ATMOS-2024
Conference Report and User Recommendations

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1 Introduction

1.1 Scope

The purpose of this document is to present a summary of the findings and conclusions presented or discussed at the **'ATMOS-2024 Conference'** (https://www.atmos2024.org/) that took place on 1—5 July 2024 in Bologna (Italy). It summarises the latest scientific developments in atmospheric satellite remote sensing as presented at the conference. Based on discussions at the conference with the scientific community a number of recommendations were made to ESA indicating priorities for activities on the exploitation of atmospheric satellite measurements. This document supports the definition of future of R&D activities in the frame of the ESA Earth Observation Programme, under the banner of the Atmospheric Cluster of the ESA/ESRIN Earth System Science Hub (https://sciencehub.esa.int/).

1.2 ATMOS-2024

In the context of the Earth Observation (EO) Science for Society Programme Element, the European Space Agency (ESA) has organised ATMOS-2024 on the topical theme Atmosphere, aimed at exploiting data from ESA and EO Missions for science and application development. The purpose of this conference was to provide scientists and data users with the opportunity to present first-hand and up-to-date results from their ongoing research and application development activities, by using data from past and current atmospheric missions like Copernicus Sentinel-5P, EarthCARE and ESA Third Party Missions. Other important aspects included discussing activities and opportunities regarding future missions, and networking opportunities.

The statistics on the conference are:

Number of participants	>300
Number of thematic sessions	24
Number of oral presentations	147 + 3 keynote addresses
Number of poster presentations	145
Number of sponsored students	5

2 List of Acronyms

3MI Multi-Polarization Imager
AAS Absorbing Aerosol Sensor
ACE Atmospheric Chemistry Experiment
ACE-FTS Atmospheric Chemistry Experiment Fourier Transform Spectrometer
ACTRIS Aerosol, Clouds and Trace Gases Research Infrastructure
AEC Aerosol Extinction Coefficient
AERONET Aerosol Robotic Network
AIRWAVE Infra-Red WAter Vapour Estimator
ALADIN Atmospheric LAser Doppler Instrument
ALH Aerosol Layer Height
ALTIUS Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere

AMF Air Mass Factor
ANN Artificial Neural Network
ANNI Artificial Neural Network for Infrared Atmospheric Sounding Interferometer
AOD Aerosol Optical Depth
APE Automated Pollution Emission
AQ Air Quality
ARSA Analysed Radio Sounding Archive
ASI Italian Space Agency
ATM-MPC Atmospheric Mission Performance Cluster
ATSR Along Track Scanning Radiometer
AVHRR Advanced Very High Resolution Radiometer
BIRA-IASB The Royal Belgian Institute for Space Aeronomy
BrO Bromine monoxide
BRDF Bi-directional Reflectance Distribution Function
BVOCs Biogenic Volatile Organic Compounds
C_2H_6 Ethane
C_2H_2 Acetylene
C3S Copernicus Climate Change Service
CAIRT Changing-Atmosphere Infra-Red Tomography Explorer
CALIOP Cloud-Aerosol LIDAR with Orthogonal Polarisation
CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAMS Copernicus Atmosphere Monitoring Service
CCD Convective Cloud Differential
CCM Copernicus Contributing Missions
CCl_4 Carbon tetrachloride
CCI Climate Change Initiative
CEA Commissariat à l'énergie atomique
CFCs Chlorofluorocarbons
CH_3OH Methanol
$CH_3C(O)CH_3$ Acetone
CH_3COOH Acetic acid
CHOCHO Glyoxal
CHORA-CCD Cloud Height Ozone Reference Algorithm-CCD
CMCC Centro euro-Mediterraneo sui Cambiamenti Climatici
CNES Centre national d'études spatiales
CNR National Research Council
CNRS Centre national de la recherche scientifique
CO Carbon monoxide
CO_2 Carbon dioxide
CO_4 Methane
CO2M Copernicus Carbon Dioxide Monitoring mission
COBRA Covariance-Based Retrieval Algorithm
CPR Cloud Profiling Radar
CrIS Cross-track Infrared Sounder
DECSO Daily Emissions Constraint by Satellite Observations
DISC Data Innovation and Science Cluster
DLER Directional Lambertian Equivalent Reflectivity
DLR Deutsches Zentrum für Luft- und Raumfahrt
DOAS Differential Optical Absorption Spectroscopy
EarthCARE Earth Cloud Aerosol and Radiation Explorer
ECVs Essential Climate Variables
ECMWF European Centre for Medium-Range Weather Forecasts
EDF Environmental Défense Fund
EDGAR Emissions Database for Global Atmospheric Research
EMAC ECHAM/MESSy Atmospheric Chemistry

EMIT Earth Surface Mineral Dust Source Investigation
EMPA Swiss Federal Laboratories for Materials Science and Technology
ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
ENMAP Environmental Mapping and Analysis Program
ENVISAT ESA Environmental Satellite
EO Earth Observation
ERB Earth Radiation Budget
ESA European Space Agency
EUMETSAT European Organisation for the Exploitation of Meteorological Satellites
EVDC ESA atmospheric Validation Data Centre
FDR4ATMOS Fundamental Data Records in the domain of satellite Atmospheric Composition
FDR Fundamental Data Record
FIR Far-Infrared
FMI Finnish Meteorological Institute
FOCAL Fast atmOspheric traCe gAs retrievaL
FORUM Far-infrared Outgoing Radiation Understanding and Monitoring
FRESCO Fast Retrieval Scheme for Clouds from the Oxygen A band
FRP Fire Radiative Power
GCM Global Climate Model
GCOS Global Climate Observing System
GEMS Geostationary Environment Monitoring Spectrometer
GFAS Global Fire Assimilation System
GHGSat Greenhouse gas satellite constellation
GHGs Greenhouse gases
GLORIA-B Gimballed Limb Observer for Radiance Imaging of the Atmosphere
GOME-2 The Global Ozone Monitoring Experiment−2
GOMOS Global Ozone Monitoring by Occultation of Stars
GOSAT Greenhouse gases Observing SATellite
GRASP Generalised Retrieval of Aerosol and Surface Properties
H2O Water Vapour
HCN Hydrogen cyanide
HCOOH Formic acid
HCFCs Hydrochlorofluorocarbons
HCHO Formaldeyde
HFCs hydrofluorocarbons
HITRAN HIgh-resolution TRANsmission molecular absorption database
HLOS Horizontal Line Of Sight
HONO Nitrous acid
HYSPLIT Hybrid Single-Particle Lagrangian Integrated Trajectory
IASI Infrared Atmospheric Sounding Interferometer
IASI-NG Infrared Atmospheric Sounding Interferometer Next Generation
IMEO International Methane Emissions Observatory
IMF Remote Sensing Technology Institute
IMK-ASF Das Institut für Meteorologie und Klimaforschung - Atmosphärische Spurengase und Fernerkundung
IMS Infrared and Microwave Sounder
INOE National Institute of Research and Development for Optoelectronics
IPCC Intergovernmental Panel on Climate Change
ISS International Space Station
LISA Laboratoire Interuniversitaire des Systèmes Atmosphériques
LMD Laboratoire de Météorologie Dynamique
LSR Lidar Surface Returns
JAXA Japan Aerospace Exploration Agency, Japan

JPSS Joint Polar Satellite System
KIT Karlsruhe Institute of Technology
KNMI Royal Netherlands Meteorological Institute
LSCE Laboratory for Climate and Environmental Sciences
LOS Line Of Sight
LRTAP Long-range Transboundary Air Pollution
MARSTRO Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
MAIA Multi-Angle Imager for Aerosols
MAMAP Methane Airborne MAPper
MAP Multiangular-Polarimetric measurements
MARS Methane Alerts and Response System
MEGRIDROP MErged GRIdded Dataset of Ozone Profiles
MetOp Meteorological Operational Satellites
MERRA-2 Modern -Era Retrospective Analysis for Research and Applications, version 2
MIPAS Michelson Interferometer for Passive Atmospheric Sounding
MLS Microwave Limb Sounder
MODIS MODerate Imaging Spectrometer
MOPITT Measurements Of Pollution In The Troposphere
MPI Max Planck Institute
MS Multiple Scattering
MUSICA MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water
N2O Nitrous oxide
NAO North Atlantic Oscillation
NASA National Aeronautics and Space Administration
NCEO National Centre for Earth Observation
NDACC Network for the Detection of Atmospheric Composition Change
NH3 Ammonia
NIR Near-Infrared electromagnetic spectrum
NMVOCs Non-Methane Volatile Organic Compounds
NN Neural Network
NO2 Nitrogen dioxide
NO3 Nitrate
NOAA National Oceanic and Atmospheric Administration
NOA National Observatory of Athens
NOx Nitrogen oxides
NWP Numerical Weather Predictions
OClO Chlorine dioxide
OCO Orbiting Carbon Observatory
ODS Ozone Depleting Substances
OLR Outgoing Longwave Radiation
OMI Ozone Monitoring Instrument
OMPS-LP Ozone Mapping and Profiler Suite - Limb Profiler
OMS-N Ozone Monitor Sensor-Nadir
ORAC Optimal Retrieval of Aerosol and Cloud
OSES Observing System Experiments
OSIRIS Optical Spectrograph and Imaging System
PACE Plankton, Aerosol, Cloud, ocean Ecosystem
PAN Peroxyacyl nitrates
PCA Principal Component Analysis
pCO2 CO2 partial pressure
PGN Pandonia Global Network
PFCs Perfluorocarbons
PMAp Polar Multi-sensor Aerosol optical properties product

PM Particulate Matter
PRISMA PRecursore IperSpettrale della Missione Applicativa
PRNU Photo-Response Non-Uniformity
PSD Particle Size Distribution
PSF Point Spread Functions
RAL Rutherford Appleton Laboratory
ROCINN Retrieval of Cloud Information using Neural Networks
S5P-PAL Sentinel5-P Product Algorithm Laboratory
SAF Satellite Applications Facility
SAGE Stratospheric Aerosol and Gas Experiment
SCDs Slant Column Densities
SCIAMACHY SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY
SF6 Sulphur hexafluoride
SIF Solar-Induced Fluorescence
SLSTR Sea and Land Surface Temperature Radiometer
SNR Signal-to-Noise Ratio
SRF Spectral Response Functions
SRON Netherlands Institute for Space Research
SSA Single Scattering Albedo
SSM/I Special Sensor Microwave/Imager
SUOMI-NPP The Suomi National Polar-orbiting Partnership
SVD Singular Vector Decomposition
SEVIRI Spinning Enhanced Visible and InfraRed Imager
SWIR Short-wave infrared electromagnetic spectrum
TANGO Twin Anthropogenic Greenhouse Gas Observers
TCCON Total Carbon Column Observing Network
TCWV Total Column Water Vapour
TEMPO Tropospheric Emissions: Monitoring of Pollution
TIR Thermal Infrared electromagnetic spectrum
TOA Top Of the Atmosphere
TOC Total Ozone Column
TROPOMI Tropospheric Monitoring Instrument
TRUTHS Traceable Radiometry Underpinning Terrestrial- and Helio- Studies
TUT turnover Time
ULB Université libre de Bruxelles
UNEP United Nations Environment Programme
UoL-FP University of Leicester Full Physics retrieval algorithm
UPV Universitat Politecnica de Valencia
UVAI Ultraviolet Aerosol Index
UV Ultra Violet electromagnetic spectrum
VCDs Vertical Column Densities
VIIRS Visible Infrared Imaging Radiometer Suite
VIS Visible electromagnetic spectrum
VOC Volatile Organic Compounds
WFM-DOAS Weighting Function Modified Differential Optical Absorption Spectroscopy
WIVERN WInd VElocity Radar Nephoscope
WVRT Water Vapour Residency Time
WWLN World Wide Lightning Location Network

3 Objectives, Themes and Session Chairs

The science objectives of ATMOS-2024 were:

- Provide a platform for scientific exchange and to assess the state of the art of atmospheric applications;

- Foster the scientific community in atmospheric research;
- Present mission status, algorithms, and products for the currently operating Copernicus Sentinel-5p and EarthCARE missions;
- Provide updates on development and science activities regarding future missions, e.g Copernicus Sentinel-4, Copernicus Sentinel-5, CO2M, FORUM, Altius;
- Provide updates on activities regarding ESA Third Party missions;
- Demonstrate the synergistic use of different atmospheric instruments;
- Present large scale international initiatives to support the R&D activities relevant to atmosphere satellite missions and promote synergy with Copernicus Sentinels, Earth Explorers, and other missions;
- Present scientific results related to the Copernicus Atmospheric Services CAMS & C3S;
- Discuss novel atmospheric mission, instrument and algorithm concepts, e.g., Scout Missions, SmallSats, constellations, HAPS, miniaturisation, AI in algorithms;
- Review and assess the progress according to the recommendations of the ESA 2018 Atmospheric Science Conference;
- Provide a forum for scientists to formulate community recommendations.

The conference focused around the following themes:

- Reactive trace gases in the atmosphere;
- Clouds and aerosols;
- Anthropogenic greenhouse gases;
- Biogenic sources of greenhouse gases;
- Volcanic emissions;
- Water vapour;
- Air quality and climate monitoring from space;
- Stratospheric and middle-atmosphere processes;
- Atmospheric dynamics;
- Earth's radiation budget;
- Results on the generation of atmospheric Essential Climate Variables;
- Atmospheric applications and service development;
- Data assimilation and forecasting;
- Numerical methods in Atmospheric Remote Sensing;
- New and innovative technologies for atmospheric remote sensing;
- Synergy with other Copernicus Sentinels, ESA Earth Explorers and other missions.

The organizing committee consisted of:

- Thorsten Fehr, ESA
- Diego Fernandez, ESA
- Edward Malina, ESA
- Simon Pinnock, ESA
- Claus Zehner, ESA
- Christian Retscher, ESA

The sessions were chaired by (non-ESA chairs):

- Ilse Aben, SRON
- Vassilis Amiridis, NOA
- Hartmut Boesch, University of Bremen
- Michael Buchwitz, University of Bremen
- Elisa Castelli, CNR
- Ugo Cortesi, CNR
- Claudia Di Biagio, LISA/CNRS
- Bianca Maria Dinelli, CNR
- Oleg Dubovik, CNRS/University of Lille
- Claudia Emde, DLR/LMU
- Henk Eskes, KNMI

- Federico Fierli, EUMETSAT
- Luis Guanter, UPV
- Otto Hasekamp, SRON
- Itziar Irakulis-loitxate, UNEP
- MariLiza Koukuli, Aristotle University of Thessaloniki
- Akihiko Kuze, JAXA
- Ruediger Lang, EUMETSAT
- Diego Loyola, DLR
- Marta Luffarelli, Rayference
- Tiziano Maestri, University of Bologna
- Bas Mijling, KNMI
- Emal Rumi, RALSpace
- Viktoria Sofieva, FMI
- Kerstin Stebel, NILU
- Gabriele Stiller, KIT
- Johanna Tamminen, FMI
- Nicolas Theys, BIRA-IASB
- Michel Van Roozendaal, BIRA-IASB
- Pepijn Veefkind, KNMI
- Lucy Ventress, RALSpace
- Mark Weber, University of Bremen
- Nedjeljka Žagar, University of Hamburg

The conference organisation was also supported by an external and internal scientific committee, who reviewed all submitted abstracts and helped shape the structure of the conference. The names of the committee members are available on the ATMOS-2024 website (https://www.atmos2024.org/).

