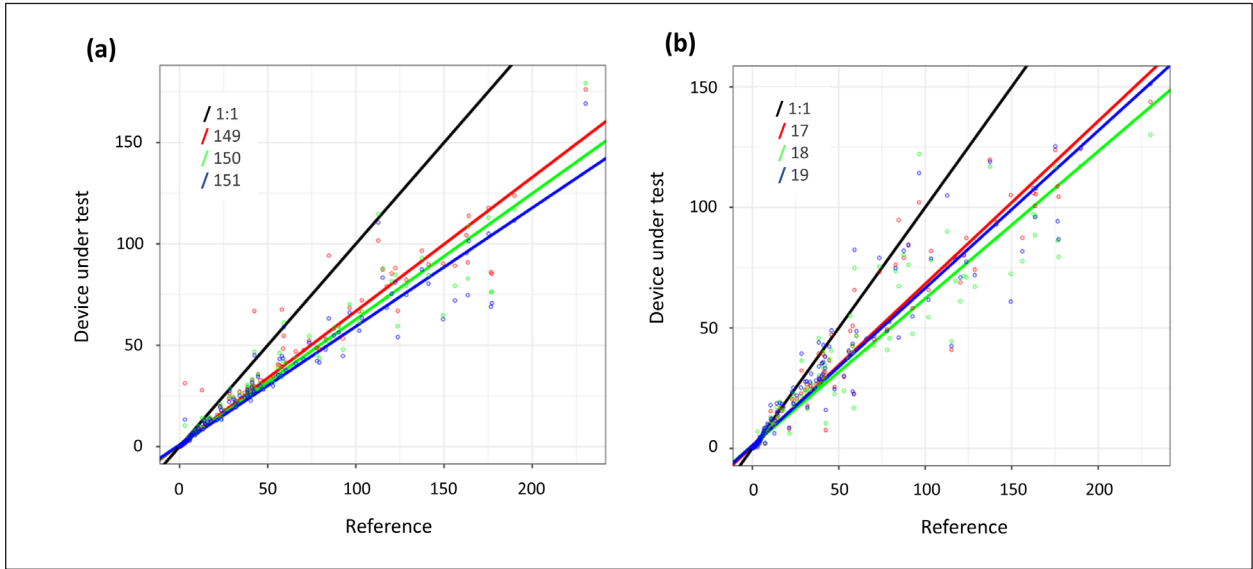


Fig. 1: Scatterplots of the comparison of PM<sub>2.5</sub> concentrations reported by LCS from EDIAQI commercial partners: provider 1 (a) and provider 2 (b), to a reference TROPOS set up (MPSS & OPC).

were assessed; for instance, incense, acetone, and ambient air were monitored in chamber experiments. Results support technical use recommendations across diverse setups and the development of data-correction algorithms.

Figure 1 shows the comparison of PM<sub>2.5</sub> concentrations reported by six LCS from two providers with respect to a TROPOS reference setup (a mobility particle size spectrometer [MPSS, 10-800 nm] and a regular-size OPC [300 nm to 10 μm], PNSD used to calculate PM<sub>2.5</sub>). The data correspond to chamber measurements of aerosols produced from incense burning (Max. PM<sub>2.5</sub> = 300 μg m<sup>-3</sup>). Overall, the LCS underestimated PM<sub>2.5</sub>. Provider 1 (P1, Fig. 1a) LCS slope and R<sup>2</sup> ranged between 0.342 and 0.391, and

0.728 and 0.777, respectively. Provider 2 (P2, Fig. 1b) LCS slope and R<sup>2</sup> ranged between 0.356 and 0.399, and 0.706 and 0.767, respectively. In this case, the LCS from P1 appear to better represent PM<sub>2.5</sub>. Yet, the results show that sensor measurements have limitations relative to reference instruments.

Overall, results indicate acceptable unit-to-unit precision across the LCS, whereas accuracy relative to reference instruments varied, underscoring the need for calibration prior to deployment. Although absolute concentration agreement with reference instruments was limited, the sensors exhibited stable, repeatable responses under laboratory conditions. Experiments provided a robust foundation for identifying the most suitable low-cost air quality monitors

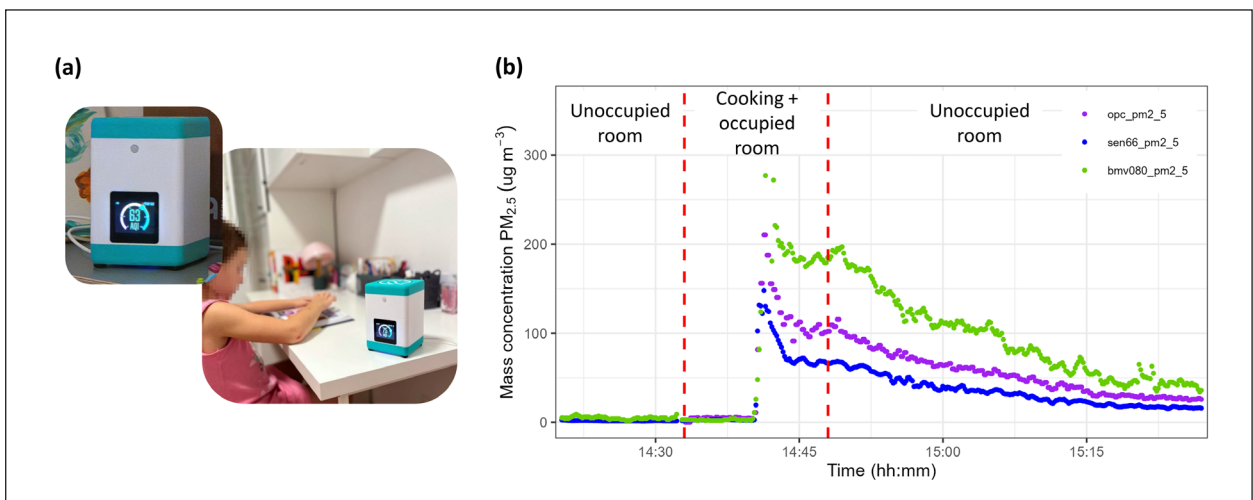


Fig. 2: (a) Photographs of the IAP monitor AQBIE and (b) Time series of PM<sub>2.5</sub> concentrations measured by the sensors and OPC incorporated in the monitor.

for long-term indoor air quality applications, based on performance and practical operational considerations.

### Development of a multi-sensor monitor

A portable multi-sensor monitor was designed to perform IAP measurements (Fig. 2a). The device, named AQBIE (Air Quality Beacon and Immission Evaluator), integrates commercial LCS and miniaturized optical particle counters (OPC, 300 nm to 10  $\mu\text{m}$ ) to monitor  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ ,  $\text{CO}_2$ , VOCs, and  $\text{NO}_x$  concentrations, particle number size distributions (PNSD), meteorological variables, and room motion. Compared with standard commercial IAP monitors, AQBIE employs three distinct PM sensors, which enhances source apportionment and improves discrimination between particle size fractions.

AQBIE was designed to assess children's exposure to IAP and features a robust, toy-like design. Community participation was incorporated into the design process through surveys that solicited participants to describe the ideal characteristics of an IAP monitor. As a result, the device is noiseless, user-friendly, and interactive, with activity logging that matches pollution variability to major sources (e.g., cooking, use of air purifiers, outdoor ventilation). These characteristics support data processing

and assessment of source-dependent impacts. Data transfer is supported via MQTT to remotely store and display real-time data. Also, local storage is enabled to prevent data loss in the event of connectivity issues.

From September to December 2025, a field campaign was deployed in fifteen households in Zagreb, Croatia, using AQBIEs. Data provide an overview of how air pollutants respond to different sources, household behaviour, weather conditions, and seasonality (autumn-winter).

Figure 2b presents preliminary results for  $\text{PM}_{2.5}$  concentrations measured using the AQBIE before, during, and after cooking in a single household. The coloured lines correspond to measurements from two sensors (BMV080 and SEN66) and to the calculated concentration from the PNSD obtained using the small-size OPC. Overall, the devices captured similar temporal patterns in  $\text{PM}_{2.5}$  concentrations, indicating consistent detection of indoor pollution events, despite differences in absolute values. In this case, the OPC and the SEN66 exhibited strong agreement in both temporal variability and concentration levels, whereas the BMV080 overestimated  $\text{PM}_{2.5}$  concentrations. AQBIE enables continuous, spatially distributed measurements, thereby opening new opportunities for large-scale indoor air quality studies and data-driven mitigation strategies.

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# Appendices





### Publications

#### Publication statistics

	2024	2025
<b>Total number of publications</b>	<b>409</b>	<b>492</b>
Books (author, editor) #	1	3
Book sections #	-	2
Contributions to collected editions #	9	4
Articles in peer reviewed journals #	124	130
Articles (others)	62	61
Presentations (invited)	18	18
Presentations (others)	165	241
Reports/Patents/Datasets/Software/Technical Notes/AV Material #	30	33

#### Publications #

##### 2024

- Aiyuk, M. B. E., Hoffmann, E. H., Tilgner, A., Wolke, R. and Herrmann, H.** 2024. A CAPRAM modeling study on the role of heterogeneous reactions on dust in tropospheric chemistry. *ACS Earth Space Chem.*, **8**, 2052-2066. <https://doi.org/10.1021/acsearthspacechem.4c00154>
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## Appendices: Publications

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## Appendices: University courses

### University courses

Lecturers	Lecture	WS 2023/ 2024	SS 2024	WS 2024/ 2025	SS 2025	WS 2025/ 2026
Baars, H., Engelmann, R., Floutsi, A., Gast, B., Haarig, M., Hofer, J., Jimenez, C., Seifert, P.	Active Remote Sensing of the Atmosphere using Lidar	x		x		x
	Seminar Active Remote Sensing	x		x		x
Beck, J., Tilgner, A.	Postgraduate programme: "Analytics and Spectroscopy" (atmospheric chemistry)		x			
Breitenstein, C., Arora, S., Bright, M., Kaushik, A., Poschart, E.	Seminar "Chemistry for physicians" and practice	x		x		
Breitenstein, C., Hell, M., Poschart, E.	Chemistry for medics					x
Carmona Martinez, E.	Master programme "Environmental Chemistry" at RWTH Aachen University, Lectures: "Plastics. An environmental problem."; "Sample Preparation"		x			
Deneke, H., Macke, A.	Leipzig Graduate School for Clouds, Aerosols and Radiation (LGS-CAR), Advanced Training Module LGS-CAR 16 "Remote Sensing of Cloud Development"	x				
Fomba, K. W.	Master programme in "Marine Science and Climate Change", Atlantic University, Cabo Verde, Course: "Ocean-atmosphere interactions"	x				
Haarig, M.	Leipzig Graduate School for Clouds, Aerosols and Radiation (LGS-CAR), Advanced Training Module LGS-CAR 17 "Scattering of irregularly shaped particles"		x			
Henning, S.	ACTRIS CAIS-ECAC Aerosol In-Situ Course, Guest Lecture: "Cloud Condensation Core Counters"		x			

## Appendices: University courses

Lecturers	Lecture	WS 2023/ 2024	SS 2024	WS 2024/ 2025	SS 2025	WS 2025/ 2026
Herrmann, H.	Atmospheric Chemistry, basics and exercise		x		x	
	Atmospheric Chemistry “The Multiphase System” and exercise	x		x		x
	Seminar Atmospheric Chemistry	x	x	x	x	x
	Practical course in atmospheric chemistry	x	x	x	x	x
	Atmospheric Chemistry, Shandong University	x		x		x
Hermann, M., Müller, T., Stratmann, F., Pöhlker, M.	Atmospheric Aerosols, Master	x	x			
	Seminar Atmospheric Aerosols	x				
Heinold, B., Kubin, A., Mustard, F., Schrödner, R., Tegen, I.	Scales and Parameterisations of Atmospheric Models and practical course		x		x	
Macke, A.	Atmospheric Radiation		x		x	
Macke, A., Deneke, H., Hünerbein, A., Bley, S.	Satellite Remote Sensing and exercise		x		x	
Macke, A., Hartmann, S., Stratmann, F., Wex, H.	Cloud Physics and Exercise		x		x	
Mothes, F.	ACTRIS CAIS-ECAC Aerosol In-Situ Course, guest Lecture: “Organic tracers”				x	
Pöhlker, M.	Atmospheric Aerosol and exercise	x		x		x
	Aerosol Physics		x		x	
	Practical Aerosol measurements		x	x	x	x
	Lecture as part of the lecture series on education and sustainability at Leipzig University, entitled: “Aerosol as a Climate Driver”			x		

## Appendices: University courses

Lecturers	Lecture	WS 2023/ 2024	SS 2024	WS 2024/ 2025	SS 2025	WS 2025/ 2026
Seifert, P.	Remote Sensing of the Atmosphere with Radar and Microwave Radiometer and exercise	x		x		x
Tegen, I.	Modelling of atmospheric trace substances	x		x		x
	Seminar Modelling of Atmospheric Trace Substances	x		x		x
	Modelling the Atmosphere		x		x	
	Contribution to module SQ15 “Energy and Environment”, Leipzig University: “Transport of Atmospheric Pollutants”			x		
	Basics of Mesoscale Models and practical course	x			x	
van Pinxteren, M.	Guest lecture: “Analysis and spectroscopy: gas chromatography”, lecture as part of a one-week course	x		x		
van Pinxteren, D.	Postgraduate studies: “Analytics and Spectroscopy”, guest lecture on atmospheric chemistry and analytics		x			
Wandinger, U.	Scattering and Atmospheric Optics	x		x		x
	Seminar Applied Scattering Theory	x		x		x
Zeppenfeld, S.	“Ocean-Atmosphere Interactions” at The fifth Sino-European School on Atmospheric Chemistry (SESAC5), Shanghai, China					x

## Academic degrees

### Completed academic qualifications

Academic degree*)	Name	Title	Faculty	Year
Ph.D.	Akansu, E.	Estimating the surface mixing layer height in the Arctic atmospheric boundary layer using tethered balloon-borne observations	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Bauer, T.	Multirate time integration methods and their application for coupled atmosphere-ocean models	Martin-Luther-University Halle-Wittenberg, Faculty of Natural Sciences II - Chemistry, Physics and Mathematics	2025
	Deabji, N.	Characterization of the chemical composition of atmospheric particles at ATLAS UM5 Station	Leipzig University, Faculty of Chemistry and Mineralogy	2025
	Hajipour, M.	Identification of hydrometeor types in Doppler spectra from polarimetric cloud radar observations	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Kwieszinski, C.	Developments concerning the chemical characterization of airborne aerosol particles	Leipzig University, Faculty of Chemistry and Mineralogy	2025
	Leon-Marcos, A.	Modelling emission patterns and trends of primary marine organic aerosol with focus on the Arctic	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Luttkus, M.	Biogenic emissions and urban air quality modelling: Development and application of a new gas-phase chemical mechanism and semi-explicit gasSOA approach	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Madueño, L.	Experimental quantification of respiratory tract deposition of black carbon	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Marvel, A.	Heterogeneous and interfacial chemistry model development and simulations on aerosol particles and cloud droplets: CAPRAM-HET	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Mettke, P.	Aerosol simulation chamber investigations of inorganic and organic peroxides and their role in atmospheric multiphase chemistry	Leipzig University, Faculty of Chemistry and Mineralogy	2024

## Appendices: Academic degrees

Academic degree*)	Name	Title	Faculty	Year
Ph.D.	Pilz, C.	Investigating the vertical aerosol distribution above the Arctic Sea ice with a tethered balloon	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Romshoo, B.	Influence of the complex morphology of soot particles on their optical properties: Numerical simulations and applications to atmospheric soot.	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Souza, E. J. dos Santos	Reactive Chemical Properties of Saharan Aerosol Particles: Insights into Partice-bound Mercury and Oxidative Potential	Leipzig University, Faculty of Chemistry and Mineralogy	2025
	Weger, M.	Urban air-pollution modelling at gray-zone resolutions	Leipzig University, Faculty of Physics and Earth System Sciences	2024
Dipl.-Ing. (FH)	Böhm, W.	Korngrößendifferenzierte Aerosolcharakterisierung als Indikator der Schwermetallbelastung der Luft 2024/25 in Freiberg	TU Bergakademie Freiberg, Faculty of Chemistry, Physics, and Biosciences	2025
	Potts, H.	Experimentelle und numerische Charakterisierung eines aktiven Gitters zur Erzeugung turbulenter Strömungen	TU Bergakademie Freiberg, Faculty of Mechanical, Process and Energy Engineering	2024
M.Sc.	Eckermann, O.	Antarctic particles and where to find them	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Fischer, S.	Untersuchung von Bioaerosol- und eisnukleierenden Partikel-Populationen an der Hintergrund-Messtation Melpitz in Zusammenhang mit Saharastaub-Ereignissen	Friedrich Schiller University Jena, Institute for Inorganic and Analytical Chemistry	2025
	Fritzsich, F.	Validation of the novel coherent Doppler-lidar ProDoLi	Ernst Abbe University Jena, University of Applied Sciences	2024
	Gaudek, T.	Co-located observations of liquid and ice precipitation hydrometeors with a two-dimensional video disdrometer, a holographic cloud in-situ probe, and active remote sensing	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Gebauer, H.	Characterisation of the annual cycle of aerosol and clouds over Mindelo (Cabo Verde) by means of continuous multiwavelength lidar observations	Leipzig University, Faculty of Physics and Earth System Sciences	2024

## Appendices: Academic degrees

Academic degree*)	Name	Title	Faculty	Year
M.Sc.	Kellermann, M.	Tethered balloon measurements of Arctic Ultrafine Aerosol Particles during Melting Season 2024	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Kunze, P.	Toward Convection-Resolving Dust Emission Modeling	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Mikhalkov, M.	Seasonality and origin of vertical aerosol distribution profiles observed between 2021-2022 in Ny-Ålesund	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Müller, M.	Role of Atmospheric Rivers for the Supply of Cloud Condensation Nuclei and Ice Nucleating Particles in the Arctic	Universität Bremen, Institute for Geography	2025
	Pieper, L.	Insights into the turbulence structure and microphysical properties of “dusty cirrus” from lidar-radar synergies	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Pietsch, P.	Untersuchung der Kinetik der Reaktion von Sulfit mit ISOPOOH	Leipzig University, Faculty of Chemistry and Mineralogy	2025
	Ramezankhah, B.	Marine Carbohydrates in Surface Seawater and Aerosol Particles over the Heavily Human-Impacted Environment of the Indian Ocean	Leipzig University, Faculty of Chemistry and Mineralogy	2025
	Senff, P.	Investigation of the temperature dependences of Fenton reactions involving oxalic acid and study of the reaction system	Leipzig University, Faculty of Chemistry and Mineralogy	2024
	Wackermann, J.	Titel The Effect of Bark Beetle Infestation on Secondary Organic Aerosol and Ozone	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Walter, G.	Development of a Dust Detection Algorithm for EarthCARE’s Multi-Spectral Imager	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Wetzel, B.	Comparing cloud residual and ambient aerosol particle size distribution for a better understanding of low Arctic cloud formation	Leipzig University, Faculty of Physics and Earth System Sciences	2025

## Appendices: Academic degrees

Academic degree*)	Name	Title	Faculty	Year
M.Sc.	Wieltch, J.	Analysing pollen measurements from a holographic fluorescence spectrometer at the rural background station Melpitz	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Winter, H.	Entwicklung und Konzeption eines Aerosoleinschubs zur Partikelmessung mittels der hubschraubergetragenen Plattform ACTOS	Leipzig University of Applied Sciences (HTWK Leipzig)	2025
B.Sc.	Hardt, A. M.	Ice formation in supercooled stratiform clouds over the Swiss Plateau	TU Bergakademie Freiberg	2024
	Höschele, D. C. F.	Investigation of the kinetics and reactivity of halogen-containing radicals in aqueous solution	Leipzig University, Faculty of Chemistry and Mineralogy	2024
	Küchler, J.	Globale Analyse der potenziellen Bedeutung von sekundärer Eisproduktion	Leipzig University, Faculty of Physics and Earth System Sciences	2025
	Lamprecht, M.	Implementierung eines Subgrid-Scale-Fluktuationsmodells für Temperatur und Wasserdampfgehalt in OpenFOAM	TU Bergakademie Freiberg, Faculty of Chemistry, Physics, and Biosciences	2025
	Lipken, F.	Relating cloud and aerosol properties from long-term lidar observations in Tajikistan	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Metzner, N.	Analysis, comparison and estimation of longwave downward radiation under clear skies during MOSAiC	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Müller, G. H.	Seasonal analysis of dust and non-dust aerosol properties above Dushanbe, Tajikistan	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Müller, S.	Comparison of the simulation results of the COSMO-MUSCAT chemical transport model with data from the air quality monitoring networks focussing on ozone	Leipzig University, Faculty of Physics and Earth System Sciences	2024
	Skupin, N.	Evaluation of cross-talk effect on the retrieval of atmospheric particle extinction coefficient profiles by using a rotational-Raman lidar	Leipzig University, Faculty of Physics and Earth System Sciences	2024
Sührig, A.	Impact of the lockdown in spring 2020 on air quality in Germany	Leipzig University, Faculty of Physics and Earth System Sciences	2024	