4 Session Summary and Highlights

4.1 ESA Missions

Thirty years ago, ESA launched its first Earth observation satellite ERS-1 – a historic milestone that paved the way to a new era in satellite technology and Earth-system science. Now, ESA operates one of the world's largest fleet of EO satellites, and is placed firmly as a world leader in EO. Nevertheless, the need to understand more about the intricacies of how Earth works as a system and how humanity is affecting natural processes is more urgent than ever so that the climate crisis and environmental challenges such as those outlined in Europe's Green Deal can be addressed as effectively as possible.

The diminished quality of our planet's air affects not only human health, but has wide impacts and implications on vegetation and, equally importantly, influences climate change. When the first EO satellite sensors were launched, maps of pollutant concentrations revealed the most affected regions on a global scale, the contribution of individual emitting sectors and the magnitude of regional and inter-hemispherical transport of pollution. The improvement of observing systems, provided increasing evidence that monitoring human activities over the whole planet is necessary for identifying and mitigating human impact on the Earth system. In a keynote address, MariLiza Koukouli from the Aristotle University of Thessaloniki moved from the past into the future of spaceborne monitoring highlighting the significance of the contribution of ESA to the major international agreements and treaties on air pollution and climate change.

The Sentinel-5 Precursor mission, launched on Oct. 13 2017, is the first Sentinel mission dedicated to atmospheric remote sensing, supporting Copernicus services, including activities such as air quality, ozone and climate monitoring and forecasting. The mission ensures continuity of atmospheric satellite data provision from the ESA GOME, SCIAMACHY and prepares for future atmospheric Copernicus Sentinel-4 and Sentinel-5 instruments. ESA presented an overview of the Sentinel-5 Precursor Mission status.

Operational monitoring of anthropogenic GHG emissions requires high precision CO2 and CH4 observations with, on average, weekly effective coverage at mid-latitudes and relatively high spatial resolution (4 km²). The Copernicus CO2 Monitoring (CO2M) Mission will provide observations from Near Infrared (NIR) and Shortwave Infrared (SWIR) radiance spectra at a spectral resolution of 0.12 nm and 0.35 nm, respectively. ESA provided the status of the on-going implementation of the space segment of the Copernicus CO2M mission which will form a keystone in supporting future global stocktakes and is implemented in an international coordination framework.

First results from the CO2M operational processing system developments have been presented by EUMETSAT. This includes first results for the dedicated CO2M aerosol, cloud, and NO2 products, as well as from the innovative three-algorithm GHG (XCH4, XCO2) retrieval approach. An update on the status of preparation and planning of product commissioning and their operational monitoring throughout the operations phase has been provided.

The Copernicus satellite missions Sentinel-4 and Sentinel-5 were introduced by ESA. They will carry out atmospheric composition observations on an operational long-term basis to serve the needs of CAMS and C3S. Sentinel-4 forms the European component of a constellation of geostationary instruments, with a strong air quality focus, together with the NASA mission TEMPO and the Korean mission GEMS. Sentinel-5 will provide composition data with global daily coverage serving climate, air quality, and ozone/surface UV applications.

EUMETSAT focussed on the latest updates concerning Sentinel-4, Sentinel-5 and the related ground segment developments. The status of the data processing and monitoring facility developments for commissioning and routine operations of Sentinel-4 and -5 was presented and the current state of planning for the calibration/validation of the operational atmospheric chemistry products was introduced.

Further, DLR presented the Sentinel-4 Level 2 operational products being developed in the framework of the ESA S4 L2OP project. The Sentinel-4 mission focuses on monitoring of trace gas column densities and aerosols over Europe at high spatial resolution with an hourly revisit time.

4.2 ESA Future Missions and Candidates

The future ESA Earth Watch mission Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS) will enhance by up to an order-of-magnitude our ability to estimate the spectrally resolved Earth Reflected Solar Radiation Budget through direct measurements of incoming and outgoing energy in the UV-VIS-SWIR spectral domain. These observations at unprecedented accuracy (up to 0.3% expanded uncertainty, k=2) will shorten the time to detect and disambiguate trends from natural variability in the Earth's Climate system. ESA presented the mission status and design, the scientific objectives, data products and the unique calibration opportunities for climate and operational user communities.

An overview of the FORUM mission and its applications was provided by ESA. Reliable climate change prediction remains uncertain because of the lack of an accurate modelling of the radiative properties related to atmospheric water vapour, trace greenhouse gases, clouds, and

surface emissivity across the full infrared spectrum. FORUM has been selected to be ESA's ninth Earth Explorer mission and will fill the long-standing gap in Far Infrared (FIR) spectral observations from space, measuring the Earth's thermal emission in the FIR between 100 and 667 cm-1 (15 – 100 μm).

The two remaining candidate missions competing for implementation as ESA's Earth Explorer 11 were presented. Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) aims to reveal, resolve, and unravel the complex coupling between composition, circulation, and climate in our middle atmosphere, by improving our knowledge of the chemical-dynamic-radiative interactions that govern our climate system. CAIRT would produce a unique three-dimensional dataset of numerous trace gases, temperature and aerosols across the entire middle atmosphere to the edge of space. ESA presented the mission design and the latest developments.

The WInd VElocity Radar Nephoscope (WIVERN) concept is the second candidate missions of the ESA Earth Explorer 11 program. WIVERN promises to complement the Aeolus Doppler wind lidar that measures predominantly clear air winds by globally observing, for the first time, the vertical profiles of winds in cloudy areas. The mission hinges upon a single instrument, i.e., a dual-polarization Doppler W-band scanning cloud radar with a circular aperture non-deployable main reflector larger than 3 m. Politecnico di Torino provided an update on the refinement of the scientific objectives and on the development of the Level-2 algorithms for the derivation of the geophysical variables.

4.3 EarthCARE and Aeolus

The EarthCARE was launched in May 2024. Profiles of cloud, aerosol and precipitation properties, along with collocated radiative fluxes, will be measured by EarthCARE on a global scale. ESA presented the EarthCARE Data Innovation and Science Cluster (DISC), aiming to ensure a high data quality during the mission exploitation phase (i.e. Phase E2). In particular, the DISC will be responsible for the routine and long-term quality control monitoring of the European instrument performance as well as for the Level 1 and Level 2 products.

An update on the status of EarthCARE processors and products have been provided by ESA. An overview of ESA's ground science data processing chain, which includes the production of calibrated instrumental data (Level 1 data products) and retrieved geophysical data (Level 2 data products) was presented.

Assuring the data quality of EarthCARE's 47 data products, including 25 Level 2 science products early after launch is an essential effort. The product validation will begin during the 6-month commissioning phase and will continue during the entire exploitation phase. This will be realised based on contributions from the independent EarthCARE validation team (ECVT) under coordination by ESA. An overview of the planned EarthCARE campaign activities and selected airborne and ground-based instrument developments critical for the validation were presented.

ESA presented the main outcomes from 5 years of wind, aerosol and atmospheric lidar science from the Aeolus mission. A full reprocessed Aeolus dataset was released in 2024. The main scientific outcomes from the mission are related to the use of Horizontal Line of Sight (HLOS) data in operational numerical weather predictions, the monitoring of volcanic eruptions such as the Hunga-Tonga, the observations of desert dust plumes in the atmosphere and optical characterization of polar stratospheric clouds.

4.4 Altius and the Stratosphere

Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere (ALTIUS) is an atmospheric limb sounder mission for monitoring of the distribution and evolution of stratospheric ozone number density profiles in support of operational services and long-term trend monitoring. The mission will be launched in November 2026. ESA presented the current status and planning with respect to flight model manufacturing, ground segment qualification and deployment, launch, commissioning, validation, and routine operations.

In addition to the primary ozone product intended for the ALTIUS mission, various secondary scientific products have been added, among which is stratospheric aerosol extinction. The aerosol secondary product presented by University of Saskatchewan is based on algorithms that have successfully been used to retrieve stratospheric aerosol extinction from both OSIRIS and OMPS-LP measurements.

BIRA-IASB presented the ALTIUS mission focussing on its relevance for the stratospheric ozone community. Limb-scatter and occultation retrieval algorithms were presented, and the expected performance of the mission were discussed based on end-to-end simulations. As the maturity of the retrieval algorithms has now reached a point where L1 datasets from previously flown UV-VIS-NIR limb instruments can also be processed. The expected in-flight performance of ALTIUS based on the processing of data from GOMOS/ENVISAT, OMPS-LP/JPSS-2, and SAGE-III/ISS was discussed.

University of Saskatchewan provided an overview of the in-flight calibration activities developed for the three optical channels, UV, VIS and NIR, of the ALTIUS instrument. The in-flight calibration is based upon observation of natural targets. They presented modelling results related to the PRNU, PSF and SRF calibrations from simulated observations of the solar and lunar disk.

Artifacts in the results from 1D limb-scatter retrievals, which assume homogeneous atmospheric properties along the satellite LOS, are known and are generally associated with variations in the trace gas concentration, temperature or surface reflectivity. University of Bremen focussed on the investigation of a retrieval artifact in Tropical tropospheric ozone data and ozone limb profiles from OMPS-LP observations, which is associated with an inhomogeneity in surface reflectivity.

BIRA-IASB showed a consolidated approach based on an Artificial Neural Network (ANN) for the inversion of limb radiances scattered by the Earth atmosphere illuminated by solar radiation in the UV-VIS-NIR range. Their research has been conducted in parallel with the development of the data processor for the ALTIUS Earth Watch mission where operational ozone number density profiles are the main target.

University of Toronto presented a new version of the Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) ozone and NO_2 profile products, version 4, which nominally covers the period from February 2004 to December 2023. They presented comparisons of the v4 MAESTRO ozone and NO_2 measurements against coincident, both spatially and temporally, measurements from an ensemble of 11 other satellite limb-viewing instruments: ACE-FTS, OSIRIS, SMR, MIPAS, GOMOS, SCIAMACHY, Aura-MLS, OMPS-LP, SAGE II, SAGE III/M3M, and SAGE III/ISS.

Finally, ESA discussed an upcoming Announcement of Opportunity call to solicit proposals for the validation of the ALTIUS products, namely vertical profiles of stratospheric and mesospheric ozone, aerosol extinction, NO2, H2O, OClO, BrO, NO3 and Temperature. This Announcement of Opportunity is international and non-restrictive, i.e. it is open to participants from anywhere in the world.

4.5 Greenhouse Gases

Satellite observations of CO_2 and CH_4 play an essential role for tracking progress towards GHG emission reduction targets, and for verifying the effectiveness of mitigation policies. Satellites also provide information on natural land and oceanic sinks which store vast amounts of carbon. Understanding processes behind carbon sources and sinks are key in the pathway towards the goals of the Paris agreement. In a keynote address, Professor Hartmut Boesch of the University of Bremen showed the key concepts for satellite observations of CO_2 and CH_4 and how dedicated satellite missions can be used to diagnose and quantify regional surface fluxes of natural and anthropogenic sources. Further, data from these dedicated missions can be complemented by hyperspectral satellites measuring with very high spatial resolution, allowing the observation of point source emissions.

CEA-LSCE presented the preliminary results of the SMART-CH4 project. The key objectives and tasks of SMART-CH4 are the enhancing TROPOMI retrievals and multi-sensor products, incorporating SWIR/TIR data from IASI and TROPOMI and advancing fine-scale emission detection using mid-resolution mappers like TROPOMI and high-resolution imagers such as GHGSat, MethaneSAT, EnMAP, or PRISMA. These improvements will lower detection thresholds, enabling the identification of smaller emitters like landfills, wetlands, and agricultural sources.

Climate change is warming the Arctic four times faster than the global average. As the Arctic permafrost stores large amounts of carbon, its thawing may result in releasing stored carbon to the atmosphere as GHGs, that can further accelerate climate change. FMI presented the results from the MethaneCAMP project where the potential of space-based methane observations for monitoring permafrost regions was demonstrated, through analysing long-term methane trends in the northern high latitudes and permafrost regions by using satellite observations and inverse modelling.

The University of Bremen improved the WFMD retrieval algorithm to generate a high-quality scientific XCH4 data product from TROPOMI. They also have produced a data product which combines WFMD scientific XCH4 product and the official ESA operational product so that users can easily compare both XCH4 products and can use both products in their analysis to find out to what extent their results depend on the underlying method used to generate a given product. Comparisons of both products highlights similarities and differences, e.g., in terms of spatial XCH4 pattern and coverage have been performed. The first results related to high resolution retrieval of methane (approximately 30 m) from PRISMA and EnMAP have been presented.

In August 2021, a large-scale international campaign called MAGIC2021 took place in Scandinavia to validate satellite missions retrieving GHGs (TROPOMI, OCO-2, IASI) in the circumpolar region. CNRS and CNES presented the main results derived from the unique dataset of gas concentration vertical profiles (from the ground to the mid-stratosphere), weighted columns (from the ground or from aircrafts) and 2D coverage at several altitudes of emission hotspots gathered during the MAGIC2021 campaign by means of three research aircrafts and stratospheric balloons.

For a complete understanding of the Earth's climate, it is essential to consider other atmospheric gases with significant greenhouse effects or a strong impact on the ozone layer. This is the case for N_2O, SF_6, and chlorofluorocarbons. These gases are collectively known as 'Other long-lived greenhouse gases' and are recognized collectively as part of the GCOS Essential Climate Variables (ECV)s. CNR presented the CCI LOLIPOP project in which they investigated if the quality of the existing data is sufficient to be used for selected applications in climate and atmospheric chemistry models and services.

In the framework of the Methane+ project, a combined wavelength scheme has been developed by RALSpace specifically to resolve near-surface information. This exploits the high signal-to-noise of Sentinel-5P (SWIR/column) with co-located soundings from IASI MetOp-B (TIR/height-resolved). Both the IASI-only and IASI-S5P datasets have been used in inverse

modelling trials and the data sets will be publicly available via CEDA (http://www.ceda.ac.uk/).

JAXA has developed a new retrieval product of the partial-column carbon dioxide (CO_2) densities in the lower (typically 0–4 km) and upper (typically 4–12 km) troposphere (XCO2LT and XCO2UT). Combining the GOSAT XCO2LT minus XCO2UT and TROPOMI NO_2, they estimated CO_2 emissions over global megacities. Given the co-emitted nature of the two gases from fossil fuel combustion, they examined the use of NO_2 data for characterizing the upwind source contributions and to improve CO_2 emission estimates calculated by an inverse relationship with wind speed.