## Appendices: Academic degrees / Awards

Academic degree*)	Name	Title	Faculty	Year
B.Sc.	Triantafyllou, A.	Multiphase Chemical Transformation of Organic Compounds during Convective Cloud Ascent over the Amazon Rainforest: A Box Model Study using SPACCIM	Leipzig University, Faculty of Physics and Earth System Sciences	2025

\* *Habil.:* Habilitation, *Ph.D.:* Doctoral theses, *Dipl.-Ing. (FH):* Diploma (FH), *MSc.:* Master of Science, *B.Sc.:* Bachelor of Science

### Summary of completed academic qualifications

Academical degrees	Number		Total
	2024	2025	
Habilitation	0	0	0
Doctoral theses	7	7	14
Dipl.-Ing.	1	1	2
Master of Science	6	12	18
Bachelor of science	8	3	11

### Awards

Name	Prize	Awarding institution	Comments/Description
Cuesta-Mosquera, A.	Best Poster Award	European Aerosol Conference (EAC) 2025, Lecce, Italy	title "Evaluation of Aerosol Optical Properties of cooking emissions in rural East African homes"
Fritzsich, F.	Best Poster Award	ACTRIS Science Conference, 2024, Rennes, France	title: "Green, broadband coherent Doppler lidar for aerosol-cloud-dynamics interaction studies"
Haarig, M.	AS&T Young Scientist Award	American Association for Aerosol Research	at 21st Electromagnetic and Light Scattering Conference, Milazzo, Italy
Hartmann, S.	One of three runners up of the 2024 ACP Paul Crutzen Publication Award	ACP Journal, 2024	for ACP article "Secondary ice production – no evidence of efficient rime-splintering mechanism"
	Best Poster Award	ICCP 2024, Jeju, Südkorea, Juli	title: "Secondary ice production - No clear evidence of a very productive rime-splintering mechanisms during dry and wet growth"

## Appendices: Awards

Name	Prize	Awarding institution	Comments/Description
Heinold, B.	IOP Publishing Top Cited Paper Award 2024	IOP Publishing, 2024	
Herrmann, H.	Honor award, Scientific Excellence in "Physical and Analytical Chemistry of Atmospheric Multiphase Systems: Experimental and Model Studies"	Environmental Chemistry Division of the American Chemical Society (ACS), 2024	Five-day symposium at the ACS Fall Meeting in Denver in August 2024
	Hartmut Herrmann Festschrift, special issue in ACS Earth and Space Chemistry to celebrate the career of Prof. Hartmut Herrmann	ACS Earth and Space Chemistry	2025
Jimenez, C.	Research Prize of the Reinhard-Süßing-Foundation	Reinhard-Süßing-Stiftung	topic area: "New techniques, methods, and applications for remote sensing of the atmosphere"
Kaushik, A.	Best Poster Award	SOLAS Open Science Conference 2024, Goa, India	title: "Nano- and micro-plastics in the atmosphere: an analytical approach using Py-GC-MS"
Kubin, A.	IOP Publishing Top Cited Paper Award 2024	IOP Publishing	
Luttkus, M.	Early Career Award: First Prize	ITM Conference 2024, Kopenhagen, Denmark	title: "Modeling taxonomic biodiversity driven effects on regional air quality using the new chemical mechanism URMELL"
Macke, A.	Elsevier van de Hulst Award for Light Scattering	Elsevier Publisher	at 21st Electromagnetic and Light Scattering Conference, Milazzo, Italy
Niedermeier, D.	Best Poster Award	ICCP 2024, Jeju, Südkorea, Juli	title: "Secondary ice production - No clear evidence of a very productive rime-splintering mechanisms during dry and wet growth"
Poschart, E.	Best Poster Award	Gas Kinetics 2024	title: "GC-MS studies of Iron-Catalyzed Decomposition of Isoprene Hydroxy Hydroperoxide (ISOPROOH) in the Aqueous Phase"

## Appendices: Editorships / Memberships

### Editorships

Name	Committee
Althausen, D.	Editor of proceedings "Second Central Asian DUst Conference" (CADUC-2)
Deneke, H.	Section Editor "Atmospheric Remote Sensing"
Heinold, B.	Associate Editor "Atmosphere - MDPI"
	Guest Editor "Frontiers Environmental Science"
Herrmann, H.	Associate Editor "Atmospheric Measurement Techniques"
	Member of the editorial board of "Atmospheric Pollution Research"
	Member of the editorial committee "Aerosol and Air Quality Research" (AAQR)
	Associate Editor "Journal of Geophysical Research" (JGR) Atmospheres
	Associate Editor "International Journal of Chemical Kinetics" (IJCK)
	International Advisory Board "Environmental Science and Technology"
Hofer, J.	Editor of proceedings Second Central Asian DUst Conference (CADUC-2)
Macke, A.	Member of the advisory board of the "Meteorologische Zeitschrift"
	Associate Editor "Atmospheric Measurement Techniques"
	Member of the editorial committee "promet"
Tegen, I.	Associate Editor "Journal of Geophysical Research"
van Pinxteren, D.	Scientific advisory board of the journal "Gefahrstoffe, Reinhaltung der Luft"
Wandinger, U.	Member of the editorial committee "Atmospheric Measurement Techniques"
Wehner, B.	Member of the editorial board of "Atmospheric Chemistry and Physics"

### Memberships

Name	Committee
Althausen, D.	Commission for Air Quality Control in the VDI and DIN - Standards Committee KRdL, NA 134-02-01-22 UA "Ground-based remote measurement of meteorological variables" in Department II Environmental Meteorology
Baars, H.	Member and speaker of the EARLINET Council
	Member of the "ESA Aeolus Science Advisory Group"
	ACTRIS Expert Group for Satellite Validation (EG-Sat)

## Appendices: Memberships

Name	Committee
Baars, H.	Management Committee (MC) Member for the COST-Action CA24135 “European Atmospheric Research Lidar COoperation on Science and Technology (EARLICOST)” for Germany
Carmona Martinez, E.	Member of the “Spanish Scientific Society of Chromatography and Related Techniques” (SECyTA)
	Member of the American Chemical Society (ACS)
Cremer, R. S.	Student board member of the “Society for Aerosol Research” (GAeF)
Deneke, H.	Member of the “International Radiation Commission”
	Member of the “Convection Working Group”
	Member of the “International Cloud Working Group” (ICWG)
Faust, M.	Member of the “International Society for Aeolian Research” (ISAR)
Fomba, K. W.	Member of the “African Society for Air Quality”
Heinold, B.	Member of the “HAMMOZ” steering committee
Hellmuth, O.	Member of the “International Association for the Properties of Water and Steam” (IAPWS), working group “Thermophysical Properties of Water and Steam” (TPWS)
	Member of the “Leibniz-Sozietät der Wissenschaften zu Berlin e.V.”
Henning, S.	Co-Chair of the EAA Working Group: “Atmospheric Aerosol Studies (AAS) for Aerosol-cloud-interaction in warm, mixed-phase and ice clouds”
Hermann, M.	Member of the “HALO” Board of Trustees
	Member of the VDI guideline committee “NA 134-04-02-18 UA Measurement of particles in ambient air - Determination of the number of particles”
Herrmann, H.	Chairman of the working group “Atmospheric Chemistry” in the GDCh Division “Environmental Chemistry and Ecotoxicology” (AKAC)
	Member of Society DECHEMA/GDCh/Bunsen, Joint Committee “Chemistry of the Atmosphere”
	DECHEMA/GDCh/KRdL, Chairman of the Particulate Matter Expert Group
	Member of the “IUPAC Task Group on Atmospheric Chemical Kinetic Data Evaluation”
	Member of the advisory board of the ProcessNet specialist group “SuPER”
	Fellow of “International Union of Pure and Applied Chemistry” (IUPAC)
	Member of the “American Chemical Society” (AMS)
	Member of the committee of the “Second International Indian Ocean Expedition”
	Adjunct Visiting Professor of Environmental and Engineering Sciences at Fudan University, Shanghai, China

## Appendices: Memberships

Name	Committee
Herrmann, H.	Distinguished Visiting Professor for Environmental Sciences and Engineering at Shandong University, Qingdao, China
	Member of the Academia Europaea (AE), member of the “Earth and section Cosmic Sciences”
	Member of the “Leibniz-Sozietät der Wissenschaften zu Berlin”
	Member of the Evaluation Commission of the Czech Academy of Sciences
Hünerbein, A.	Member of the International Radiation Commission
Jimenez, J.	Member and speaker of the “Lidar Developments working group” of the ACTRIS NF Forum, member of the “Bioaerosols working group”
Macke, A.	Deputy Chairman of Section E of the Leibniz Association
	Member of the steering committee of the Transregio TR 172 “Arctic Amplification”
	Member of the Standing Committee for Scientific Infrastructure Facilities and Research Museums of the Leibniz Association
	Member of the “Environment and Climate” Advisory Board of the Physikalisch-Technische Bundesanstalt
	Member of the National Committee “Antarctica InSync” (joint, multidisciplinary scientific programme in Antarctica and the Southern Ocean)
	Member of the Steering Committee of the Leibniz Research Network “Integrated Earth System Research”
Mertes, S.	Ordinary member of the DFG collaborative research center TR 172 “Arctic Amplification”
	Member of the Science Team of CIRRUS-HL: The airborne experiment on CIRRUS in High Latitudes with the highaltitude long-range research aircraft HALO
Müller, Ke.	Member of the “German Library Association” (dbv)
	Member of the Professional Association Information Library (BIB)
Niedermeier, D.	Member of the “German Society of Humboldtians” - Regional Group Halle-Leipzig
Pöhlker, M.	Representative for “Climate Change and Green Deal” from Leipzig University
	Scientific Steering Committee (SSC) HALO
Schrödner, R.	Member of the European Aerosol Assembly, Working Group 2 “Transport, global modelling and climate forcing”
Seifert, P.	Vice Co-Chair of the “Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere in Antarctica and the Southern Ocean (PICCAASO)”
	Ordinary member of the DFG Collaborative Research Center TR 172 “Arctic Amplification”
Stratmann, F.	Member of the Science Team of CIRRUS-HL: The Airborne Experiment on CIRRUS in High Latitudes with the Highaltitude Long-range Research Aircraft HALO

## Appendices: Memberships / Reviews

Name	Committee
Tegen, I.	Member of the steering committee of the initiative “natESM” (National Earth System Modelling)
	Member of the “HAMMOZ” steering committee
Tilgner, A.	Member of the VDI/DIN Commission on Air Quality Control (KRdL) - Standards Committee, NA 134-02-01-08 UA Subcommittee Environmental Meteorology - Deposition Parameters
van Pinxteren, D.	Member of the European working group CEN/TC 264/WG 44 “Source apportionment”
	Member of KRdL national mirror committee to CEN/TC 264/WG 44 “Source apportionment”
van Pinxteren, M.	German representative of the “Surface Ocean Lower Atmosphere Study” (SOLAS)
Wandinger, U.	Member of the “ESA-JAXA EarthCARE Joint Mission Advisory Group”
	Member of the ACTRIS Research Infrastructure Committee
	Member of the “ESA-JAXA EarthCARE Quality Working Group”
Wehner, B.	Member of the VDI/DIN Commission on Air Quality Control (KRdL) - Subgroup Meteorological Measurements
	Secretary General of the “Society for Aerosol Research” (GAeF)
Wex, H.	Vice-President of the International Commission on Clouds and Precipitation (ICCP)

## Reviews

Reviews	Number	
	2024	2025
Journals	193	88
Projects	34	15
Statements, position papers	0	1
Others	36	89
Total	263	193

## Appendices: Guest scientists

### Guest scientists

Name	Start	End	Institution
Mahesh, M.	01.08.2023	31.01.2024	Indian Institute of Science Education and Research
Hey, Y.	16.08.2023	31.08.2024	Wuhan University, China
Romshoo, B.	01.10.2023	31.07.2024	Max Planck Institute for Chemistry Mainz, Germany
Seidel, C.	01.01.2024	30.06.2024	Leipzig University, Germany
Ochei, M. C.	01.01.2024	31.03.2024	Federal University of Technology, Nigeria
Wu, Z.	24.01.2024	31.12.2024	Peking University, China
Dr Ene, D.	12.02.2024	01.03.2024	ERATOSTHENES Centre of Excellence, Cyprus
Poutli, M.	20.02.2024	07.03.2024	ERATOSTHENES Centre of Excellence, Cyprus
Areal, A.	04.03.2024	31.03.2024	Leibniz Institute for Environmental Medical Research, Germany
Mikhalkov, M.	01.04.2024	31.05.2024	Leipzig University, Germany
Opp, C.	06.04.2024	29.04.2024	Philipps University Marburg, Germany
Abdullaev, B.	12.04.2024	24.04.2024	National Academy of Sciences of Tajikistan
Khalifaeva, S.	12.04.2024	24.04.2024	National Academy of Sciences of Tajikistan
Makhmudov, A.	12.04.2024	24.04.2024	National Academy of Sciences of Tajikistan
Rahmatov, M.	12.04.2024	24.04.2024	National Academy of Sciences of Tajikistan
Mathes, T.	01.05.2024	30.06.2024	Technische Universität Berlin, Germany
Müller, J.	01.05.2024	30.06.2024	Leipzig University, Germany
Kuntz, V.	10.06.2024	31.07.2024	Helmholtz Centre for Environmental Research, Germany
Gialitaki, A.	20.06.2024	04.07.2024	National Observatory of Greece
Saito, M.	29.06.2024	03.07.2024	University of Wyoming, USA
Kanngießer, F.	30.06.2024	03.07.2024	GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Lopatin, A.	30.06.2024	03.07.2024	GRASP SAS, France
Tsekeri, A.	30.06.2024	04.07.2024	National Observatory of Greece
Shahid, I.	08.07.2024	12.07.2024	University of Engineering and Technology, Pakistan
Richnow, H. H.	01.08.2024	31.07.2027	Helmholtz Centre for Environmental Research, Germany

## Appendices: Guest scientists

Name	Start	End	Institution
Schachard, M.	05.08.2024	09.08.2024	Braunschweig University of Technology, Germany
Zhao, M.	01.09.2024	30.08.2025	Environmental Research Institute of Shandong University, China
Wen, L.	01.09.2024	31.12.2024	Environmental Research Institute of Shandong University, China
Ahlawat, A.	01.09.2024	31.08.2025	Technical University of Delft, The Netherlands
Khalifaeva, S.	01.09.2024	31.08.2027	National Academy of Sciences of Tajikistan
Malollari, G.	16.09.2024	15.02.2025	Agricultural University of Tirana, Albania
Kutschka, A.	16.09.2024	20.09.2024	enviscope, Germany
Schell, D.	16.09.2024	20.09.2024	enviscope, Germany
Rautenberg, W.	20.09.2024	20.09.2025	Johannes Gutenberg University Mainz, Germany
Raff, J.	14.10.2024	22.11.2024	Indiana University, USA
Melssen, L.	14.10.2024	22.11.2024	Indiana University, USA
Sun, K.	01.11.2024	31.12.2025	Ocean University of China
Kamprad, N.	01.11.2024	15.12.2024	Helmholtz Centre for Environmental Research, Germany
Kuntz, V.	01.11.2024	15.12.2024	Helmholtz Centre for Environmental Research, Germany
Chai, B. C.	04.11.2024	31.01.2025	Friedrich Schiller University Jena, Germany
Preece, J.	10.11.2024	16.11.2024	University of Georgia, USA
Hölling, A.	12.11.2024	13.11.2024	University of Oldenburg / ForWind, Germany
Machado, L.	24.11.2024	25.11.2024	Max Planck Institute for Chemistry, Germany
Ghemulet, S.	25.11.2024	29.11.2024	INCAS, Romania
Vlad, A.	25.11.2024	29.11.2024	INCAS, Romania
Mohr, C.	28.11.2024	29.11.2024	ETH Zurich, Switzerland
Jinglan, F.	16.12.2024	20.12.2024	Centre for Isotope Research, The Netherlands
Frey, W.	01.01.2025	31.01.2025	University of Wageningen, The Netherlands
Gordon, H.	26.01.2025	29.01.2025	Carnegie Mellon University, USA
Scheirer, R.	29.01.2025	01.02.2025	Swedish Meteorological and Hydrological Institute
Robert, O. D.	03.02.2025	06.02.2025	University of Oslo, Norway

## Appendices: Guest scientists

Name	Start	End	Institution
Sun, K.	15.02.2025	31.05.2025	Ocean University of China
Wasey, K.	17.02.2025	28.02.2025	Leipzig University, Germany
Wu, Z.	01.03.2025	31.05.2025	Peking University, China
Chrysostomou, C.	10.03.2025	21.03.2025	Erastosthenes Centre of Excellence, Cyprus
Berkemeier, T.	17.03.2025	21.03.2025	Max Planck Institute for Chemistry, Germany
Koob, T.	17.03.2025	21.03.2025	Paderborn University, Germany
Kiselev, A.	17.03.2025	30.03.2025	Karlsruhe Institute of Technology, Germany
Seidel, J.	17.03.2025	30.03.2025	Karlsruhe Institute of Technology, Germany
Weber, B.	21.03.2025	31.03.2025	University of Graz, Austria
Schell, D.	01.04.2025	30.04.2025	Enviscope, Germany
Vollmer, A.	01.04.2025	30.04.2025	Pilotendienste Alwin Vollmer, Germany
Schütz, J.	01.04.2025	30.04.2025	Air Lloyd Flight Services, Germany
Kutschka, A.	01.04.2025	30.04.2025	Enviscope, Germany
Strzałka, A.	01.04.2025	31.07.2025	University of Gdansk, Poland
van Loon, R.	02.04.2025	09.04.2025	Wageningen University & Research, The Netherlands
Pawlak, K.	15.04.2025	15.06.2025	Institut of Physical Chemistry PAS Warsaw, Poland
Rindelaub, J.	07.05.2025	09.05.2025	University of Auckland, New Zealand
Poutli, M.	07.05.2025	23.05.2025	Erastosthenes Centre of Excellence, Cyprus
Coulson, G.	21.05.2025	25.05.2025	The Air Quality Collective, New Zealand
Schmale, J.	25.06.2025	27.06.2025	EPFL Valais Wallis Switzerland
Raff, J.	25.06.2025	27.06.2025	Indiana University, USA
Abdelmonem, A.	01.07.2025	31.12.2025	Karlsruhe Institute of Technology, Germany
Klimach, T.	01.07.2025	31.12.2025	Max Planck Institute for Chemistry, Germany
Kabore, N.	01.08.2025	31.01.2026	University Mohamed VI Polytechnics, Morocco
Strzałka, A.	01.08.2025	31.03.2026	University of Wisconsin-Madison, Dept. of Atmos. & Ocean. Sci., Poland / USA
Wang, C.	18.08.2025	17.08.2026	School of Environmental Science and Engineering, China
Cabañ Galán, B.	18.08.2025	31.08.2025	Universidad de Castilla La Mancha, Spain

## Appendices: Guest scientists / Visits of TROPOS scientists

Name	Start	End	Institution
Humphries, R.	25.08.2025	31.12.2025	CSIRO: Commonwealth Scientific and Industrial Research Organisation, Australia
Rosenberg, S.	01.09.2025	30.09.2025	Leipzig University, Germany
Wendisch, M.	01.09.2025	30.09.2025	Leipzig University, Germany
Wolf, K.	01.09.2025	20.10.2025	Leipzig University, Germany
Ahlawat, A.	01.09.2025	31.08.2026	Delft University of Technology, The Netherlands
Ehrlich, A.	15.09.2025	20.10.2025	Leipzig University, Germany
Schäfer, M.	15.09.2025	20.10.2025	Leipzig University, Germany
Chen, W.	22.09.2025	21.09.2026	Qilu University of Technology, Shandong, China
Frey, W.	22.09.2025	25.09.2025	Wageningen University & Research, The Netherlands
van Loon, R.	22.09.2025	03.10.2025	Wageningen University & Research, The Netherlands