A non-linear inference scheme has been developed at LMD to tackle the very small seasonal variability of CO_2, CH_4 and N_2O compared to their background values, combined to the strong dependence of IR radiances to atmospheric temperature and the simultaneous sensitivity of the channels to several gases. The latest development of the retrieval and application of methane has been presented focussing on the extension and validation of the retrieval to the high latitude regions achieved during the ESA MethaneCAMP project. This was done using AirCore 0-30 km profiles of methane concentration acquired at Sodankylä and several stations of the French AirCore network.

The European CO2M mission consists of a constellation of at least two satellites of which the first one is planned to be launched in 2026. The analysis of CO2M measurements will provide the global and local distributions of anthropogenic greenhouse gases (esp. CO2 and CH4) with the aim to obtain relevant information on the sources and sinks of these gases. University of Bremen showed recent results generated using the CO2M version of FOCAL (Fast atmOspheric traCe gAs retrievaL) method showing that it is in principle able to fulfil the challenging requirements on systematic errors (XCO2 bias < 0.5 ppm) for the CO2M mission.

The University of Bremen presented the optimal estimation FUSIONAL-P algorithm, designed to retrieve CO2, CH4 and SIF from CO2M, and make use of scene-dependent information from the MAP instrument to characterize aerosol optical properties and concentrations as an input for CO2 and CH4 retrievals. This is done as a preliminary processing step via the GRASP algorithm. The UOL-FP processing chain has been described, and its performance on simulated orbits over land and ocean scenes was summarised.

One of the main obstacles to fulfil the required accuracy in the satellite retrieval of XCO2 and XCH4 is the atmospheric aerosol characterization. Multiangular-Polarimetric measurements (MAP) provide the most advanced knowledge about aerosol properties from space-borne platforms. GRASP code approach has been extended to combine both MAP and SWIR spectrometric measurements from CO2M to provide a synergistic combined product of aerosol properties with the additional information of columnar XCO2 and XCH4.

SRON presented a comprehensive survey of landfill methane emissions using facility-level 2021-2022 GHGSat data covering 152 different sites (with 5th and 95th mean emission percentiles of 0.1 t/hr and 6.3 t/hr, respectively) located in 131 different urban areas across 6 continents. They compared GHGSat-based emission rates against values included in national reporting programs (r=-0.02) or calculated by the Climate TRACE initiative (r=0.18) and found that top-down and bottom-up understandings of solid-waste emissions cannot currently be reconciled at facility-scale.

KIT presented a method for optimally combining IASI and TROPOMI level 2 data. Products from the individual satellites were collocated in time and space (geomatching). Subsequently, the collocated data were optimally merged by fully considering the individual data characteristics (uncertainties and sensitivities) by the application of a Kalman filter. The procedure is robust and computationally cheap, allowing the efficient combination of billions of IASI and TROPOMI observations, and the combined product offers good global coverage. The combined product was validated by comparison to available reference datasets such as 14

globally distributed TCCON stations, CH_4 profile measurements made by 36 individual AirCore soundings.

Wetland methane emissions are an important source of uncertainty in the methane budget due to their significant spatial and temporal variabilities. The Lake Chad Basin is located in central Africa and comprises a number of transboundary waterbodies, which exhibit dramatic expansion and contraction. However, methane emissions from Lake Chad seem not to be properly captured in bottom-up emission inventories. Significant annual methane emissions over the Lake Chad Basin were detected by KNMI using both the official reprocessed (S5P_RPRO_L2__CH4) and WFM-DOAS (TROPOMI/WFMD v1.8) TROPOMI XCH4 products by means of an improved divergence method.

In 2023, the MARS program was launched by UNEP's IMEO as part of their efforts to reduce global anthropogenic methane emissions. MARS is the first global system connecting satellite methane detection to transparent notification processes that promote direct and immediate action to curb emissions. MARS harnesses state-of-the-art satellite data to identify major emissions events, activates its partners to notify relevant stakeholders, and supports and tracks progress toward mitigation. The first phase of MARS has been focused mostly on detecting and notifying emissions from the oil and gas sector due to its rapid fix potential, to date, notifying more than 220 emissions in different countries worldwide.

EDF and UPV presented the MethaneSAT mission, launched on 4 March 2024 and is currently (status July 2024) undergoing a commissioning phase. The instrument consists of two spectrometers, one covering the 1249-1305 nm window sampling oxygen absorption, and one covering 1598-1683 nm for methane and CO2 retrievals, with <0.1 nm spectral sampling and <0.3 nm spectral resolution, which will enable methane concentration maps with high accuracy and precision. The mission will sample up to 25 sites per day, with a swath width of about 220 km and a spatial sampling of about 110 m x 400 m. These capabilities uniquely allow MethaneSAT to quantify total regional methane emissions, at the same time detect high-emitting point sources and characterize diffuse area sources.

KNMI introduced the Twin Anthropogenic Greenhouse Gas Observers (TANGO) mission: a pioneering cubesat satellite mission comprising two satellites, TANGO-Carbon and TANGO-Nitro. The goal of TANGO is to quantify emissions of the greenhouse gases methane (CH_4) and carbon dioxide (CO_2) at the level of individual industrial facilities and power plants. The first satellite measures spectral radiances in the shortwave infrared part of the solar spectrum (1.6 µm) to detect moderate to strong emissions of CH_4 (≥ 5 kt/yr) and CO_2 (≥ 2.5 Mt/yr). The second satellite yields collocated NO_2 observations from radiance measurements in the visible spectral range, supporting plume detection and exploiting the use of CO_2/NO_2 ratio.

GHGSat operates a constellation of small satellites designed to detect and quantify methane emissions down to ~25 m resolution and ~100 kg/hr source rates. In order to validate their estimates, GHGSat presented results from a series of single-blind controlled releases, both self-organized and through independent third parties. Fitting their results to a probability-of-detection model they obtained a detection threshold of 102 kg/hr, at 50% probability of detection and wind speed of 3 m/s.

EMPA presented the results from a large measurement campaign called ROMEO conducted in October 2019 using ground- and drone-based measurements to better constrain methane emissions from O&G in Romania. During the campaign 25 super emitters were identified with emissions ranging from 16 to 501 kg/h. They were located at oil production sites, O&G processing facilities and, unexpectedly, in the open field, i.e. not directly linked to O&G infrastructure visible in aerial images. Many of these sources could later be confirmed by ground survey teams.

SRON provided an overview of detected methane super emitters and illustrated the synergy between TROPOMI and high-resolution instruments by focusing on one of the world's largest

surface coal mines. The Bogatyr and Severny coal mines are responsible for over 40% of coal production in Kazakhstan, producing ~42 million tonnes of coal annually. The results were combined with high-resolution GHGSat observations to get a full picture of emissions. They found large discrepancies between our estimates and reported bottom-up emission inventories.

The EnMAP satellite is a hyperspectral satellite instrument for the monitoring of terrestrial and aquatic ecosystems. It provides high spatial resolution (30 x 30 m^2) but relatively low spectral resolution. It is possible to analyse atmospheric NO2 and CO2 from EnMAP spectra for large emission plumes only. MPI presented spectral analyses of both trace gases and showed measurement results for power plant plumes from Riyadh in Saudi Arabia and the Highveld in South Africa. They compared ENMAP NO2 results to observations from the TROPOMI instrument on S5P, and aircraft measurements. The results show that EnMAP NO2 and CO2 measurements can be used to study the chemical and dynamical evolution of power plant plumes.

Satellite-based imaging spectrometers, such as EMIT and EnMAP, can be used for methane plume detection. UPV assessed the detection capability of these instruments for identifying point-source emissions from offshore platforms using both real data and WRF-LES simulations. The results presented for case studies of emissions from various offshore areas such as Malaysia, the Gulf of Mexico, and Qatar identified the importance of an angular configuration enabling sunglint to detect a large portion of offshore emissions.

SRON combined three high-resolution (30~60 m) hyperspectral instruments (EMIT, EnMAP, and PRISMA) to quantify and monitor emissions from 38 'super emitter' landfills, focusing on methane hotspots identified by the TROPOMI. The total area-source methane emissions from these landfills are 194 ± 12 t h-1, with a majority of the analysed landfills located in India, Argentina, Brazil, and Mexico. Results were compared against the facility-level Climate TRACE and city-level WasteMAP solid waste emission inventories showing that for the super-emitting landfills, SRON estimations exceed Climate TRACE and WasteMAP by a factor of 2.0 and 5.5, respectively.

Among the different anthropogenic methane sources, the palm oil industry significantly contributes to the rise of methane emissions. UPV have used the Matched-Filter retrieval to obtain methane concentration enhancement maps over palm oil mills from PRISMA and EnMAP, at 30m spatial resolution, and EMIT, at 60m spatial resolution. Two methane emissions within 13 minutes of each other have been detected in Colombia with methane quantifications estimated at roughly 130 kg/h. Additionally, in Indonesia, three more methane emissions from different palm oil mills using a GHGSat satellite were detected.

Across Europe, one of the largest CH_4 hotspots observable in Sentinel-5P TROPOMI data originates from the urban area of Madrid where enhanced CH_4 concentrations are continuously detected. To quantify the emissions from this landfill sites, an aircraft campaign was conducted in summer 2022 in which high-resolution GHGSat airborne data (1 x 1 m^2) was obtained. Using CH_4 emissions derived from these aircraft data, the University of Leicester conducted an intercomparison with GHGSat satellite data and found strong consistency between overlapping observations across both aircraft and satellite spatial scales.

University of Leeds presented the monitoring and quantification, by means of GHGSat's satellites, of the CH_4 emissions from an active gas leak from a downstream natural gas distribution pipeline near Cheltenham, UK, in the spring and summer of 2023 and provide the first validation of the satellite-derived emission estimates using surface-based mobile greenhouse gas surveys. The results showed that GHGSat's observations can produce flux estimates that broadly agree with surface-based mobile measurements and the study highlighted the importance of satellite data being used to mitigate the human impact on climate change.

GEO-K srl developed a matched filtering algorithm (MAG1C) to estimate methane concentrations from the ASI satellite PRISMA radiance information, utilizing RGB bands, the band with maximum methane absorption (2349.7915 nm), and a band for surface albedo correction (406.9934 nm). The results were then compared with the best available state-of-the-art data, in particular Level 2 CH4 data from the Sentinel-5P observations and the data available via the free GHGSat (SPECTRA) portal. The results obtained by analysing the estimated concentrations of the two state-of-the-art satellites and those generated with PRISMA to which the estimation algorithm has been applied are promisingly aligned.

4.6 Air Quality

KNMI presented the results from the CitySatAir project in which the NO_2 product provided by the TROPOMI instrument on the Sentinel-5P platform has combined with other information such as from models and air quality monitoring stations. Four contrasting study sites across Europe (Madrid, Oslo, Rotterdam, Warsaw) were chosen differing in size, pollution levels, dominant emission sources, and cloud cover. The data sets for the different cities are showcased in the Lobelia Explore viewer that is based on a serverless architecture. As a result of the user interacting with the viewer, the web application requests air pollution data from the cloud as static files and uses this data to render maps, display charts and aggregate data over user-defined areas, all of this browser-side.

The detection of trace gas plumes allows us to improve attribution of pollutant emissions and our understanding of photochemical processing in the global troposphere. University of Edinburgh developed a machine learning models for automatically detecting plumes of three trace gases: SO_2, NO_2 and methane. For each species, a separate U-Net style segmentation model was trained to identify emission plumes in TROPOMI level 2 data. Using a segmentation model allowed them to predict boundaries of plumes within an image, from which we can estimate emissions using integrated mass enhancement along with ERA-5 wind fields.

A new version of the inversion algorithm DECSO (Daily Emissions Constraint by Satellite Observations) has been developed by KNMI for deriving NOx and NH3 emissions for Europe on a daily basis, averaged to monthly mean maps with a precision of 25%. These are based on observations of TROPOMI (Sentinel 5p) and CrIS. In a newly developed post-processing step anthropogenic NOx emissions are separated from soil NOx emissions. In several cases, new sources of emissions are found, especially in Africa. For Europe the emissions are verified by comparison with the reported emissions of the bottom-up community (CAMS, LRTAP, NEC, EDGAR).

During the summer of 2023, a large number of megafire events occurred all over Greece, triggered by an extremely long-lasting heatwave and strong winds. Aristotle University of Thessaloniki by means of S5P/TROPOMI observations of the aerosol index and aerosol layer height showed the spread of the particulate load in the region, while observations of nitrogen dioxide, formaldehyde and carbon monoxide demonstrated how far these gaseous species may reach during such a megafire. Unprecedented high values of both aerosols and gaseous species were observed over the city of Thessaloniki also from ground-based observations, which amply demonstrate what could be expected in the future in terms of summer-time air quality burden.

KNMI presented the TROPOMI NO2 v2.7.0, the latest algorithm update for the retrieval of NO2 columns. The main change compared to v2.4.0 is the upgrade of the TROPOMI DLER database from v1.0 to v2.1. The former was based on the v1 Level-1B radiances/irradiances, while the latter is based on the v2 Level-1B product with in-flight degradation corrections and an improved calibration. A quantification on how this new DLER impacts the cloud properties (fraction, pressure), the air-mass factors and finally the tropospheric NO2 column has been presented.

Africa plays a crucial role for atmospheric composition, primarily due to the large amounts of BVOCs released by vegetation. Given the intricate interplay between NOx and VOCs, BIRA-IASB presented a novel inversion setup relying on a concomitant use of TROPOMI HCHO and NO2 column data in order to simultaneously optimize VOC and NOx emissions.

Since February 2022, the full-scale war in Ukraine has been strongly affecting society and economy of Ukraine and beyond. Satellite observations are crucial tools to objectively monitor and assess the impacts of the war. FMI combined satellite-based tropospheric NO2 and CO2 observations to detect and characterize changes in human activities, as both are linked to fossil fuel combustion processes. The results provide timely insights into the impacts of the ongoing war on Ukrainian society and illustrates how the synergic use of satellite observations from multiple platforms can be useful in monitoring significant societal changes.

DLR developed an advanced retrieval algorithm for tropospheric NO_2 columns from geostationary satellite spectrometers and apply it to GEMS measurements. The retrieved DLR GEMS tropospheric NO_2 columns show good capability to capture hotspot signals at the scale of city clusters and describe spatial gradients from city centers to surrounding areas. The hourly sampling and high spatial resolution of GEMS tropospheric NO_2 columns demonstrate the capability for a detailed analysis of the diurnal evolution of NO_2 burden and emission strengths over Asia from space.

University of Leicester investigated how the Coriolis effect influences the trajectory of Sentinel-5P observed emission plumes and assess the impact of this influence on satellite-derived emission estimates. Of the 16 industrial sites investigated, 9 showed the expected curvature for the hemisphere they reside in, 5 showed no or negligible curvature, and 2 showed opposing or unusual curvature.

University of Edinburgh aimed to infer emissions of nitrogen oxides ($NOx \equiv NO + NO2$) across Asia from GEMS column observations of NO2 by using the adjoint of GEOS-Chem atmospheric chemical transport model. For this purpose, they used the anthropogenic emissions from the MEIC and MIX inventories as our a priori emissions. Diurnal variations in their top-down estimates of NOx emissions across diverse Asian cities have been reported, assessing their implications for emission policy formulation.