## Visits of TROPOS scientists

Name	Start	End	Institution
Heinold, B.	04.02.2024	17.02.2024	Leibniz Australian Delegation 2024 (Melbourne, Canberra, Sydney, Brisbane)
Seifert, P.	10.03.2024	27.03.2024	National Institute for Water and Atmospheric Research, New Zealand
Gaudek, T.	10.03.2024	27.03.2024	National Institute for Water and Atmospheric Research, New Zealand
Bright, M.	22.08.2024	18.10.2024	Fudan University Shanghai, China
Poschart, E.	26.11.2024	01.12.2024	Institute of Chemistry of Clermont-Ferrand, France
Radenz, M.	01.04.2025	31.08.2025	École Polytechnique Fédérale de Lausanne, Switzerland
Scheres Firak, D.	17.11.2025	21.11.2025	University of Le Mans, France

Meetings

Scientific event	Date	National/ international	Number of participants
CADUC 2, Central Asian Dust Conference, Nukus, Uzbekistan	15. - 22.04.2024	international	80
HAMMOZ Workshop 2024, online	29.04.2024	international	20
Measurement Technology Colloquium Mainz, Germany	06. - 08.05.2024	national	80
STIPMEX 2024, Stratosphere-Troposphere Interactions and Prediction of Monsoon weather Extremes, Pune, India, Session: "Observations in Monsoon Region" and "Atmospheric composition, chemistry, and dynamics of the UTLS"	03. - 05.06.2024	international	300
EARLINET General Assembly, Landshut, Germany	23.06.2024	international	60
HALO-South Kick-Off Meeting, online	28.06.2024	international	38
ACS 2024, American Chemical Society Fall - Special Symposium on "Physical and Analytical Chemistry of Tropospheric Multiphase Systems: Experimental and Model Studies: A Symposium in Honour of Prof. Hartmut Herrmann", Denver, USA	18. - 21.08.2024	international	72
EAC 2024, The European Aerosol Conference, Tampere, Finland, Organisation of Session "Transport of Atmospheric Aerosols, Modelling and Climate Forcing"	26. - 30.08.2024	international	60
Aeolus DISC project meeting, Leipzig, Germany	05. - 07.11.2024	international	25
HALO-South – the interplay of Clouds, Aerosol, and Radiation above the Southern Ocean, 2. Project Meeting, Leipzig, Germany	28. - 29.01.2025	international	42
Kick-Off-Meeting DFG Research Unit "Cloud 3D Structure & Radiation" C3SAR, Leipzig, Germany	29. - 31.01.2025	international	25
Kick-off Meeting LSC "BioSmoke", Leipzig, Germany	13. - 14.02.2025	national	32
GIVE (German Initiative for Validation of the EarthCARE mission) Annual Meeting	05. - 6.03.2025	national	25
HAMMOZ-Workshop 2025, online	19.03.2025	international	20
HALO-South, 3. Project Meeting, online	19.05.2025	international	32
Co-organisation of ACTRIS-D Annual Meeting 2025, Karlsruhe, Germany	03. - 05.06.2025	national	60

## Appendices: Meetings / International and national field campaigns

Scientific event	Date	National/ international	Number of participants
C3SAR - 2nd Project Meeting, Leipzig, Germany	25. - 27.08.2025	international	20
EAC 2025 The European Aerosol Conference, Organization of Session "Transport of atmospheric aerosols, modelling and climate forcing", Lecce, Italy	01. - 05.09.2025	international	41
CARGO-ACT Community Meeting, Evora, Portugal	21.10.2025	international	50
CARGO-ACT Internal project meeting, Evora, Portugal	21.10.2025	international	25
2nd general meeting LSC "BioSmoke," Leipzig, Germany	10.11.2025	international	35

## International and national field campaigns

Campaign	Project partners
<b>(AC)<sup>3</sup></b> , Station North, Greenland Observations of transition phases using tethered balloon measurements TROPOS: AMP***	(AC) <sup>3</sup> -Consortium, Aarhus University, The Netherlands; EPFL Switzerland
<b>ADOnis</b> , TROPOS, Leipzig Chamber studies for the DFG project "Towards an Advanced DMS oxidation mechaNiSm (ADOniS)" TROPOS: ACD*	no
<b>AEROFOG I</b> , Henties Bay, Manila Investigating the effects of fog chemistry on nutrient availability and endemic plants in the Namib desert region TROPOS: ACD	Karlsruhe Institute of Technology, Germany; Gobabeb, Namibia; North West University, South Africa, Laboratoire Interuniversitaire des Systèmes Atmosphériques Paris, LCE, France
<b>AEROFOG II</b> , Henties Bay, Namibia Role of aerosols in the formation of fog and effects on nutrient availability and endemic plants in the Namib desert region TROPOS: ACD	Karlsruhe Institute of Technology, Germany; GOBABEB Namib Research Institute, Namibia; North West University, South Africa; Laboratoire Interuniversitaire des Systèmes Atmosphériques, Laaboratoire Chimie Environment, France
Aerosol characterisation in southern Chile, Punta Arenas TROPOS: AMP	University de Magallanes, Chile
<b>AIDA</b> , Ny-Ålesund, Svalbard (Spitsbergen) Aerosol variability and interaction with ambient conditions based on small-scale vertical and horizontal distribution of Arctic measurements TROPOS: AMP	TU Braunschweig, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany

## Appendices: International and national field campaigns

Campaign	Project partners
<p><b>APAICA</b> (within the framework of ATWAICE) Polarstern measurements (aerosol / turbulence) in the Arctic TROPOS: ACD, AMP</p>	<p>Technische Universität Berlin, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany</p>
<p><b>atmo4ACTRIS</b>, e.g. Leipzig, Mindelo, Dushanbe Validation of data from the EarthCARE satellite incl. corresponding preparations TROPOS: RSD****</p>	<p>ESA, ACTRIS consortium</p>
<p><b>BASS</b> Helgoland, Germany Investigation of chemical reactions in the surface film TROPOS: ACD</p>	<p>University of Oldenburg, GEOMAR - Helmholtz Centre for Ocean Research Kiel, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, University of Jena, Germany</p>
<p><b>BACSAM II</b>, Longyearbyen, Norway Aircraft measurements of aerosol size distribution, CCN and INP on Polar 6 and with the T-Bird trailing body TROPOS: AMP, ACD</p>	<p>Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany</p>
<p><b>BIOCAT-IIOE2 SO305</b>, Indian Ocean, Bay of Bengal Quantification of the contribution of different aerosol sources and the input of mineral nutrients such as phosphorus, iron and other bio-relevant trace metals TROPOS: ACD</p>	<p>GEOMAR- Helmholtz Centre for Ocean Research Kiel, University of Hamburg, Germany; University of Southern Denmark</p>
<p><b>BOW-TIE</b>, tropical Atlantic (Mindelo &gt; Barbados), Meteor Meteor ship campaign to explore the Intertropical Convergence Zone TROPOS: AMP</p>	<p>GEOMAR- Helmholtz Centre for Ocean Research Kiel, Max Planck Institute for Chemistry Mainz, Germany</p>
<p><b>CAFE-Brazil</b>, Brazil HALO aircraft campaign to study the formation of new particles in the UTLS TROPOS: AMP</p>	<p>Max Planck Institute for Chemistry Mainz, Germany; ATTO consortium; HALO consortium</p>
<p><b>CAFE-Pacific</b>, Australia HALO aircraft campaign to study the formation of new particles in the UTLS over the Pacific Ocean TROPOS: AMP</p>	<p>Max Planck Institute for Chemistry Mainz, Germany; HALO consortium</p>
<p><b>CAINA</b>, Eemshaven, The Netherlands Interaction between clouds and aerosols in a nitrogen-dominated atmosphere TROPOS: AMP</p>	<p>University of Groningen, Wageningen University, Utrecht University, Delft University of Technology, The Netherlands; Max Planck Institute for Chemistry, Karlsruhe Institute for Technology, Germany; Cyprus Institute</p>
<p>CCN &amp; INP in North Greenland, Villum Research Station TROPOS: AMP</p>	<p>Aarhus University, Denmark</p>
<p><b>CLARINET</b>, Mindelo, Cabo Verde CLOUD and Aerosol Remote sensing for EarthCare, validation of EarthCARE measurements TROPOS: RSD</p>	<p>European Space Agency, German Aerospace Centre, Leipzig University, Max Planck Institute for Meteorology, Germany; University of Oslo, Norway; Laboratoire de Meteorologie Dynamique (LMD/IPSL), LATMOS, France</p>

## Appendices: International and national field campaigns

Campaign	Project partners
<b>CLOUD17</b> , Geneva, Switzerland Nucleation experiment to study the formation of new particles in the Southern Ocean TROPOS: AMP	CERN, Switzerland
<b>CLOUDLAB</b> , Eriswill, Switzerland Investigation of microphysical processes in stratus clouds as a natural laboratory TROPOS: RSD, AMP, MODEL**	ETH Zurich, Switzerland; EPFL Lausanne, Switzerland; Leipzig University, Germany
Continuous ammonia immission measurements TROPOS: ACD	Saxon State Office for Environment, Agriculture and Geology, Germany
<b>DropCC</b> , TROPOS, LACIS-T Droplet Collision and Coalescence, Campaign as part of the project "From drop to rain - turbulence matters" at NWO Open Competition Domain Science TROPOS: AMP	Wageningen University, The Netherlands
<b>DUSTRISK</b> (main campaign), Cabo Verde Investigation of harmful aspects of mineral dusts in combination with adhering microbes TROPOS: ACD	Leibniz Institute DSMZ - German Collection of Microorganisms and Cell Cultures, Research Centre Borstel Leibniz Lung Centre, Leibniz Institute for Environmental Medical Research, Germany; institutions from Cabo Verde, including hospitals, universities and public health institutes
<b>EARLINET</b> (permanent experiment) European Aerosol Research Lidar Network, Leipzig, Germany, Dushanbe, Tajikistan TROPOS: RSD	EARLINET consortium
<b>EDIAQI</b> , Zagreb, Croatia Evidence-based indoor air quality improvement TROPOS: AMP	18 partners from Belgium, Austria, Hungary, UK, Germany, Italy, Greece, Denmark, Spain, Estonia, Lithuania, Slovenia
<b>Freiberg Berner</b> , Germany Size-resolved metal concentrations in geogenically contaminated region TROPOS: ACD	Saxon State Office for Environment, Agriculture and Geology, Germany
<b>goSouth-2</b> , Invercargil, New Zealand TROPOS: AMP, RSD Contrast study of cloud properties in clean Antarctic air versus clouds in aerosol-polluted Australian air TROPOS: AMP, RSD	Leipzig University, Germany; Met Service New Zealand, University of Canterbury in Christchurch, New Zealand
<b>HALO-South</b> , Oberpfaffenhofen, Germany; Christchurch, New Zealand Interactions between clouds, aerosols and radiation over the Southern Ocean TROPOS: AMP	German Aerospace Center, Leipzig University, Forschungszentrum Jülich, Max Plack Institute for Chemistry, Goethe University Frankfurt, Johannes Gutenberg University Mainz, Germany
<b>Impactor III</b> , TROPOS, Leipzig Regional chemical composition and source attribution of size-resolved Particles TROPOS: ACD	Saxon State Office for Environment, Agriculture and Geology, Germany

## Appendices: International and national field campaigns

Campaign	Project partners
<p><b>LCS Biosmoke 2025</b>, Albacete, Spain The first controlled combustion as part of the BioSmoke project for better understanding of the relationships between biodiversity, vegetation type, smoke and PBAP emissions, and their atmospheric distribution and further processing TROPOS: AMP, MOD, RSD</p>	<p>Universidad Castilla-La Mancha, Spain; Leipzig University, Deutsches Biomasseforschungszentrum, Helmholtz Centre for Environmental Research, Germany</p>
<p><b>Leipzig Berner III</b>, Leipzig, Melpitz Size-resolved PM composition and source attribution compared to previous decades TROPOS: ACD</p>	<p>Saxon State Office for Environment, Agriculture and Geology, Germany</p>
<p><b>METEOR 207</b>, Belem - Mindelo Investigation of the western boundary current circulation, Atlantic meridional overturning circulation, precipitation and dust in the tropical Atlantic TROPOS: RSD</p>	<p>GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany</p>
<p><b>ORACLE</b> Aerosol-Cloud Interactions: the Role of organic compounds in Cloud droplet activation TROPOS: AMP</p>	<p>ETH Zurich, Switzerland; LISA - Laboratoire Interuniversitaire des Systemes Atmospheriques, Aix-Marseille University, France</p>
<p><b>PARAMOUNT</b>, Paris, France Laboratory studies on the production of organic aerosol particles in clouds in the CESAM cloud chamber in Paris TROPOS: ACD, AMP</p>	<p>Laboratoire Interuniversitaire des Systemes Atmospheriques Paris, Laboratoire de Chimie de l'Environnement Marseille, France</p>
<p><b>PollyNet</b> (permanent experiment) Network of institutions with a PollyXT TROPOS: RSD</p>	<p>PollyNet Consortium</p>
<p>Pyranometer Network campaign, Liebenwerda, Germany Modelling the PV yield TROPOS: RSD</p>	<p>Leipzig Institute for Meteorology, Leipzig University, Germany</p>
<p><b>RACE-LE</b> (RADar Comparison Experiment LEipzig), TROPOS, Leipzig Comparative measurements of ACTRIS radars TROPOS: RSD</p>	<p>Institute Pierre Simon Laplace (IPSL), Ecole Polytechnique, France; Leipzig Institute of Meteorology, University of Leipzig</p>
<p>Radeburg, Germany Temporal and spatial resolution study of air pollution from wood-burning heating systems, accompanied by backpack measurements TROPOS: ACD, AMP</p>	<p>Saxon State Office for Environment, Agriculture, and Geology, Germany</p>
<p><b>REACTE</b>, Le Mans, France Determination of iron species by Mössbauer spectroscopy TROPOS: ACD</p>	<p>University of Miami, USA</p>

## Appendices: International and national field campaigns / Cooperations

Campaign	Project partners
Round robin test for NH <sub>3</sub> passive samplers, Melpitz, Germany TROPOS: ACD	North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection, Hildesheim State Trade Inspectorate and other partners from Germany, France, The Netherlands and Belgium
<b>SOPORTE</b> Source apportionment of size-resolved atmospheric particles and their oxidative potential in Córdoba, Argentina and Leipzig, Germany TROPOS: ACD	National University of Cordoba, Multidisciplinary Institute of Plant Biology IMBIV-CONICET, Argentina
<b>ULTRAFLEB</b> , Berlin, Germany Stationary and mobile field measurements of ultrafine particles (UFP) and other quantities in the vicinity of Berlin Brandenburg Airport TROPOS: AMP	Brandenburg State Office for the Environment, Braunschweig University of Technology, Technische Universität Berlin, Flughafen Berlin Brandenburg GmbH, Ingenieurbüro Janicke GbR, Society for Environmental Physics, IVU Umwelt GmbH, Germany; TNO, The Netherlands
<b>VACCINE</b> , Neumayer Station, Antarctica Variation of Antarctic Cloud Condensation (CCN) and ice nucleating particle concentrations (INP) at Neumayer Station TROPOS: AMP	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany
<b>VOC campaign</b> , Melpitz, Germany EMEP modelling TROPOS: AMP	European Monitoring and Evaluation Programme (EMEP) for long-range transport of air pollutants

\* Atmospheric Chemistry Department

\*\* Department Modeling of Atmospheric Processes

\*\*\* Department Atmospheric Microphysics

\*\*\*\* Department Remote Sensing of Atmospheric Processes

## Cooperations

### International cooperations

Research project	Cooperation partner
<b>ACD-C</b> Atmospheric Chemistry Chamber	University of British Columbia, Dept. of Chemistry, Canada; University College Cork, Ireland; Institute of Chemistry, Slovenia
<b>ACDC2</b> Aerosol-Cloud-Drizzle Convection Chamber	9 Partners from the USA
<b>ACPV</b> CEOS Protocol for spaceborne profiler validation	European partners, partners from the USA and Japan
<b>ACROSS</b> Atmospheric Chemistry of the suburban forest	> 10 partners from France and the USA

## Appendices: Cooperations

Research project	Cooperation partner
<b>ACTRIS</b> Aerosol, Clouds and Trace Gases Research Infrastructure	> 100 partners from 21 European countries
<b>ACTRIS container at Poligon</b>	S.U. Umarov Physical-Technical Institute (PhTI) Academy of Sciences of Republic of Tajikistan
Aerosol, Clouds and Trace Gases Research Infrastructure - Copernicus Atmosphere Monitoring Service	Norwegian Institute for Air Research, Kjeller, Norway; Centre National de la Recherche Scientifique Paris, France
<b>ACTRIS measuring station Melpitz</b> Cooperation partners involved in research projects at the TROPOS Research Station Melpitz	Norway, UK, Italy, Switzerland, Czech Republic, Hungary, Ireland, Finland, Austria, Sweden, Bulgaria, Belgium, France, Greece, The Netherlands, Spain, Denmark, Latvia, Poland, Portugal
<b>EarthCARE</b> ACTRIS for EarthCARE L2 product evaluation	approx. 50 international partners
<b>Aeolus DISC</b> Data, Innovation, and Science Cluster - ESA's data quality framework to support the Aeolus mission	German Aerospace Centre, DoRIT, Germany; Centre National de la Recherche Scientifique, France; European Centre for Medium-Range Weather Forecasts, UK; Royal Netherlands Meteorological Institute, ASEA Brown Boveri, Switzerland
<b>AEROFOG</b> Aerosols and fog in southern Africa: processes and impact on biogeochemistry	GOBABEB, Namibia; Centre National de la Recherche Scientifique, Laboratoire Interuniversitaire des Systèmes Atmosphériques, LISA Paris, Laboratoire de Chimie de l'Environnement UMR7376, Université Aix-Marseille, France; Karlsruhe Institute of Technology, Germany
<b>AIRSENSE</b> Aerosol and Aerosol-Cloud Interaction from Remote Sensing Enhancement	7 partners from France, Greece, The Netherlands, Poland
The importance of wave-induced exchange between ocean and atmosphere on air pollutants and their influence on climate	First Institute of Oceanography, Ministry of Natural Resources, Shandong University, China
<b>ATMO-ACCESS</b> Sustainable Access to Atmospheric Research Facilities	Cooperation between the European research infrastructures ACTRIS, ICOS and IAGOS
<b>ATTO</b> Amazon Tall Tower Observatory	18 partners from Brazil and Germany
<b>BRACE MY</b> Town twinning project to strengthen science at the Romanian Cloud Microphysics Centre	Institutul National de Cercetare-dezvoltare Aerospatiale "Elie Carafoli", Romania; Universitetet I Oslo, Andøya Space, Norway
<b>CAFE-Brazil</b> Aircraft measurement campaign (HALO) and ground measurements at ATTO, to investigate new particle formation in the upper troposphere over the Amazon rainforest	Max Planck Institute for Chemistry, Goethe University Frankfurt, Germany

## Appendices: Cooperations

Research project	Cooperation partner
<b>CAINA</b> Cloud-aerosol interactions in a nitrogen-dominated atmosphere	University of Groningen, Wageningen University, Delft University of Technology, Utrecht University, The Netherlands; Max Planck Institute for Chemistry, Germany
<b>CARDINAL</b> Clouds, Aerosol, Radiation - Development of integrated algorithms	9 partners from the Netherlands, Germany, Belgium, Canada, Spain, UK, France
<b>CARGO-ACT</b> Cooperation and Agreements enhancing Global interoperability for Aerosol, Cloud and Trace gas research infrastructures	15 partners from Canada, Belgium, France, Italy, Finland, Norway, Romania, USA
CEOS protocol: Best practices for the validation of Aerosol, Cloud, and Precipitation Profiles	International partners, primarily from Europe, the USA and Japan
Decameter Scale Characterisation of Shallow Cumulus and their Effects on Solar Radiation	UC Berkley, School of Meteorology, University of Oklahoma, Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, NOAA NESDIS, USA
<b>DropCC</b> Droplet Collision and Coalescence, Campaign as part of the project "From drop to rain - turbulence matters" at NWO Open Competition Domain Science	Wageningen University, The Netherlands
<b>CleanCloud:</b> Clouds and climate transitioning to post-fossil aerosol regime	18 international partners from the Netherlands, Sweden, Germany, UK, Finland, Cyprus, France, Italy, Switzerland
<b>CLOUD</b> Cosmics Leaving Outdoor Droplets	16 partners from Germany, Switzerland, Finland, Austria, Portugal, Russia, Great Britain, USA
<b>COST</b> Chemistry transport model intercomparison	Germany, Denmark, Finland, France, Bulgaria, Estonia, Italy, Malta, Spain, The Netherlands, Norway, Poland, Switzerland, United Kingdom, Greece, Israel
Development and application of Polly systems	11 partners from Finland, Poland, Portugal, Korea, Greece, Israel, Tajikistan, Cyprus, Cabo Verde, Germany
<b>DUSTRISK</b> A risk index for health effects of mineral dust and associated microbes	The University of Cape Verde, The National Institute of Meteorology of Cape Verde, The National Directorate of Environment, The Instituto Nacional de Saúde Pública, Dr Baptist de Sousa Hospital, Dr Agostinho Neto Hospital Praia, Cabo Verde
<b>EARLINET</b> European Aerosol Research Network	including Germany, Italy, Spain, Greece, Switzerland, Sweden, Portugal, Poland, Belarus, France, Bulgaria, Romania, Norway, The Netherlands, Finland, Ireland, Cyprus