ECMWF is ramping up its data assimilation capabilities to launch a new monitoring and verification service for greenhouse gases emissions in 2026. They presented the evaluation of the new emission estimation system. A comparison of global and regional emission budgets against independent emission estimates have been performed, including both top-down inventories and bottom-up studies.

In general, governmental AQ monitoring relies on in-situ measurements of surface concentration, with geographical gaps between these sparse observations filled in with numerical models. To facilitate the use of the new-generation satellite AQ data, BIRA presented temporally aggregated and spatially oversampled satellite tropospheric column observations converted to near-surface concentrations tied to the reference in-situ measurements with geostatistical techniques. First case studies presented focus on S5P NO2 and in-situ data in the heavily urbanized regions of Belgium and Japan.

The RAL Infrared Microwave Sounder (IMS) scheme is an optimal estimation scheme initially created to combine measurements from the Metop sounding instruments. RAL presented an extended IMS scheme optimised for the retrieval of carbon monoxide, cloud parameters, two types of aerosols (dust and volcanic sulphate), and column retrievals of several minor species including ammonia, isoprene (CrIS only), other VOCs, and sulphur dioxide.

EUMETSAT presented a satellite data value chain, e.g. the integration in CAMS Global Fire Assimilation System (GFAS) to monitor wildfires and their impact worldwide. Datasets addressing wildfires (e.g. Fire Radiative Power, atmospheric composition, and smoke)

currently generated at EUMETSAT and its Satellite Applications Facility (SAF) have been showed. They also introduced upcoming (based on the Flexible Combined Imager on-board the Meteosat Third Generation) and future products (Sentinel-4 and 5), with an example of potential joint use for a past intense fire case in the Mediterranean (Greece, August 2023).

HONO is a key atmospheric species primarily due to its role as a source of OH through its rapid photolysis. In the framework of DINAR project, BIRA has been demonstrated the capability of TROPOMI instrument to detect HONO, highlighting the potential of the IASI instrument to detect HONO as well in the IR. This opens new possibilities in terms of research and algorithmic developments. Understanding the differences between UV and IR HONO data is particularly interesting since both retrievals have complementary vertical sensitivities.

Among the VOCs observed from space, HCHO stands apart, as it is produced photochemically from the oxidation of most other VOCs released into the atmosphere. Many groups have used HCHO measurements in combination with atmospheric models and inverse modelling techniques to update the bottom-up emissions used in those models. A major outcome of those studies is the indication that biogenic VOC emissions are significantly overestimated in models. However, this finding is at odds with several recent studies, and there is evidence of biases in spaceborne data. BIRA-IASB discussed a simple method for resolving the discrepancy and presented an inverse modelling study using HCHO column from the OMI sensor.

NH_3 is being released into the atmosphere in excessive amounts due to human activities, with devastating consequences on the environment and air quality. ULB explored the question of whether instrumental designs are possible at lower spectral resolution that maintain the core measurement aspects (spatial resolution and detection limit). Based on existing IASI measurements and ESA-funded campaign measurements that took place in Italy in 2022, they explored the performance of hypothetical instruments that measure infrared radiation within two to five spectral channels or bands of various extent (1 cm^{-1} to 10 cm^{-1}).

SRON presented an update on the current status of the operational CO data product and illustrated applications of the product. They introduced a novel destriping method for the data product, capable of accounting for stripes varying in the flight direction of the instrument while preserving pollution features. Additionally, they showed a fully automated framework, the Automated Pollution Emission (APE) system, designed to identify pollution signatures from steel plants and wildfires.

Total Column Water Vapour (TCWV) is an ECV. It affects the atmosphere at both a local and global scale and can be retrieved from satellite measurements exploiting different spectral regions. The AIRWAVE algorithm was first developed to retrieve TCWV from the Along Tack Scanning Radiometer (ATSR) instrument series (ATSR-1, ATSR-2, AATSR). CNR presented AIRWAVE-v3 dataset and showed the results of the validation against other satellite data, such as Special Sensor Microwave/Imager (SSM/I) and the Analysed Radio Sounding Archive (ARSA) radio soundings.

In the frame of the AIRWAVE-Sea and Land Surface Temperature Radiometer (SLSTR) Follow-On study an improved version of the AIRWAVE-SLSTR algorithm was developed for the Sentinel-3 SLSTR series of instruments. CNR introduced the latest version of the AIRWAVE-SLSTR algorithm and the results of the validation of the obtained TCWV with ground-based (IGRA and AERONET) and satellite-based (SSMI/S and AMTROC-MWR) products.

Water vapour is an important natural greenhouse gas influencing the radiative balance of the Earth as well as surface and soil moisture fluxes. Water Vapour Residency Time (WVRT) is a key diagnostic for hydrological sensitivity, it is a variable we cannot directly observe. University of Leicester used the long-established turnover time (TUT) method to estimate WVRT from observational, reanalysis, and climate model ensembles as part of a comparative

analysis. A global and large-scale regional analysis of TUT between 1988 and 2014 from these ensembles has been presented.

OClO serves as a valuable indicator for chlorine activation, although it does not directly contribute to ozone destruction. The ClO-BrO cycle catalyzes ozone destruction, leading to the formation of the ozone hole over polar regions. DLR presented a study focused on a new OClO TROPOMI product, which involves preliminary tests to optimize DOAS retrieval parameters. These parameters include the fit window, polynomial degree, and treatment of interfering species included in the fit. The optimized retrieval methodology developed in this study will serve as the basis for future missions, such as Sentinel-5.

MPI presented a global database of SO_2 emissions from point sources generated from TROPOMI observations of SO_2 (COBRA product) for the time range from May 2018 to July 2022. A fully automated iterative detection algorithm of point sources from around the world forms the basis of the catalogue. The catalogue includes a list of 176 locations identified as substantial anthropogenic SO_2 point sources. The emissions detected are in good agreement with those recorded in existing SO_2 datasets but are lower by about 33%.

DLR introduced the PEGASOS project (Product Evaluation of GEMS L2 via Assessment with Sentinel-5P and other Sensors) aims at the evaluation of the operational GEMS L2 data products Ozone (total, tropospheric, profile), NO2, SO2, HCHO as well as cloud-, aerosol- and surface parameters. For the evaluation of the GEMS L2 products, comparisons with space-borne instruments (TROPOMI/S5P, OMI/Aura, GOME-2/MetOP-ABC, VIIRS/S-NPP, AMI/GK-2A, CALIOP/CALIPSO) and with ground-based measurements/networks (ozone-sondes, Dobson, Brewer, Max-DOAS, NDACC, PGN) were performed.

University of Tor Vergata presented the PRIMARY which aims at improving air quality monitoring at urban scale exploiting data from the PRISMA mission. Analyzing PRISMA's hyperspectral data, the project aimed to derive the content and composition of atmospheric aerosols, essential for evaluating environmental and health effects in urban areas. To train neural networks for estimating aerosol characteristics using PRISMA data, a synthetic PRISMA-like dataset was created exploiting data from CAMS. To evaluate the accuracy of CAMS data for the training dataset, comparisons were made with observed data from the SPARTAN network.

4.7 Aerosol and Clouds

Lidar depolarization sensitivity can be leveraged for aerosol typing and discrimination of desert dust in aerosol mixtures. In a keynote address, Vassilis Amiridis from NOA presented the progress on dust profiling from ground and space along with its applications on estimating the dust impact on radiation and cloud formation. Furthermore, the impact of dust profiling assimilation was discussed for atmospheric composition and NWP applications. Suggestions were given on how to construct a 3D climate data record for desert dust over past, current and forthcoming lidar space missions .

CNRS/University of Lille introduced the AIRSENSE (Aerosol and aerosol-cloud Interaction from Remote SENSing Enhancement) project. AIRSENSE uses cutting-edge capabilities of novel observations and on the use of advanced products from multi-instrument synergy processing for conducting studies of aerosol, aerosol-cloud interactions or other science questions. Based on data availability and maturity, AIRSENSE team plans to gradually generate novel products using three complementary approaches: (i) synergy and combined products of passive instruments, (ii) adding advanced active remote sensing products from Aeolus and EarthCARE, (iii) products from MAP observations such as PACE, MAIA, 3MI, CO2M, GAPMAP.

Satellite aerosol observation products can provide reliable data sources for aerosol pollutant monitoring and aerosol climate effect assessment. From the AAS and OMS-N, which were launched in September 2021 and August 2023 respectively, Ultraviolet Aerosol Index (UVAI) products with high spatial resolution can be retrieved as shown from Chinese academy of sciences. The results from the two instruments were compared with other UVAI products obtained from similar payloads such as TROPOMI and GOME-2.

Desert dust suspended in the atmosphere has a significant impact on the energy budget of the atmosphere through its scattering and absorption of light. The National Centre for Earth Observation (NCEO) and the University of Leicester presented a study on the synergistic use of ALADIN with CALIOP to produce a superior retrieval of dust properties. A statistical analysis of retrievals from both instruments during a June 2020 Saharan dust release demonstrates consistency between the observed backscatter and extinction coefficients.

Although previous spaceborne lidar missions such as CALIPSO and Aeolus have been primarily developed for studying atmosphere, lidar surface returns have been shown to be useful for various environmental applications. KNMI developed an Aeolus LIDAR Surface Returns (LSR) product (and on incorporating CALIPSO experience in such development) for making a realistic scientific application roadmap stemming from LSR products. They used Aeolus results to explain what incidence angle (nadir/non-nadir), wavelength (UV/visible), type of surface (water/land), signal-to-noise ratio and other parameters mean in terms of LSR scientific applications.

Volcanic eruptions can inject significant amounts of ash and sulphur dioxide into the stratosphere. The resultant aerosols (ash and droplets of sulphuric acid) impact atmospheric chemistry and Earth's radiation balance. University of Oxford presented research focused on the ash deposition process following the eruption of Puyehue-Cordón Caulle, which injected the ash plume up to 13 km into the stratosphere, using CALIOP version 4's upgraded automated aerosol classification products (which now include volcanic ash as a subtype of stratospheric aerosols). HYSPLIT model and IASI observations were employed to ensure consistent tracking of the ash cloud across different CALIOP profiles.

On February 8, 2024, the NASA PACE mission was launched with the SPEXone Multi-Angle Polarimeter onboard. SRON presented the first aerosol data from SPEXone including a global view on aerosol composition. The synergy of SPEXone with the ESA EarthCARE mission and the upcoming ESA/EUMETSAT METOP-SG mission with onboard, 3MI was also discussed.

Global information about aerosols can be obtained from space-borne measurements only. At present time there are a number of different satellites in Earth orbit dedicated to aerosol studies, but no single instrument satisfies all requirements which are necessary for global, high-temporal and extended aerosol characterization. In the frame of GROSAT and SYREMIS projects, GRASP-SAS presented a synergetic approach tested on different synergetic instrument constellations: (i) synergy of satellite and ground-based measurements; (ii) synergy of polar-orbiting (LEO) satellites and (iii) synergy of LEO and geostationary (GEO) satellites.

Accurate knowledge of Aerosol Layer Height (ALH) is essential in determining the impact of lofted aerosol plumes on the climate system and can be useful for aviation and air quality alerts. University of Thessaloniki investigated the potential of passive satellite sensors to deliver accurate geometrical features of lofted aerosol layers through a long-term quantitative statistical assessment of L2 products based on the availability of datasets (GOME-2 [2007-]; TROPOMI [2018-]). Furthermore, they assessed the performance of the Geostationary Environment Monitoring Spectrometer (GEMS) to provide accurate ALH retrievals over Asia.

The mineralogy of dust aerosols is of key relevance in driving climatic and environmental effects. Starting from exemplary data acquired in the CESAM simulation chamber on dust aerosols from global sources, LISA-CNRS demonstrated that the extinction signature of

suspended dust aerosols in the 740–1475 cm−1 infrared spectral range (6.8–13.5 μm) can be used to derive dust mineralogy in terms of its infrared–active and coarse–sized minerals: quartz, clays, feldspars and calcite. IASI–NG (Next Generation) and FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) instruments can provide an open unique perspective for their application to aerosol remote sensing and climate studies.

Aerosol pollution has well-documented health effects, both short- and long-term. University of Bologna discussed a methodology to exploit low-cost Optical Particle Counter sensors in an empirical method to infer the local Aerosol Optical Depth (AOD)-Particulate Matter (PM) relationship, with a multi-platform approach that also uses auxiliary information about meteorology, mixing state and chemical composition of local aerosols. Sparse networks of low-cost Optical Particle Counters in a city airshed are offered as a suitable option to support the process of calibration of the AOD-PM relationship over a larger area.

Detecting spatial variations of atmospheric aerosols helps evaluate air quality and understand their role in climate change. The Chinese Academy of Sciences developed a conventional algorithm that incorporates a radiative transfer model and employs the Tikhonov regularization algorithm for the retrieval AOD and aerosol layer hight. The retrieval results were compared with official TROPOMI height products and CALIPSO height products.

A common parameter used to characterize stratospheric aerosols is the aerosol extinction coefficient (Ext). However, this parameter derived from limb scatter instruments is dependent on the assumed particle size distribution (PSD). Although the aerosol particle size changes with strong perturbations, most Ext retrievals assume a constant PSD. The University of Bremen showed the influence of the assumed PSD on Ext obtained from the limb scatter instruments SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) and OMPS-LP (Ozone Mapping and Profiler Suite Limb Profiler) in the aftermath of selected volcanic eruptions (Manam 2005, Hunga Tonga 2022).

NASA presented Near UV AOD and SSA products derived by applying NASA retrieval algorithms, OMAERUV and TROPOMAER, to observations from the Aura OMI and the TROPOMI Instrument respectively. The OMAERUV record spanning over 19 years has been recently reprocessed using Collection 4 Level-1b data.

NCEO-University of Leicester presented the development of the Cloud and Precipitation Microphysics (C-CLD) algorithm. The algorithm utilizes data from the EarthCARE 94-GHz Doppler CPR to retrieve microphysical details of cloud and precipitation systems. It applies an optimal estimation technique that combines CPR measurements with prior climatological information about clouds and precipitation. The algorithm was tested with simulated EarthCARE CPR observations across various climate regimes demonstrated accurate rain parameter estimation, aided by the Doppler capability. Retrieving ice particle information remained challenging.

Due to their fast computational performance and accuracy, Neural Networks (NNs) are nowadays commonly used in the context of remote sensing. The application of NNs is not straightforward and there are at least two main approaches: 1. NNs used as forward model, where a NN accurately approximates the radiative transfer model and can thus replace it in the inversion algorithm. 2. NNs for solving the inverse problem, where a NN is trained to infer the atmospheric parameters from the measurement directly. DLR applied and evaluated both approaches for the retrieval of cloud properties and consider their potential as operational algorithms for current (Sentinel-5P) and future (Sentinel-4) Copernicus atmospheric composition missions.