## Appendices: Cooperations

Research project	Cooperation partner
<b>EarthCARE-DISC</b> Data Innovation and Science Cluster to support the EarthCARE mission	> 10 partners from Europe and Canada
<b>EDIAQUI</b> Evidence driven indoor air quality improvement	17 partners from Austria, Belgium, Croatia, Estonia, Greece, Italy, Lithuania, Slovenia, Spain
<b>ESA-Aeolus</b> European Space Agency, Atmospheric Dynamics Mission	European Space Research and Technology Center, The Netherlands, ESA Centre for Earth Observation, Frascati, Italy
<b>ESA-EarthCARE</b> European Space Agency, Earth Cloud, Aerosol, and Radiation Explorer	European Space Research and Technology Center, The Netherlands, ESA Centre for Earth Observation, Frascati, Italy
<b>EXCELSIOR</b> ERATOSTHENES: Excellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment	Cyprus, Germany, Greece
Fjord ecosystems in a changing climate: socio-cultural and ecological interactions	Extreme Environments Research Laboratory, EPFL, Switzerland
<b>GoSouth</b> Measurements for a better understanding of aerosols in the southern hemisphere	NIWA, University Canterbury, University Auckland, New Zealand; University of Hannover, Germany
<b>HAMMOZ hosting</b>	ETH Zurich, Center for Climate Systems Modelling - MeteoSwiss, Switzerland; University of Oxford, UK; Finnish Meteorological Institute; GEOMAR Helmholtz Centre for Ocean Research Kiel; Max Planck Institute Hamburg, Leipzig Institute for Meteorology, Germany
<b>H-AMS/ACROSS</b> Development of an online approach parameterisation to predict the hygroscopicity of organic aerosol in the environment based on high-resolution AMS measurements	Laboratoire des Sciences du Climat et de l'Environnement, Université Paris-Saclay, Gif-sur-Yvette; Institut national de l'environnement industriel et des risques, Verneuil-en-Halatte, France
<b>HALO-(AC)<sup>3</sup></b> Characterisation of Arctic aerosol particles, cloud particle residuals, cloud condensation nuclei and ice nuclei	Max Planck Institute for Chemistry, Alfred Wegener Institute, German Aerospace Centre, University of Mainz, Germany; University of Clermont-Ferrand, France
<b>HALO-South</b> Interplay of clouds, aerosols and radiation over the Southern Ocean	German Aerospace Center, Leipzig University, Forschungszentrum Jülich, Max Planck Institute for Chemistry, Goethe University Frankfurt, Johannes Gutenberg University Mainz, Germany
<b>IAGOS-CARIBIC</b> Deployment of aircraft for a global observation system - Civil aircraft for remote sensing and in-situ measurements in the troposphere and lower stratosphere based on an instrument container	Germany, UK, France

## Appendices: Cooperations

Research project	Cooperation partner
<b>ICON-HAMMOZ development</b> Model development	Max Planck Institute for Meteorology Hamburg, Leipzig University, Germany; ETH Zurich, Institute for Atmosphere and Climate, Zurich, Switzerland; Oxford University, UK
<b>LACIS-T</b> Turbulent Leipzig Aerosol Cloud Interaction Simulator	Leibniz Institute for Solid State and Materials Research Dresden, University of Ilmenau, University of Hamburg, OVGU Magdeburg, TU Freiberg, Germany; Michigan Technological University, Houghton, University of Utah, Salt Lake City, USA; University of Warsaw, Poland
NH3 round robin test	INRAE-Rennes, France; UBA Austria; Administration de l'environnement, Luxembourg; National Institute for Public Health and the Environment, The Netherlands; Flanders environmental Agency, Belgium; FUB, Switzerland
<b>Ocean-Gate</b> Measurements in the Southern Ocean and Antarctica	Institut de Ciències del Mar, CSIC, Barcelona, Spain
<b>OLALA</b> Optical Lab for Lidar Applications	University of Wyoming, USA; Lyon 1 University, France; Technical University of Darmstadt, Germany; National Observatory of Athens, Greece
<b>OSCM</b> Ocean Science Centre Mindelo	Instituto Nacional de Desenvolvimento das Pescas, Mindelo, S. Vicente, Cabo Verde; Helmholtz Centre for Ocean Research Kiel, Germany
Ozone and particulate matter air pollution in China	Fudan University, China
<b>PolarCAP</b> Determination of polarimetric signatures of ice formation processes under controlled aerosol conditions	ETH Zurich, Switzerland
Development and application of Polly systems	11 partners from Finland, Poland, Portugal, Korea, Greece, Israel, Tajikistan, Cyprus, Cabo Verde, Germany
<b>REACTE</b> Photochemistry of organic complexes of transition metal ions (TMI) in tropospheric aerosols and clouds	ICCF - Clermont-Ferrand, France
<b>RI-URBANS</b> Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial Areas	Spain, Finland, France, Germany, Italy, The Netherlands, Great Britain, Greece, Switzerland, Belgium, Norway, Romania, Poland
<b>S2VSR</b> Small-scale Variability of Solar Radiation Campaign S2VSR	University of Oklahoma, School of Meteorology

## Appendices: Cooperations

Research project	Cooperation partner
<b>SOPORTE</b> Source apportionment of size-resolved atmospheric particles and their oxidative potential in Córdoba (Argentina) and Leipzig (Germany)	National University of Cordoba, Multidisciplinary Institute of Plant Biology IMBIV-CONICET, Argentina
<b>SOURCE FFR measurements and modelling</b> Ultrafine particulate matter pollution in the vicinity of Frankfurt Airport	12 partners from Germany and the Netherlands
<b>StanBC</b> Standardisation of Black carbon	10 partners from Germany, Greece, Switzerland, Slovenia, Finland, France, Canada
<b>Tobac</b> Development of an open-source Python software for tracking and object-based analysis of clouds in observations and simulations	University of Oxford, UK; Colorado State University, Texas Tech University, Argonne National Laboratory, USA
<b>TINIA</b> Investigations on ice formation and ice crystal growth under turbulent temperature and humidity conditions	Michigan Tech, USA; University of Hamburg; OvGU Magdeburg, Germany

### National cooperations

Research project	Cooperation partner
<b>(AC)<sup>3</sup> Project A-01</b> DFG-SFB/Transregio 172, Shipborne characterisation of Arctic aerosols and clouds and their radiative forcing	Leipzig Institute for Meteorology, Leipzig University, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam
<b>(AC)<sup>3</sup> Project A-01</b> DFG-SFB/Transregio 172, Aerosol, cloud and radiation properties from observations and big data analysis	Leipzig Institute for Meteorology, Leipzig University, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam
<b>(AC)<sup>3</sup> Project A-01</b> DFG-SFB/Transregio 172, Transformation of mixed-phase clouds in the Arctic during cold air outbreaks characterised by remote sensing from the air and by satellite	Leipzig Institute for Meteorology, Leipzig University, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam
<b>(AC)<sup>3</sup> Project D-02</b> DFG-SFB/Transregio 172, Model-based quantification of aerosol and cloud processes and their effects in the Arctic	Leipzig Institute for Meteorology, Leipzig University, University of Bremen; Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam
<b>(AC)<sup>3</sup> Project A-02</b> DFG-SFB/Transregio 172, Tethered balloon-borne measurements of the energy balance in the cloudy central Arctic	Leipzig Institute for Meteorology, Leipzig University, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam

## Appendices: Cooperations

Research project	Cooperation partner
<b>(AC)<sup>3</sup> Project B-04</b> DFG-SFB/Transregio 172, Properties and sources of ice and droplet nucleating cloud particles in the Arctic, based on shipboard measurements	Leipzig Institute for Meteorology, Leipzig University, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Alfred Wegener Institute Potsdam
<b>ACTRIS-D</b> Aerosol, Clouds and Trace Gases Research Infrastructure - Germany	10 Project partners
Aerosol chamber studies to characterise the transmission of SARS-CoV-2 by aerosol particles	Helmholtz Centre for Environmental Research (UFZ), Leipzig, Institute of Virology, Leipzig University Hospital
<b>Air-Q-Drone</b> Measurement of air quality parameters with a new type of drone as part of the new SPP 2433	Braunschweig University of Technology
<b>AirPlast</b> Frequency and fate of synthetic materials in atmospheric particles below 10 µm	Leibniz Institute for Polymer Research, Dresden Helmholtz Centre for Environmental Research, Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg, TU Berlin
<b>ALADINA</b> Investigation of the small-scale vertical and horizontal variability of the atmospheric boundary layer aerosol with unmanned aerial vehicles	Braunschweig University of Technology, Tübingen University of Technology
<b>APAICA</b> (within the framework of ATWAICE) Polar star measurements (aerosol / turbulence) in the Arctic	Technische Universität Berlin, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Bremerhaven
<b>Atmo-Plast</b>	Leibniz Institute for Polymer Research Dresden, University Oldenburg, Institute for Chemistry and Biology of the Marine Environment
<b>AVANTI</b> Aerosol variability over the Arctic Ocean and sea ice	Braunschweig University of Technology, SPP2433 consortium
Ammonia measurements in Saxony	Saxon State Office for Environment, Agriculture and Geology, Dresden
<b>BASS</b> Biogeochemical processes and exchange processes between ocean and atmosphere in marine surface films	Carl von Ossietzky University Oldenburg, GEOMAR - Helmholtz Centre for Ocean Research Kiel, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Bremerhaven
<b>BeCoLe</b> UVC air sterilisation indoors	8 partners
<b>BioSmoke</b> Leibniz ScienceCampus Smoke and Bioaerosols in Climate Change	Leipzig University, Deutsches Biomasseforschungszentrum, Helmholtz Centre for Environmental Research (UFZ)