Initial ground-based measurements have confirmed the potential of G-band radar (frequency between 110 and 300 GHz) for a better characterization of the microphysics of drizzle, light precipitation and ice microphysics. Politecnico di Torino discussed the possibility of the deployment of a G-band radar in a space mission in the framework of an Earth-Explorer like

mission where the G-band radar is operated in synergy with a Ka-band system; thanks to high transmitted powers and large antenna dimensions both systems achieve unprecedented performances.

The sensitivity of cloud properties to changes in the climate and to anthropogenic aerosol emissions are highly uncertain. SRON gave an overview of the cloud products that are provided by NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission focussing on the advanced, pixel-level cloud products that will be produced from observations by the polarimeters and their combinations with Ocean Color Instrument OCI, including cloud top phase, droplet number concentrations and full droplet size distributions.

Retrievals of trace gas concentrations from satellite observations are impacted by cloud effects. Even fully clear pixels can be affected by clouds in the vicinity, either by shadowing or by scattering of radiation from clouds into the clear region. The current operational retrieval algorithms for NO2 vertical columns use the DOAS method, with the AMF calculated through 1D monochromatic radiative transfer simulations. To mitigate cloud interference in the NO2 retrieval, various cloud products have been developed, using different physical processes to estimate cloud parameters such as cloud fraction, height, and optical thickness.

In the frame of the project "Handling of 3D Clouds in Trace Gas Retrievals" (3DCTRL), DLR-LMU tested these approaches using synthetic data, enabling the quantification of errors caused by cloud scattering.

One parameter of particular interest for process and radiative studies is the height of the bottom layer of clouds. DLR illustrated a solution to the radiative transfer problem in the molecular oxygen absorption band, measured by TROPOMI aboard Sentinel-5P, leading to the inference of cloud bottom altitude. The validation of the derived cloud parameters (top and bottom altitude, cloud phase and optical thickness) provides constraints for the prospective production of a long-term data record for climate applications.

Understanding the role of clouds in the Earth's radiation budget is crucial for mitigating climate change. Rmib presented a study on the estimation of the radiative forcing of cirrus clouds and contrails, both of which are having a radiative forcing effect on climate with their uncertainty, mainly resulting from their coverage and optical depth. Optimal Cloud Analysis (OCA) product based on MSG/SEVIRI data over the extended European area and for a specific time period have been used for the detection and characterization of cirrus clouds.

4.8 FORUM Mission

With the improvement of the spatial resolution of satellite spectrometers such as TROPOMI, Sentinel-4 and Sentinel-5, more homogeneous cloudy scenes can be resolved. KNMI presented the retrieval of cloud pressure and cloud optical thickness for fully cloudy pixels (possibly partly cloudy pixels and cloud fraction) using the O2 absorption band. In order to train a neural network model, KNMI generated a large high resolution spectral dataset of O2-A and O2-B bands for specified cloud parameters, atmospheric parameters (temperature, pressure profiles), surface parameter, and TROPOMI satellite geometries.

The spectral dimension in climate studies is crucial for studying climatology and the evolution of key climate variables, characterizing relevant driving climate mechanisms, and identifying biases in climate model simulations. CNR compared 12 years (2008-2019) of IASI Metop-A measurements to simulated spectral radiances provided by the EC-Earth GCM (ECE, version 3.3.3) based on the atmospheric and surface fields predicted in all-sky conditions by the model. Spectral biases within the climate model were identified through long-term comparisons of the radiances and further examined by analysing trends.

The FORUM mission will be the first to collect spectral radiation observations of the FIR spectral range with a relatively fine spectral resolution. LISA-IPSL analysed, for the first time,

the expected sensitivity of FORUM observations to the presence and properties of dust aerosol layers. While the FIR spectra are primarily sensitive to water vapour profiles, clouds and surface properties, they showed that significant sensitivity is also found to relatively coarse dust particles.

Enhanced accuracy in the Top of Atmosphere (TOA) spectral measurements within the FIR is imperative for mitigating uncertainties in climate models. Current instruments lack the capability, necessitating the utilization of innovative computational methodologies. These novel observations are anticipated to augment understanding across various atmospheric parameters, including tropospheric water vapor, ice cloud properties, and notably, surface emissivity in the FIR. CNR presented work focussed on data assimilation of future observations from FORUM into climate and meteorological models.

ESA presented some examples of calibrated FIR radiance spectra acquired during the Andøya field campaign, which took place in February and March 2023 at the ALOMAR observatory in northern Norway, and then focused on the application of the measurements for the retrieval of ice and snow emissivity in the FIR. ESA demonstrated that the retrieved emissivities of ice and snow agree well with model results.

University of Basilicata presented retrievals of cloud microphysical properties obtained from IASI data. The methodology is based on an optimal estimation tool originally developed for clear sky IASI soundings called δ-IASI. The technique applied to IASI spectra over Antarctica demonstrates its ability to retrieve both concentrations and effective particle sizes of liquid and ice water, showing high sensitivity for polar stratospheric ice clouds.

Ice and mixed-phase clouds play a key role in the Earth Radiation Budget (ERB), as they may exert either feedback or a forcing action, depending on their optical and microphysical properties and thermodynamic phase. CNR presented a new, advanced and accurate scheme to model ice cloud optical properties for clouds composed of mixed ice crystal habits. Using this model, they investigated the possibility to retrieve the ice cloud habit fractions from simulated FORUM measurements.

FIRMOS-B is the balloon adaptation of the Far-Infrared Radiation Mobile Observation System, developed by CNR-INO with the ESA support for the preparation of the FORUM mission. CNR introduced he results from the Strato-Science 2022 campaign at the ASC/CSA stratospheric balloon base in Timmins (Canada), showing that the measurements acquired are valuable for future studies to assess the new algorithms that are under development for the data analysis of the FORUM mission.

4.9 Methods

Spascia explored the application and added value of a Principal Component Analysis (PCA) approach to process Level 1 hyperspectral atmospheric sounding measurements in near-real-time for the detection of extreme events. Multi-year results of IASI processing were analysed for discussing performances and limitations of this approach for the detection, characterisation and classification of fires and volcanoes, and for identifying new or unexpected atmospheric signatures in the spectra. Tests cases are analysed with S5P, and the potential and complementarities of combining IASI and S5P/TROPOMI were discussed.

SPEXone, a multi-angle spectropolarimeter (385-770 nm), is used to characterize atmospheric aerosols for climate research. SRON presented a set of algorithms for calibrating in-flight detector images to level 1 data products. Simulations and on-ground characterization of the SPEXone instrument showed a strong pixel dependence of stray light. They developed a stray light correction algorithm which that combines multiple stray light kernels, as measured for different regions of the detector, in a computationally efficient manner.

The long-term in-flight optical degradation of the TROPOMI instrument can be determined by combining the irradiance measurements of the daily and the weekly solar diffuser. KNMI presented a robust dynamic in-flight straylight correction based on exterior detector. Such a correction will again enable a proper degradation correction. An update of the L01b Processor that includes these improvements is scheduled for 2025.

Preliminary analysis of the CoMet 2.0 campaign revealed some artefacts, which have been identified as instrumental stray light, which is an important unwanted error source for remote sensing spectrometers. University of Bremen presented the effect of a post-flight stray light correction, based on the stray light correction performed for the SWIR channel of TROPOMI, applied to the MAMAP2D-Light spectral imaging data collected during the CoMet 2.0 mission.

Ammonia is the most abundant alkaline atmospheric gas. It is emitted from a range of anthropogenic sources, most notably through the use of nitrogen-based fertilizers in agriculture. NCEO reported the measurement of new, high-resolution infrared spectra of pure and air-broadened ammonia. They determined new spectroscopic line parameters for the NH3 bands, including the first reported values of self- and foreign- pressure-induced shifts.

The global evolution of the Earth climate is mainly driven by the imbalance in the Earth Radiation Budget between the net shortwave incoming solar radiation and the Outgoing Longwave Radiation (OLR) from the Earth and its atmosphere. CNRS-LMD presented a machine learning method to estimate and study the OLR and corresponding heating rate from hyperspectral infrared sounders, such as IASI, IASI-NG and FORUM. The retrieval scheme has been applied to 17 years of observations from the IASI instruments showing that the resulting OLR reproduces direction computation with a very small bias of 0.52 ± 0.31 W.m-2 (0.19 % ± 0.11 %) over the tropical oceans with a computation time 10’000 times faster than the 4A-Flux computation.

In most remote sensing applications targeting the Earth's atmosphere, providing an accurate forward model alongside its Jacobian is crucial. Istituto De Astrofisica De Andalucia demonstrated an unbiased calculation of frequency-integrated fluxes over the entire infrared range. This enables the direct use of spectroscopic databases (HITRAN, GEISA) in the algorithm, without the need for intermediate constructions such as look-up tables.

CloudFlight showed the use case of a notebook development platform and a flexible, scalable, parallel cluster for processing data of the Sentinel-3 mission. It was further outlined how notebook development platforms offer the necessary environment to foster collaborative working as they allow for joint development (code snippets) and provide different data spaces: shared working vs. personal persistent dataspace.

4.10 Datasets

Traditionally, long-term Hyperspectral observations from satellite-based sensors are derived by performing spatial and temporal averaging of level-2 satellite products. There are two shortcomings of this approach: first it is a time-consuming process to generate level-2 products, second differences in level-2 retrieval algorithms can lead to errors in the fused multi-satellite climate products. NASA developed a radiometrically consistent spectral fingerprinting method, which overcomes the above-mentioned shortcomings, to derive climate change signals from multiple satellite sensors using spatiotemporally averaged level-1 data.

Vegetation fires are observed at global scale with relatively high temporal frequency from space with the Essential Climate Variable "Burnt Area" and FRP. While GFAS is currently based on FRP observations from the NASA Terra, Aqua and NASA/NOAA Suomi-NPP satellites, it will benefit greatly from ingesting FRP products from European satellites in the future. NILU presented recent climate monitoring results using GFAS, along with suggested

pathways for also using FRP products from current, past and future European satellites in GFAS.

KIT presented trace gas retrievals from the last level-1b data version of the MIPAS observations on Envisat using the IMK/IAA research processor with updated retrieval set-ups. Besides the standard retrievals, an additional representation was made available on a coarser vertical grid which does not require the application of averaging kernels for comparison to e.g. atmospheric model data.

The ACE-FTS instrument on the Canadian SciSat satellite has been operating and making atmospheric measurements since early 2004. The University of Toronto compared v5.2 data to correlative data from other satellite-borne limb sounding instruments. Their study focussed on ACE-FTS comparisons of ozone, water vapour, and temperature with those from ACE-MAESTRO, MLS on Aura, OSIRIS on Odin, and SABER on TIMED, comparing zonal mean profiles and long-term trends in the stratosphere and mesosphere.

Continuous ground-based NO2 measurements by the Pandonia Global Network (PGN) are important sources of data for satellite validation, air quality estimates and chemical closure studies. Enhanced scattered light is contaminating the direct light path for (sun) measurements taken close to the horizon and during (lunar) measurements at twilight conditions. Luftblick proposed two methods to reduce this radiance contamination. Firstly, they considered inelastic molecular scattering in the retrieval algorithm and secondly measure the radiance in the vicinity of the lunar disc.

A Fundamental Data Record (FDR) is a long-term record of selected Earth observation Level 1 parameters (radiance, irradiance, reflectance), possibly multi-instrument, which provides improvements of performance beyond the individual mission data sets. DLR-IMF presented the results from the Fundamental Data Record for ATMOSpheric Composition (FDR4ATMOS) project providing an overview of the FDR datasets and describing the harmonisation algorithms.

RHEA introduced the latest developments of the ESA EVDC. It provides an online information system supporting users to exploit campaign datasets for Earth Observation missions and applications. The platform also provides an access to satellite data for specific missions, in particular: Sentinel-5P, Aeolus, ENVISAT/MIPAS and soon, EarthCARE.

4.11 Dynamics

Surface air-pressure is one of the most important parameters used in Numerical Weather Prediction (NWP) models. Regular, accurate and global-scale measurement of surface air-pressure presents a substantial technical challenge, which can only be achieved by remote sensing from space. Retrieval of atmospheric pressure from satellite observations requires very accurate knowledge of the atmospheric mixing ratio of the spectral feature to be targeted. UK Research & Innovation presented novel a design based on using a differential absorption pulsed radar with measurements of three channels on the right wing of the oxygen band.

During much of five years of Aeolus's lifetime, its wind profiles were assimilated in the operational system of ECMWF, as well as in a series of observing system experiments (OSEs). University of Hamburg presented key results from spectral diagnostics of the ECMWF OSEs in relation to the background flow, dynamical regime and spatial scales of wave motions. On average, changes in the ECMWF analyses due to Aeolus winds are largest at synoptic scales. The effects on the Rossby waves are at least an order of magnitude greater than the effects on the non-Rossby modes.

In the frame of Aeolus+ Processes project funded by ESA, the University of Hamburg diagnosed effects of the Aeolus wind assimilation on equatorial wave dynamics in the ECMWF system, with the aim to understand uncertainty sources and processes behind the forecast

improvements. The results showed that the assimilation of Aeolus winds increases the amplitudes of the Kelvin and n=1 Rossby waves in the upper troposphere and reduces the Inertia-gravity wave amplitudes throughout the equatorial troposphere and stratosphere across many scales.

The North Atlantic Oscillation (NAO) represents the dominant mode of atmospheric variability over the North Atlantic, driving winter weather conditions over large part of the European sector. Increasing the predictive skill at the seasonal timescale over the European domain is still considered a major challenge. CMCC aimed to extract the potential hidden skill in a dynamical ensemble by properly selecting relevant realizations: the idea is to define a reduced ensemble better performing in terms of NAO predictions compared to the full one.

University of Bologna presented an overview of the SPEEDY-NEMO model climatology and variability, with particular attention for the phenomenology of processes that are relevant for the predictability of the climate system on seasonal-to-decadal timescales. They demonstrated the ability of the model in simulating non-stationarity of coupled ocean-atmosphere modes of variability.

Within convective systems, multiple scattering effects are highly probable due to the large number or dense ice particles generated in the core. Politecnico di Torino proposed a neural-network-based approach for the identification of MS onset in Z-profiles sampled by spaceborne near-nadir looking radar, with a specific focus on the INCUS mission. The methodology consists of two neural network algorithms, which have as inputs a single or a set of adjacent Z-profiles.

RAL Space described a technique, singular vector decomposition, that can identify the spatial patterns that best describe the temporal variability of a global satellite dataset. Singular vector decomposition approach can provide insights into the underlying causes of observed changes in a particular dataset and provide a new tool in using global satellite observations in assessing GCM performance.

Intense cyclones form frequently in the Mediterranean region, with the potential to cause damage to life and property when they hit highly populated coastal areas. CMCC presented the first results from CYCLOPS project in which AI has been used to link those extreme events to their large-scale drivers.

4.12 Ozone

Stratospheric ozone (the "ozone layer") protects the biosphere from harmful UV radiation. It is expected to recover due to the Montreal Protocol signed in 1987 and its Amendments regulating the phase-out of ozone-depleting substances (ODS). The University of Bremen presented the OREGANO project, aimed to advance our understanding of ozone recovery using a combination of long-term ozone column and profiles observations, and model analyses.

DLR presented the novel GOME-type Ozone Profile Essential Climate Variable (GOP-ECV) data record developed in the framework of the ESA Climate Change Initiative+ ozone project (Ozone_cci+). For the first time ozone profile measurements from a series of European nadir-viewing satellite sensors including GOME, SCIAMACHY, OMI, GOME-2A, and GOME-2B were combined into a coherent long-term record which covers more than two decades (1995-2021) and which will be suitable for climate applications.

BIRA-IASB described the approach to retrieve nadir ozone profile data from TROPOMI measurements. Comparison of TROPOMI ozone profile data to co-located ozonesonde and lidar measurements have been performed and concludes to a median agreement better than 5 to 10 % in the troposphere. The bias goes up to -15 % in the upper stratosphere where it exhibits vertical oscillations. The comparisons show a dispersion of about 30 % in the troposphere and

10 to 20 % in the upper troposphere to middle stratosphere, which is close to mission requirements.

The global total ozone column data derived from nadir-viewing space-borne observations do not provide information about ozone changes in different atmospheric layers, and additional information is needed to separate the stratospheric and tropospheric ozone columns. The University of Bremen presented the latest development of the retrieval algorithm to obtain the vertical ozone distributions from TROPOMI measurements. A combination of measurements in UV (TROPOMI) and TIR (CrIS) spectral ranges have been used to retrieve ozone profiles.

Aristotle University of Thessaloniki presented the improved Umkehr ozone profile records which were also used as a reference for validating the respective satellite products of TROPOMI and the GOME-2 instruments onboard the Metop platforms. The comparison results between the satellite sensors and Umkehr, for troposphere, showed a difference of ≈1.5 % for both TROPOMI and GOME-2B/C. A small discrepancy of within ±2 % between TROPOMI and Umkehr was found for the lower stratosphere and the middle stratosphere.

FMI showed the results obtained from the analyses of stratospheric ozone variability, including updated analyses of stratospheric ozone trends. This was done using two long-term merged datasets of ozone profiles: the SAGE-CCI-OMPS+ climate data record of monthly zonal mean ozone profiles from 1984 to present, and the MErged GRIdded Dataset of Ozone Profiles (MEGRIDOP) with a resolved longitudinal structure, which covers the period from late 2001 to the present.

KNMI focussed on the thorough assessment of TROPOMI 0-6km integrated ozone partial column sensitivity to tropospheric ozone enhancement at regional to local scale. In order to evaluate and possibly increase the instrument capabilities to tropospheric ozone detection by improvements in the retrieval algorithm. They showed retrieval algorithm updates to increase its sensitivity to tropospheric ozone.

The CCI / C3S ozone Climate Data Records portfolio highlighting recent improvements and additions have been presented by BIRA-IASB. As part of the CCI program they focussed on the quantification of measurement uncertainties and their validation. They also performed a comparison of satellite ozone observations from CCI with EMAC chemistry-climate model simulations.

The ESA CCI Precursors project pioneers the generation of multi-satellite Level-3 Climate Data Records (CDRs) for several precursors of the ozone and aerosol Essential Climate Variables: NO_2, HCHO, SO_2 and CHOCHO data acquired by the GOME, SCIAMACHY, OMI, TROPOMI and/or GOME-2 missions, and carbon monoxide (CO) and ammonia (NH_3) data acquired by the IASI and/or MOPITT missions. BIRA-IASB highlighted key challenges faced during the validation of initial CCI Precursors CDRs.

The total ozone column retrievals from different satellite sensors, such as TROPOMI/Sentinel-5P, GOME2/Metop-A, -B and -C, OMI/Aura and OMPS/Suomi-NPP, were homogeneously validated by applying the geophysical validation chain developed by Aristotle University of Thessaloniki. The satellite TOC data quality and stability were evaluated through the statistical analysis of their comparisons to these ground-based measurements, in terms of relative bias (which is found to be within 1-2%), and drift for each sensor (less than ±1-2 %/decade).

In August 2023, the Canadian-led ACE mission completed its twentieth year in orbit on board the SCISAT satellite. University of Toronto presented altitude profiles of more than 50 atmospheric trace gas species, temperature and pressure retrieved from the ACE-FTS. In addition to the mission and instrument status they described current studies being undertaken using measurements of halogenated species from ACE-FTS and model output.

The University of Bremen presented the first successful application of the Convective Cloud Differential (CCD) retrieval outside the tropical region for the tropospheric ozone. They introduced CHORA-CCD (Cloud Height Ozone Reference Algorithm-CCD) for retrieving TCO from TROPOMI in middle latitudes. It utilises a local cloud reference sector (CLCD, CHORA-CCD Local Cloud Decision) to determine the stratospheric (above cloud) column ozone. This ACCO is later subtracted from the total column in clear-sky scenes to determine the TCO. The new approach minimises the impact from variances in stratospheric ozone.

Natural as well as anthropogenic factors affect stratospheric ozone concentrations at different timescales. Disentangling these processes in statistical analyses can be a challenge due to the representativeness of predictor time series, the lagged response of ozone and the possible non-orthogonality of proxies. BIRA-IASB investigated how different methodological approaches influence the regression results inferred from merged satellite ozone profile time series (SAGE-CCI-OMPS+, SWOOSH, and GOZCARDS).

The MTG – Infrared Sounder (IRS) on board EUMETSAT's Meteosat Third Generation will represent a major innovation for the monitoring of the chemical state of the atmosphere, since, at present, observations of these parameters mainly come from in situ measurements and from instruments on board of polar-orbiting satellites. University of Bologna presented many potentialities in the area of detecting different atmospheric species having the advantage of being based on a geostationary platform and to acquire data with a high temporal frequency (30 minutes over Europe), which makes easier to track the transport of the species of interest.

5 Poster Session Summary and Highlights

5.1 Other Trace Gases

BIRA-IASB presented a work aimed at a better understanding of glyoxal sources, using the novel distributions of CHOCHO and HCHO retrieved from the TROPOMI sounder from 2019 to 2021. An inverse adjoint-based framework was built on the MAGRITTE chemistry-transport model, showing a missing CHOCHO source in the model parameterization.

The Universita' Ca Foscari presented the Water vapor Isotopologue Flask sampling for the Validation Of Satellite data (WIFVOS) project. The team developed a simple but effective balloon-borne flask sampler to measure water isotopologues. The first version of the sampler was thoroughly tested in the lab at the end of 2021 and in the field with two successful launches in Sodankylä (Finland) in April 2022. During the first launches in 2022 we retrieved water vapor isotopic data from the ground up to 8000 m at 8 discrete levels.

Using IASI observations, University of Leicester presented a study on the differences in the NH_3 daily cycle between different seasons in order to infer how environmental changes (such as surface temperature or precipitation) and agricultural practices affect the NH_3 concentrations over heavily agricultural regions.

IASI offers the opportunity to monitor the atmospheric abundance of NMVOCs at the global scale. ULB exploited the extensive IASI dataset in combination with an advanced oversampling technique increasing the spatial resolution of averaged satellite data far beyond what the sounder can initially offer.

Using the ANNI method applied to IASI observations, ULB retrieved total columns of five major atmospheric OVOCs: CH_3OH, HCOOH, PAN, $CH_3C(O)CH_3$ and CH_3COOH globally and twice daily.

LATMOS-IPSL presented the first attempt to combine IASI and MOPITT level 3 CO datasets. Weighting monthly averages by errors, number of observations and a priori information have been tested in the process.

BIRA-IASB applied the COBRA algorithm to the TROPOMI time series in the S5P-PAL and showed that COBRA performs in most cases better than the current TROPOMI operational SO_2 product.

Aristotle University of Thessaloniki presented the evaluated the magnitude of anthropogenic SO_2 sources, such as by oil and gas factories, smelters, power plants, as well as natural SO_2 sources, i.e. by volcanic outgassing, sources monitored by means of different GEO & LEO instrument.

In the frame of 3D Clouds in Trace Gas Retrievals (3DCTRL) project, a novel cloud treatment has been applied to S5P/TROPOMI, tropospheric NO_2 retrievals. Specific cases where the cloud fields were found to be challenging were identified and the effect of this approach was quantified.

KIT presented the MUSICA IASI SO_2 retrieval. They used a logarithmic SO_2 concentration scale allowing a reliable detection of the altitude where the SO_2 plume is situated, because it is retrieved directly from the spectral signal and no a priori assumptions of SO_2 plume height are required.

LATMOS-CNRS investigated anomalous CO concentrations detected from space by the IASI and TROPOMI instruments. They observed discrepancies in CO detection between the two instruments, attributable in part to their sensitivity in probing gases near the Earth's surface.

The potential of the European IRS instrument, which will be launched on the MTG (Meteosat Third Generation) satellite mission, to capture the spatio-temporal variability of ammonia and temperature focusing on a case study over the Brittany region in France have been demonstrated by LATMOS-CNRS.

The ozone and aerosols precursors CCI project is developing long-term data records for six important short-lived atmospheric trace gas species such as CHOCHO. BIRA-IASB characterized the viewing angle dependencies by looking at long-term spatial averages of observed CHOCHO vertical columns from different detector rows and investigate whether those dependencies can be reduced using a modified background correction procedure.

ULB and BIRA-IASB described version 4 of the retrieval framework called ANNI, which introduces the calculation of AVKs. They demonstrated how reprocessing the IASI-NH_3 dataset using vertical profiles shapes from the GEOS-Chem chemistry transport model allows for a much more robust product. This also leads to a drastic improvement of the IASI-NH_3 nighttime distributions, pointing to a misrepresentation of the NH_3 vertical profile in the current baseline ANNI retrieval.

Thanks to the high quality of the TROPOMI HCHO dataset, BIRA-IASB pushed the boundaries of the data assimilation to weekly resolution, the highest temporal resolution of space-based HCHO data assimilation to date. This constitutes a significant advance in the top-down emission estimation, given the strong meteorology-induced variability of isoprene emissions.

BIRA-IASB developed two HCHO CDRs for mid-morning and early afternoon observations, derived respectively from the GOME, SCIAMACHY, and GOME-2 sensors, and from OMI and TROPOMI. They discussed the expected impact on ground-based validation results, and the next steps in the generation of the morning and afternoon CDRs.

An improved SO_2 LH (and VCD) retrieval algorithm for the TROPOMI has been developed by BIRA-IASB. To this end, the second spectral band is exploited instead of the third one traditionally used for SO_2, thereby taking advantage of the SO_2's greater absorption at shorter UV wavelengths.

KIT showed the diurnal evolution of photochemically active species belonging to the nitrogen (e.g. N_2O_5, NO_2), chlorine, and bromine families as measured by the GLORIA-B. These results were compared to simulations of the chemistry climate model EMAC.

The performance of GLORIA-B with regards to level-2 data of the flight in August 2021, consisting of retrieved altitude profiles of a variety of trace gases have been presented by KIT. They showed examples of selected results together with uncertainty estimations, altitude resolution as well as long-lived tracer comparisons to accompanying in-situ datasets and simulations of the chemistry climate model EMAC.

INGV analysed behaviours and trends of several climate change markers through the ECMWF time series. They evidenced the increase of approximately 1.5 °C in the global average Surface Temperature, compared to pre-industrial levels, as confirmed by the IPCC.

The University of Leicester and NCEO used the University of Leicester IASI Retrieval Scheme to retrieve profiles of CO and HCN on a global scale from IASI atmospheric spectra and to investigate the emissions from peat fires over Indonesia in 2015, in combination with the improved TOMCAT model simulations.

BIRA-IASB showed the significant impact on the S5P cloud data characteristics due to the latest upgrades. The change of the wavelength window in the FRESCO retrieval is clearly visible in the comparison with Cloudnet cloud height, as well as in validation results of the tropospheric and total NO_2 columns. The first upgrades of the ROCINN products led to an improvement in correlation with Cloudnet cloud height, but also to a more negative bias for the low clouds, which is however not clearly visible in the HCHO validation results.

LISA-IPSL explored the added value of the Earth Explorer 11 candidate CAIRT observations to the detection of initial stratospheric aerosol geoengineering applications and to follow the spatiotemporal evolution of the involved species and the effects of these techniques.

The University of Toronto presented five biomass burning products: CO, C_2H_2, C_2H_6, HCOOH, and PAN retrieved from the ACE-FTS instrument aboard the Canadian satellite SCISAT-1.

Remote sensing by application of limb-sounding instruments analysing the emitted thermal infrared radiation with high spectral resolution is a powerful tool to explore the composition of the atmosphere. KIT provided an overview of the application of this method to the analysis of gaseous ammonia and ammonium nitrate aerosols in the atmosphere especially with regard to the Asian tropopause aerosol layer.

5.2 Greenhouse Gases

8 years of OCO-2 acquisitions over the Italian territory, obtaining the main temporal trend and the seasonal behaviour of CO_2 over land have been analysed by INGV. An increment of 21 ppm has been found in the period from 2015 to 2022, meaning an average rate of about 3 ppm/year.

In the frame of MethaneCAMP project, FMI presented a parallel avenue for the evaluation of inverse modelling methane products far from ground-based measurements of methane at high latitudes, and laid ground work on data-driven emission estimation approaches at high latitudes.

Institute for systems and Robotics conducted an analysis of existing machine learning models and datasets for methane detection, highlighting gaps and setting the foundation for future technological advancements. This includes an analysis of model performance across different conditions and a critical look at dataset adequacy for model training.

The Matched Filter algorithm has already proven to be effective in the detection of both non-punctual and strong point emissions by finding enhanced CH_4 concentrations in the atmospheric column. A new formalization of the Matched Filter Method is proposed by University of Bologna and was tested on a subset of satellite measurements.

LSCE assimilated four TROPOMI XCH_4 products in atmospheric inversions of the regional emissions in Europe and South America in 2019 using the CHIMERE transport model, coupled to the inverse modeling platform Community Inversion Framework. Surface measurements were used as reference for validation.

NCEO demonstrated the potential of genetic algorithms for improving data coverage of GOSAT methane product in challenging high-latitude regions maintaining the accuracy of the data.

LSCE focused on TROPOMI methane observations spanning from 2018 to 2022 and combined them with the latest updates in isotopic signature observations. They employed inversion techniques within the Community Inversion Framework, using the GCM LMDZ and evaluated the impact of data sources on understanding global methane emissions by testing different inversion set-ups.

The Cyprus Institute presented a selection of case studies where we utilize satellite derived VCD information and inverse estimates, regarding NOx and CO_2, to assess the magnitude and trends in emissions within the last decade.

University of Edinburgh proposed a framework to automatically pinpoint hotspots and the associated plumes of atmospheric methane, using the Sentinel-2 satellite data as an illustration. Their approach involves a two-channel method for retrieving methane column enhancements from the Sentinel-2 satellite data.