## Appendices: Cooperations

Research project	Cooperation partner
Bodengebundene Fernerkundung der Atmosphäre zur Verbesserung der Charakterisierung mikrophysikalischer Wolkeneigenschaften sowie der Leistungsprognose erneuerbarer Energien	Leipzig University, German Weather Service, Ingenieurbüro Last- und Energiemanagement – LEM-Software, Hochschule Mittweida
<b>C3SAR</b> DFG Research Unit FOR 5626: Cloud 3D Structure & Climate C3SAR	German Weather Service, University of Cologne, Ludwig-Maximilians-Universität Munich, Leibniz Universität Hannover
<b>CIRRUS-HL</b> The HALO mission on cirrus formation at high latitudes	7 partners
<b>Colrawi</b> Combined Observations with Lidar Radar and Wind profiler	German Weather Service, Lindenberg
<b>ECO-N</b> DFG Research Training Group, Economics of Connected Natural Commons	Leipzig University, German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Helmholtz Centre for Environmental Research
<b>EngageMINT</b> Transfer and communication of knowledge for environmentally conscious young people to raise awareness of STEM subjects	Leibniz University Hannover, Leibniz Competence Center for Procurement at the Leibniz Institute for Educational Trajectories, Leibniz Institute for Science and Mathematics Education
<b>ESA Aeolus DISC</b> Data, Innovation, and Science Cluster for the Aeolus mission	German Aerospace Center
ESF project, improvement of the performance forecast of photovoltaic systems to support the energy transition and investigation of aerosol-cloud interactions	Leipzig University
<b>GIVE</b> German initiative for the validation of the EarthCARE mission	University of Cologne, University of Hamburg, Ludwig-Maximilians-Universität Munich, Jülich Research Centre, German Weather Service
<b>GoSouth</b> Measurements for a better understanding of aerosol in the southern hemisphere	Leibniz University Hanover
<b>GUAN</b> German Ultrafine Aerosol Network	Federal Environment Agency, Dessau-Roßlau, Langen, Garmisch-Partenkirchen, Hofgrund; German Weather Service, Hohenpeißenberg; IUTA Duisburg e. V.; Helmholtz Centre, Munich; University of Augsburg
<b>HALO</b> High Altitude and Long Range Research Aircraft	German Aerospace Center, Jülich Research Centre, Karlsruhe Institute of Technology, Max Planck Society for the Advancement of Science, German Research Foundation

## Appendices: Cooperations

Research project	Cooperation partner
<b>HALO-South</b> Clouds, Aerosol and Radiation above the Southern Ocean	Leipzig University, Leipzig Institute for Meteorology, Johannes Gutenberg University Mainz, Goethe University Frankfurt, Max Planck Institute for Chemistry, Karlsruhe Institute of Technology, an Aerospace Center, Jülich Research Centre
<b>IAGOS-CARIBIC</b>	Karlsruhe Institute of Technology, Max Planck Institute für Polymer Research Mainz, Max Planck Institute for Biogeochemistry Jena, German Aerospace Center, Jülich Research Centre
<b>IFCES2 SCALEXA</b> Optimisation of simulation algorithms for exascale supercomputers to calculate the earth system model ICON	TU Dresden - Centre for Information Services and High-Performance Computing, Max Planck Institute for Meteorology Hamburg, German Climate Computing Centre Hamburg, Jülich Supercomputing Centre, ParTec AG, Munich
Influence of the use of energy-efficient wood-burning stoves on lung health	atmosfair gGmbH, Berlin
Leibniz Research Alliance “Infections”	23 partners
Leibniz Research Network “Crises in a globalised world”	22 partners
Leibniz Research Network “Earth and Societies”	20 partners
Leibniz Research Network “Mathematical Modelling and Simulation (MMS)”	24 partners
Machine learning for predicting the optical properties of aged carbon black	TU Kaiserslautern
<b>MesSBAR</b> Automated airborne measurement of pollutant levels in the near-earth atmosphere in urban areas	Braunschweig University of Technology; Leichtwerk Research GmbH, Braunschweig; Jülich Research Centre; Federal Environment Agency, Dessau, Federal Highway Research Institute, Bergisch-Gladbach, Physikalisch-Technische Bundesanstalt, Braunschweig
<b>MINION</b> Microfluidic device for Ice Nucleation analysis In cONTinuous flow	Chemnitz University of Technology
<b>MODEX</b> Modellers Exchange	Leipzig Institute for Meteorology, Leipzig University
<b>MPI-ESM-HAMMOZ</b> Earth system model of the Max Planck Institute for Meteorology, based on MPI-ESM1.2 and extended by the aerosol and chemistry module HAMMOZ	Max Planck Institute for Meteorology, Jülich Research Centre

## Appendices: Cooperations

Research project	Cooperation partner
<b>NFDI4Earth</b> Research Data Infrastructure	59 partners
<b>PICNICC</b> Polarimetry Influenced by CCN aNd INP in Cyprus and Chile	Leipzig Institute for Meteorology, Leipzig University
Polarimetric Radar Signatures of Ice Formation Pathways from Controlled Aerosol Perturbations	PROM Initiative
Prototype Doppler lidar (design phase)	ABACUS-Laser Göttingen, Licel Berlin
<b>PV-WOW</b>	Leipzig University, Solarpark Bad Liebenwerda GmbH & Co. KG
<b>SCALEXA</b>	Deutsches Klimarechenzentrum, Jülich Research Centre, Max Planck Society, Dresden University of Technology, Centre for Information Services and High-Performance Computing
<b>SCALE-TRACK</b> A scalable, two-way coupled Euler-Lagrange algorithm for particle observation	Wikki Gesellschaft für numerische Kontinuumsmechanik mbH, Wernigerode
Spatial distribution of Antarctic Aerosol and trace gases	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Bremerhaven, Max Planck Institute for Chemistry, Mainz
<b>SOURCE FFR</b> Study On Ultrafine Particles in the Frankfurt Airport Region	Hessian State Office for Nature Conservation, Environment and Geology, Goethe University Frankfurt, Gemeinnützige Umwelthaus GmbH, Helmholtz-Zentrum hereon GmbH, Air Consulting Hellebrandt, Institute for Environment & Energy, Technology & Analytics (iuta)
<b>UV Monitoring Network</b> Germany-wide network for monitoring UV irradiance and carrying out UV index forecasts	Federal Office for Radiation Protection, Lebenstedt, German Weather Service, Federal Environment Agency Dessau
<b>VACCINE</b> Variation of Antarctic cloud condensation (CCN) and concentrations ice nucleating particle (INP)at Neumayer Station	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Bremerhaven

## Appendices: Boards

### Boards

#### Boards of trustees

Name	Institution
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RORin C. Liebner	Saxon State Ministry for Science, Culture and Tourism
Prof. Dr. F.-J. Lübken	Leibniz Institute of Atmospheric Physics at the University of Rostock (IAP)

#### Scientific advisory board

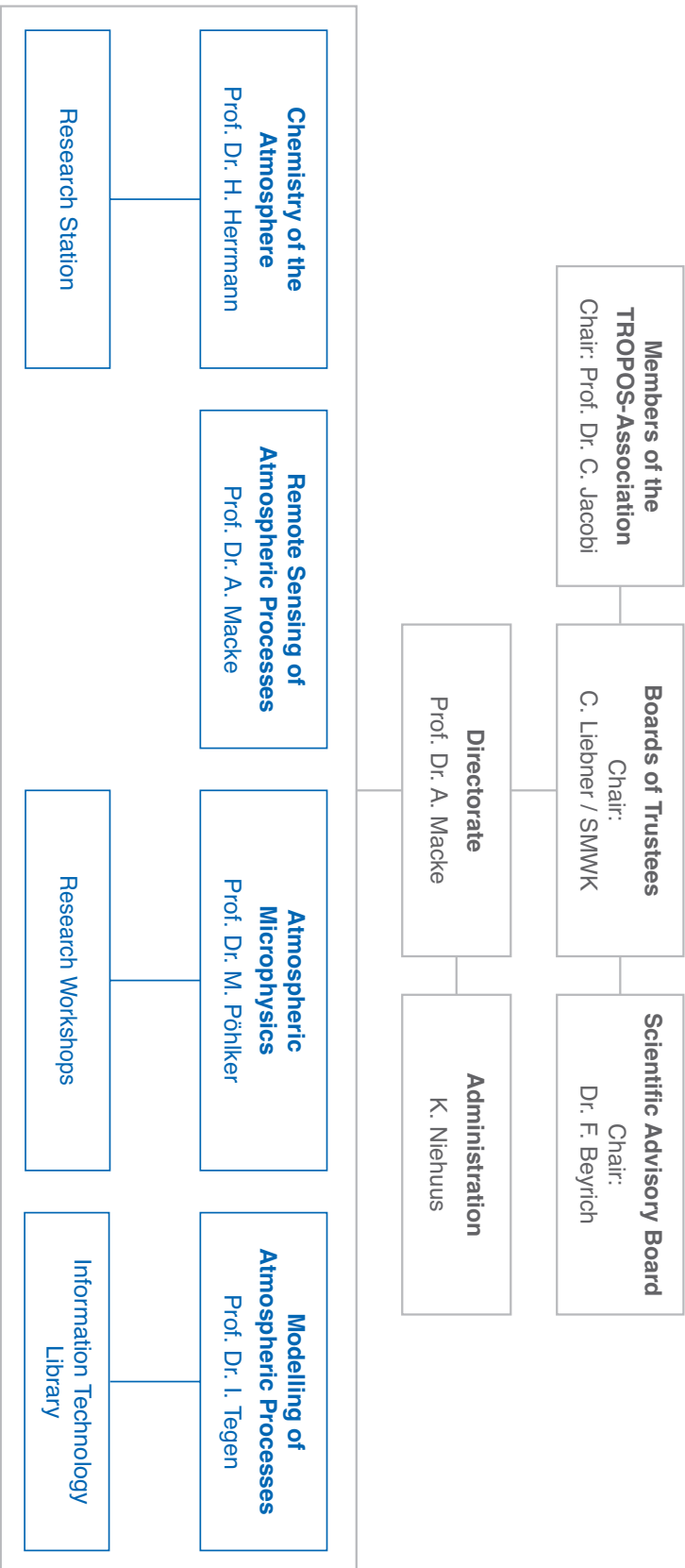
Name	Institution
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Prof. Dr. A. Engel	GEOMAR Helmholtz Centre for Ocean Research Kiel
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# Appendices: Organigram

## Leibniz Institute for Tropospheric Research (TROPOS)





## **TROPOS**

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