Retrieved GHG abundances acquired during the first year of operation of an EM27/Sun FTIR spectrometer installed in the Atmospheric Physics Laboratory (APL, 41.90° N, 12.51° E) of Sapienza University, Rome downtown, have been presented by SERCO. They also provided a preliminary comparison with independent data sources.

BIRA-IASB presented the general approach developed for the quality assessment of CCMs methane data and the main technical tasks expected from the Copernicus ATM-MPC.

UPV discussed the feasibility of methane detection with MTG-FCI. They generated a dataset of MTG-FCI that includes simulated methane point source emissions. The simulated plumes included different spatial patterns, different wind speeds and the methane flux rates span values from 1t/hr up to 100t/hr. First results suggest that it is possible to detect point source methane emissions as low as 20 t/h.

Inversions with satellite column measurements from TROPOMI and IASI (either separately, simultaneously, or as a synergistic retrieval product from both instruments) have been performed by University of Amsterdam using updated the TM5-4DVAR CH_4 assimilation system to simultaneously optimise the OH concentration and CH_4 emissions.

The status of COCCON network with example scientific results presented by KIT.

Kaioa Analytics explored the feasibility of GHG retrievals over snow from CO2M observations. A subset of results which relate to the implementation and testing of snow BRDF kernel functions in the University of Leicester Full-Physics retrieval algorithm (UoLFP) was presented.

Regional algorithms to estimate ocean pCO_2 based on in situ carbon-related measurements have been developed to estimate the spatial and temporal evolution of marine pCO_2 and CO_2 exchange with the atmosphere. Starting from November 2021, in situ measurements of ocean

pCO_2, temperature and salinity, together with ancillary quantities, including pH and chlorophyll concentration, are available at the Lampedusa (35.49°N, 12,47°E), in the central Mediterranean Sea. These observations complement measurements of atmospheric CO_2 and related parameters made at the Lampedusa Atmospheric Observatory (35.52°N, 12.63°E), about 15 km northeast of the Oceanographic Observatory.

Measurements of ocean pCO_2, temperature and salinity together with atmospheric CO_2 measurements from Lampedusa Oceanographic Observatory have been combined to retrieve the atmosphere-ocean CO_2 flux. Various regression techniques have been implemented by ENEA to retrieve the ocean pCO_2 and the atmosphere-ocean CO_2 flux based on satellite-derived parameters.

SRON presented the MEDUSA project in which they compared the various satellite methane products, both from the same instrument using different algorithms and/or research teams, as well as between different satellites. Moreover, where possible, they will validate the emission products such as through controlled releases.

SPASCIA implemented and tested an original L1/L2 approach for the joint TIR+SWIR retrieval of CH_4 profiles from L1C IASI spectra and L2 TROPOMI/S5P vertical column density estimates. These synergistic TIR+SWIR CH_4 retrieval results were analysed and compared with the individual S5P SWIR and IASI TIR products.

Long-lived halogenated compounds are potent greenhouse gases. ULB derived from IASI spectra clear-sky instantaneous radiative efficiencies for five long-lived halogenated species: CFC-11, CFC-12, SF6, HCFC-22 and HFC-134a. The comparison with the different values reported in the literature showed a very good agreement for all species, with relative differences below 20%.

5.3 Air Quality

BIRA-IASB focussed on the region of Bucharest in Romania and tested the validity of NO_2 tropospheric column densities obtained from the TROPOMI product version 2.4.0. They used the WRF-Chem model version 4.5. as an inter-comparison platform to evaluate satellite measurements.

Spatially and temporally highly resolved AMF for the NO_2 retrieval window of TROPOMI were calculated by University of Bremen over Europe, using the BRDF kernel coefficients obtained from the MODIS.

KNMI presented uncertainties of the DOAS NO2 SCD retrieval and an independent estimate based on the spatial variability of the SCDs within a remote region over the Pacific Ocean, both for TROPOMI collection 03 and OMI collection 04 data. The latter "statistical" uncertainty is always slightly lower than the DOAS uncertainty.

The vertical profiles were retrieved by University of Thessaloniki using algorithms based both on the optimal estimation method and a parameterization approach. The differential SCDs, VCDs and vertical profiles retrieved by Pandora were evaluated and compared with those measured by a collocated MAX-DOAS system.

University of Thessaloniki presented a methodology for deriving “top-down” NOx emissions originating from the maritime sector by utilizing TROPOMI NO2 observations and LOTOS-EUROS CTM simulations. Shipping NOx emissions are estimated in shipping routes crossing the Mediterranean Sea and significant ports by implementing a data assimilation scheme with the Ensemble Kalman Filter.

MPI presented a study to gain a deeper insight into the production and quantification of lightning NOx and its visibility from space by comparing NO2 column increases from

TROPOMI observations with flash rates recorded by the WWLLN shortly before TROPOMI overflights.

The global increase in wildfire events has recently raised concerns about the frequency, severity, and duration of these natural disasters, highlighting the need to understand the health consequences of exposure to wildfire events. University of Thessaloniki presented a study on the impact of the forest fires that occurred in Northern Greece in August 2023 on the local air quality.

DLR introduced the InPULS project aimed at developing user-friendly information products based on Copernicus Sentinel atmospheric data from missions S5P, and later S4 and S5. Global data and maps on cloud coverage, aerosols and trace gases are available via an interactive geoservice.

In the frame of KARLOS project, Luftblick presented a CubeSat prototype instrument with a spatial pixel resolution at sub-hectometer scale. In the first stage of the project, the instrument was developed, calibrated and installed on a mountain station, acquiring data over the city of Innsbruck in downward looking mode.

KNMI showed the application of a statistical test performed on the DOAS fit residual in order to signal for the presence of low-frequency structures remaining in the fit residual. Results of this test are included in the TROPOMI NO2 data product as of v2.7.0, to help the NO2 data user to identify possibly unreliable NO2 retrieval results.

SRON presented a detailed methodology to account for the representativity error when TROPOMI NO2 observations are missing due to e.g. cloudiness. Furthermore, they accounted for systematic errors in the retrievals leading to error correlations between nearby individual observations contributing to one super observation.

INOE investigated the decadal evolution of NO_2 column densities retrieved with OMI and TROPOMI and using a cross-comparison with the CAMS atmospheric modelling product for European and regional scales. Preliminary results from OMI retrievals, showed a reduction for the years 2009 and 2019 across Europe, particularly over regional hotspots in the Netherlands (approx. 23%) and the north of Italy (approx. 20%).

In the frame of the ITalian INtegrated Environmental Research Infrastructures System (ITINERIS) and Earth Moon Mars (EMM) projects, the Italian research institute CNR-ISAC is supposed to acquire two new Bruker FTIR spectrometers: an IFS 125HR, estimated to arrive in the next year, and an EM27/SUN almost ready to be operated. CNR presented the potentials of both instruments and showed the preliminary atmospheric measurements performed with the EM27/SUN.

To make the transition from one instrument to the other as seamless as possible OMI and TROPOMI daily and monthly NO2 retrievals were compared by KNMI at resolutions ranging from 0.2 x 0.2 degrees to 2x2.5 degrees. First results indicated that there is excellent agreement between tropospheric NO2 columns retrieved from the two sensors over polluted hotspots.

BIRA-IASB introduced an innovative deep learning framework designed to estimate the 3D distributions of NO_2 and O_3 in the lower troposphere with enhanced horizontal resolution. This framework is driven by multiple sources with varying dimensions, including meteorology, satellite observations, land use information, and emissions.

The global tropospheric HCHO and NO_2 vertical columns densities retrieved from TROPOMI in 2021 using the improved Peking University OMI NO_2 (POMINO) algorithm were presented by BIRA-IASB. POMINO retrievals showed a much-reduced bias and a correlation coefficient comparable to the one of the operational products.

Thales presented novel approach on estimating ground-level concentrations of pollutants (e.g. PM10 and SO2) at near-real time deduced from the polar-orbiting Sentinel missions. The link between the vertically integrated information on the pollutant observed by satellite and its concentration at ground level is established using machine-learning techniques.

NILU computed the daily surface $PM_{2.5}$ concentrations over Europe at 1 km spatial resolution using a stacked XGBoost machine learning model, through a synergy of information from various sources such as CAMS $PM_{2.5}$ forecast, satellite AOD, and meteorological conditions from ERA5. Validation with in-situ measurements showed that their approach derives daily $PM_{2.5}$ concentrations over Europe with a mean absolute error of 3.6 $\mu g/m^3$ and a correlation coefficient of 0.79, an improvement of ~12% compared to CAMS forecast.

KNMI presented a new gridded daily and monthly record of nitrogen dioxide tropospheric columns from the satellite instruments TROPOMI and OMI (2004-2021). This record has been generated as part of the ESA CCI+ project developing a long term, satellite-derived climate data record for the Precursors for Aerosol and Ozone Essential Climate Variables.

ECMWF showed a quality comparison of various atmospheric composition observations from Sentinel-5P-TROPOMI against the long-standing Metop-GOME-2 dataset. They also introduced the new ECMWF observations pre-processing workflow developed to enable the inclusion of such unprecedented data volumes in the next CAMS reanalysis cycle 'EAC5'.

The performance of the flux divergence approach during the summer season was presented by KNMI. Through a comparison between the flux divergence approach derived emissions and the original model-ingested emissions over Netherlands, they assessed the accuracy and sensitivity across various input data choices, including wind fields, lifetime, NO2 to NOx ratio, and the impact of the a-priori profile in the retrieval process.

During the last week of August 2023, Greece experienced a record-breaking heatwave that triggered severe wildfire incidents. University of Thessaloniki examined the spatio-temporal variations of biomass burning emissions and their impacts on regional aerosol optical properties over Thessaloniki, as well as to the solar radiation recorded at ground-level.

Swiss Federal Laboratories for Materials Science and Technology developed a realistic model to convert NO2 to NOx, which accounts for the spatiotemporal variations of NOx chemistry in plumes and apply it to TROPOMI data of 2020 and 2021. They analysed plume-resolving simulations from Large Eddy Simulation model with NOx chemistry for different powerplants.

LISA-CNRS presented the ARGONAUT projects, which aim is to develop an inverse modeling system able to provide emission estimates of AQ pollutants (NOx, CO and NMVOCs) and CO2 from the continental scale to the territorial scale at various spatial and temporal resolution harnessing the high-resolution imaging of current (Sentinel-5P) and future (CO2M) satellite missions.

Within a downwind plume, NO_2 changes are due to NO to NO_2 conversion (NO_2 source, positive divergence) and NO_2 reaction with OH (NO_2 sink, negative divergence). MPI presented a study aimed at disentangling these competing effects based on the divergence method.

KNMI presented the first-ever satellite-based NOx emission inversions for 100+ individual ships based on TROPOMI-observed NO2 plumes over the Mediterranean Sea in 2019. They developed an inversion approach that accounts for the complex, high-resolution atmospheric dynamics and chemistry that drive the relationship between the NOx emissions and observable NO2 plume.

Two-dimensional distributions of PAN observed by GLORIA in August and September 2023 above the Mediterranean Sea, the Pacific Ocean and North America have been presented by

IMK-ASF showing extensive enhancements in the extratropical transition layer in the monsoon outflow and also in connection with wildfires, which occurred during the same time period in North America.

BIRA-IASB presented a measurement campaign targeting the monitoring of the NO2 field of a city, Rome, with the aim of revealing spatio-temporal structures unobservable by TROPOMI, by means of a multi-instrument set-up, combining the TROPOMI observations, the instruments of the BAQUNIN supersite (LIDAR, ceilometer, SODAR, PANDORA, CIMEL), a MAX-DOAS from CNR, and a newly developed, hyperspectral imager: the AOTF-based NO2 camera.

CNR reported the results obtained with the two SkySpec-2D systems in the Po Valley and in Rome and explore the potentiality of the future acquisition of these systems both in the light of study of atmospheric compositions in Italy and for the use in the satellite validation framework.

MPI presented NitroNet, a new deep-learning model for the prediction of tropospheric NO_2 profiles. The model is based on a feedforward neural network, which was trained on a synthetic dataset from WRF-Chem model. NitroNet receives NO_2 VCDs from TROPOMI and ancillary variables (meteorological, emissions, etc.) as input, from which it predicts tropospheric NO_2 concentration profiles.

University of The Punjab Lahore presented a study on the use of satellite remote sensing to estimate the impact of human activities on the climate change suggesting further research on ECVs for adaptation and mitigation in South Asia.

5.4 Aerosol & Surface

University of the Punjab investigated the aerosol patterns and trends over some major cities in the Indo-Gangetic Plain of the South Asia by using simulations from the MERRA-2 model and MODIS satellite measurements from 2000 to 2020.

University of Thessaloniki assessed the AI from the Korean GEMS against spatiotemporally collocated S5P/TROPOMI and GOME-2 B&C AI products, on Low Earth Orbit, LEO, as reference datasets.

ALH is a new operational Level-2 product retrieved from space-borne instruments including ESA's TROPOMI and under development for Copernicus Sentinel 3. INOE presented the validation methodology and results of the space-borne Level 2, version 2.2 product of TROPOMI against ACTRIS' Aerosol Remote Sensing Lidar and Ceilometer systems.

A full reprocessing of operational AI from TROPOMI was carried out in 2023. KNMI presented the preliminary analysis suggesting that the amplitude of the annual seasonal cycle in global aerosol index is quite similar in magnitude to the slight downward trends in AI for the full mission time series.

CNR showed a study focused on clouds detection using machine learning techniques with only satellite radiance observations, specifically utilizing Support Vector Machines on spectral radiances from IASI - Level 1C dataset, covering the wavenumber range from 645 cm-1 to 1600 cm-1.

A coordinated the efforts for EarthCARE products validation employing data from three atmospheric observatories in Italy was submitted by CNR to ESA in 2017 and is now part of the EarthCARE Validation Team. The observatories are located in the island of Lampedusa, and in Rome, in the twin sites of Sapienza University (within the city urban area) and in the Tor Vergata CNR site (at the Rome South-East outskirts).

EUMETSAT introduced a new satellite-based dataset on dust, that is derived from the PMAp CDR. The PMAp aerosol properties are derived using multi-instrument approach, where simultaneous observations from GOME-2, IASI and AVHRR onboard Metop-A and Metop-B satellites are exploited.

FMI presented a merged time series of vertically resolved monthly mean aerosol extinction coefficients at 750 nm in 10° latitudinal bins from 90°S to 90°N, in the altitude range from 8.5 km to 39.5 km. They also provided the time series of the stratospheric aerosol optical depth (SAOD) created by the integration of aerosol extinction profiles from the tropopause to 39.5 km.

Within the framework of the IASI-FT ERC-advanced project, monthly temperature products level-3 were generated by LATMOS-CNRS from IASI level-1C radiance data. These products are surface skin temperatures, sea surface temperatures, atmospheric temperature profiles and outgoing long-wave temperatures. Data and quick-look plots are available from the IASI-FT website.

The development of dust retrievals from FORUM is hampered by the lack of knowledge on dust optical properties in the FIR. To respond to this need and support the future exploitation of the FORUM observations LISA-CNRS presented a new original laboratory activity programme.

University of Bologna introduced a new method allowing the identification of both thin and thick clouds and the classification of surface type in clear conditions based on GLORIA-B nadir observations consisting of images of 126x48 pixels of mid-infrared spectral radiance fields from 750 to 1460 cm-1 at 0.0625 cm-1 resolution.

A new four-dimensional, multiyear, and near-global climate data record of the submicrometer and supermicrometer (in terms of diameter) components of atmospheric pure-dust, was presented by NOA. The datasets are established with the original L2 horizontal (5 km) and vertical (60 m) resolution of CALIOP.

The China University of Mining and Technology proposed a new algorithm for estimating surface black carbon concentration in Italy based on MODIS satellite data. They used aerosol optical depth data, the total aerosol mixtures particle size distribution and complex refractive index as input for the 6SV model to retrieve the optical properties and total column concentration of BC.

NILU presented a study on space-based aerosol observations in the vicinity of active fires over northern high latitudes from multiple satellite instruments (TROPOMI, MODIS, VIIRS, SLSTR/OLCI and MISR). They focussed on the wildfire season April-October 2023.

The Interuniversity Laboratory of Atmospheric Systems introduced a nature run derived from the MOCAGE chemical transport model and a forward radiative transfer code for simulating synthetic observations of attenuated backscatter coefficient and depolarization ratio profiles at wavelengths of 355, 532, and 1064 nm and polarized radiances at multiple wavelengths and viewing angles.

In the frame of ESA L2A+ project, an enhanced aerosol product was developed by NOA through data fusion with other data sources such as NASA's CALIPSO mission to account for Aeolus deficiencies. The impact of this new product was assessed through assimilation experiments in regional NWP models. To ensure applicability of this work in the future, the open-source tools created for Aeolus were further developed to support EarthCARE.

Both in the retrieval algorithms and modelling of aerosol optics assumptions are made on aerosol characteristics like hygroscopicity, refractive index and size distribution. TNO developed a tool to compute optical properties of the atmosphere from aerosol concentrations

avoiding unnecessary CTM calculations. It furthermore allows quick iterations in development of the optical description of aerosols and extensions beyond currently provided diagnostics.

5.5 Ozone

BIRA-IASB introduced a stellar occultation retrieval algorithm for the ALTIUS mission. The data used to perform this validation study originates from GOMOS. They assessed the influence of scintillation on the quality of an ozone profile retrieval from an ALTIUS stellar occultation.

A study on the simulation of the ALTIUS ozone retrieval algorithm in the Solar Occultation configuration, using data from the SAGE-III instrument on board of the ISS was presented by BIRA-IASB.

BIRA-IASB examined the combined influence of El Niño-Southern Oscillation and the Indian Ocean Dipole on Upper Troposphere Lower Stratosphere ozone variability. The investigation employed data from the MLS aboard the Aura Satellite and the ECMWF ERA5 reanalysis.

DLR generated a GOME-type Tropical Tropospheric Ozone Essential Climate Variable satellite data record combining data from GOME, SCIAMACHY, OMI, the three GOME-2 missions and TROPOMI. The retrieval is based on the Convective Cloud Differential technique. The dataset will be used to investigate the tropical mean trend as well as temporal and local changes in the trends or extreme events.

TROPOMI spectrometer has both high spatial resolution and daily coverage of the Earth and provide total ozone observations. The instruments GOME-2 A, B, and C are also providing total ozone and cloud retrieval (version ≥ 4.8) data but with coarser resolution for the period 2007 to 2023. University of Bremen presented results of the time evolution of tropospheric ozone for the 4 sensors and the harmonization of the datasets.

BIRA-IASB presented the validation of the ALTIUS L2P algorithm using the OMPS LP L1 data. They compared their retrieved ozone profiles with the ones from the OMPS algorithm and discussed potential disagreements and biases in the results.

CNR tested the capability of instruments such as MIPAS-Envisat and IASI-MetOP, and their data fusion in detecting and quantifying stratospheric ozone intrusions.

BIRA-IASB described the plan envisioned for the geophysical validation of ALTIUS ozone profile data. The overall validation approach combined comparisons to Fiducial Reference Measurements collected from ground-based monitoring networks and cross-validation with other ozone profiling satellites.

Several data sets are retrieved using the LNM residual technique, either combining two satellite-based observations or satellite with model data such as OMPS-MERRA, EPIC-MERRA, and S5P-BASCOE. University of Bremen presented a comparison of the climatology of the selected data sets, their main biases and their variability.

5.6 Clouds & Water Vapour

In the frame of the ESA funded study CAIRTEX, University of Bologna have used the single GLORIA measurements to test the possibility to get information on the cloud microphysics and to retrieve the clouds geometrical extent, on the light of demonstrating the possibility to use CAIRT measurements to obtain cloud information.

As part of the project “Contribution to EarthCARE products VALidation during the commissioning phase from atmospheric observatories in Central MEDiterranean in Italy”

CNR presented available data collected from satellite and operational radars along with datasets available in the validation sites of Rome and Lampedusa, focusing on precipitation.

To evaluate a possible enhancement in Sy_2_AOD product quality related to implementing the TOA correction coefficients, FMI compared validation results for the same period (August-March) of different years.

Ice clouds play a major role in the atmospheric radiation budget. Therefore, being able to accurately simulate the radiative impact of ice clouds and its evolution under climate change is a key issue in climate science. Synchrotron Soleil performed FIR transmission measurements on water ice films in a wide range including the temperature range useful for atmospheric simulations (50 - 300 K).

KNMI showed the latest developments of the KNMI O_2–O_2 cloud retrieval algorithm for OMI and Tropomi, and in the preparation of the CO2M and Tango missions. The O_2–O_2 cloud product is considered the primary cloud input for the NO_2 retrieval for these two missions.

A scientific approach for deriving effective cloud fraction and effective cloud pressure from OMI and TROPOMI measurements, based on the O2-O2 absorption band near 477 nm was presented by BIRA-IASB. They aimed to derive consistent cloud parameters to be used as input of algorithms to retrieve atmospheric trace gases from multi-decadal satellite observations, and to mitigate the influence of clouds.

RAL-Space produced hourly images of cloud and aerosol properties from SEVIRI aboard METEOSAT-10 using the ORAC algorithm. They compared the retrieval output using the old and new cloud mask over the course of 15 days.

A methodology named MAMA for the computation of spectrally resolved upwelling radiances in the presence of atmospheric diffusive layers was presented by university of Bologna. The algorithm was developed as a new analysis tool for application to interferometric data for the study of the atmospheric components. MAMA offers fast and accurate radiance simulations of the Earth's entire longwave emission spectrum.

University of Paris Est Creteil investigated the potential of the future atmosphere observing system for deriving a quantitively the vertical profiles of several aerosol types (i.e. desert dust, smoke, continental, oceanic and urban polluted using the GRASP algorithm.

KNMI presented the ESA scientific L2 retrieval processors, developed within the CARDINAL project, fully exploit the synergies of these observations and are set to deliver twenty-five scientific (Level 2) products. These products include nadir profiles of cloud, aerosol, and precipitation.

A-FM (ATLID featuremask) and A-PRO (ATLID profile processor) were introduced by KNMI. Retrievals based on simulated data and examples based on ALADIN observations were presented.

Meteo-France-CNRS investigated how infrared spectroscopy impacts on clear-sky simulations generated by fast radiative transfer models. Utilizing different spectroscopic databases, specifically HITRAN for RTTOV and GEISA for 4AOP, IASI simulations were compared against satellite observations.

5.7 Dynamics

Research Center Julich proposed a method to calculate mean age of air up to a height of 25 km from observed mixing ratios of multiple measurable trace gas species, like trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), chlorodifluoromethane

(HCFC-22), CH_4, N_2O and SF_6. The method is based on the correlations of these trace gases with mean age.

Uncertainties in the tropical initial state in global numerical weather prediction (NWP) models are one cause of forecast-error growth in medium- and extended-range forecasts in the extratropics. University of Hamburg investigated the effects of assimilating observations within the tropics using a reduced-complexity model and a perfect-model assimilation framework.

University of Bologna presented an Observing System Simulation Experiment (OSSE) to investigate the contribution of specific water vapour-sensitive MTG-IRS channels to the representation of the physical properties of convective systems, and the impact on the ICON forecast.

Eight precipitation products were validated by University of Bologna with high spatial and temporal detail using around 1,200 hourly rain gauges in Vietnam focusing on the six typhoon-related case studies occurred in 2020.

The Scale-Aware Sea-Ice Project presented by University of Bologna aims to develop an innovative sea-ice model for climate research and for the better understanding and predicting the rapid changes caused by the warming of the polar regions. They coupled neXt-generation Sea Ice Model (neXtSIM) with an ensemble Kalman filter for state and parameter estimation.

Forschungszentrum Juelich showed how recent satellite observations have underpinned our knowledge on gravity waves and initiated improvements of climate and weather forecast models. They highlighted how CAIRT is a clear step forward from all existing global GW observations by showing results from synthetic CAIRT observations.

5.8 Platforms & Methods

BIRA-IASB presented the Terrascope platform. The platform enables easy access to and visualisation of Copernicus data for all societal sectors, the development and implementation of tailored or derived products based on Copernicus measurements and the development of innovative tools.

The ECOMAP (Exploitation of ongoing and future Copernicus Missions for Atmospheric Applications) project was presented by NILU. The project helps our understanding of greenhouse gases, contributes to air quality management, and fosters the utilization of remote sensing technologies for societal benefit.

In the last years the number of satellite instruments that are sounding the atmosphere is increasing and users will find more convenient to consult fused products rather than individual measurements. CNR considered the possibility of using new variables, independent of the a priori information with the purpose of simplifying and improving the subsequent fusion processes.

CNR presented the implementation of the Complete Data Fusion technique extension to 2D products and its first application to simulated 2D fields of CAIRT and 1D vertical profiles of IASI-NG for ozone.

CNR introduced the latest development of the sigma-IASI fast radiative transfer code. They completely revised the code using modern Fortran syntax. Variables have been grouped logically using derived types (structures). The input interface has been rewritten, and now is openSF compliant.

Within H SAF, a new ML-based algorithm for the MicroWave Imager radiometer on board the Second-Generation satellites (MetOp-SG) has been developed by CNR. The training procedure

is based on the use of observational databases built from nearly coincident measurements (in time and space) from active and passive microwave spaceborne sensors.

NILU presented The Copernicus Observations In-Situ (COINS) project which aims to enhance Copernicus Entrusted Entities by ensuring the sustainability of in situ observations and improving data coordination and exchange across Europe and beyond.

Luftblick compared the results from the two software versions (Blick v1.8 and Blick v1.9) for total and tropospheric columns of different trace gases and profiles from selected PGN locations. Furthermore, a comparison is made between Pandora NO_2 vertical profiles and profiles collected from available sonde and aircraft measurements.

The European Commission's Copernicus Polar Task Force is dedicated to enhancing and further developing the polar dimension of Copernicus Services. NILU focused on the Polar Task Force's recommendations for atmospheric observations and the CAMS, which continuously monitors and forecasts atmospheric composition, including greenhouse gases, reactive gases, ozone, and aerosols.

DLR presented the latest version of Py4CAtS—Python for Computational Atmospheric Spectroscopy. Py4CAtS has expanded its capabilities to facilitate the retrieval of gases from SWIR nadir observations and temperature fits from TIR spectra.

EMPA introduced two data-driven methods to improve the SNR of trace gas images using another co-registered trace gas image, such as NO_2 that is co-registered with CO_2 from the CO2M and GOSAT-GW missions.

To account for the spectral smoothing when highly resolved radiance is measured by finitely spectrally resolving instruments, it is common for a DOAS algorithm to apply the I_0 correction when convolving high resolved absorber cross sections to the instrument resolution. MPI for Chemistry showed that the application of a novel I_0 approximation method significantly improves the retrieval accuracy both for strong and minor absorbers.

CNR introduced the MC-FORUM (Meteo and Climate exploitation of FORUM) initiative funded by ASI. Its primary objective is to develop new tools and expertise for harnessing FORUM data in meteorological and climate studies. The project explores the impact of FORUM data across different spatio-temporal scales and various data assimilation techniques.

The Earth-Moon-Mars project presented by CNR aims to develop a first infrastructure to be deployed on the lunar surface. This infrastructure will host several instruments and, among them, the Lunar Earth Temperature Observatory, which includes a single-pixel Fourier transform spectro-radiometer and an imager. These two instruments will continuously monitor the brightness temperature and the longwave outgoing flux of the whole Earth's disk.

The DIVA project presented by GRASP-SAS serves as a prototype hub for collecting, managing, archiving, and synergistically exploiting observational data from both ground and space. Its goal is to validate ESA and Copernicus satellite missions and scientific analyses. This versatile system integrates ground-based (lidar, photometer, and spectrometer), satellite, and model data, employing standalone and synergistic algorithms for advanced data products.

Task A of the FDR4ATMOS was introduced by DLR-IMF. They used newly calculated SCIAMACHY Level 1 Earthshine data and reprocessed all Level 2 data to newly retrieve trace gas columns and profiles as well as aerosol and cloud products.

Meteo France investigated how infrared spectroscopy impacts on clear-sky simulations generated by fast radiative transfer models. Utilizing different spectroscopic databases,

specifically HITRAN for RTTOV and GEISA for 4AOP, IASI simulations were compared against satellite observations.

5.9 Calibration & Validation

The TROPOMI instrument is suffering from degradation in various parts of the light path. To this end analysis of trends in the radiance signal have been performed by KNMI. Though the radiance signal is highly variable, data seems to indicate slight downward trends. The dependence of swath angle and geographical location was also considered.

KNMI presented a correction method tailored to mitigate sharp detector features in TROPOMI observations. Their approach involves a combination of masking, filtering and interpolation which they applied to a specific feature on one of the detectors of TROPOMI. The results demonstrated a correction of up to 2% alongside new insights into instrument degradation.

A first series of ESA funded SVANTE (S5P Validation and Calibration Experiment) activities have taken place in the period 2020-2023. BIRA-IASB has been performed an analysis to point out current gaps in validation of the TROPOMI products. Identified key priorities are related to the validation of the anthropogenic SO2 product and of biogenic and wildfire emissions of VOCs (e.g. HCHO, CHOCHO, HONO).

NO2 and HCHO are key species for atmospheric chemistry. BIRA-IASB investigated the added value of the FRM4DOAS facility in terms of bringing additional validation sites providing reference measurements for both gases and harmonizing MAX-DOAS retrieval across the network.

The validation of S5P data products is an essential component of the mission's quality assurance framework and is conducted by a team composed of various research institutions and universities. SERCO presented the overall framework and the interactions with international workshops and conferences.

The ACTRIS Data Centre serves as a critical resource for researchers, providing access to well-documented and traceable measurement data, innovative data products, and essential tools. NILU highlighted the structure and importance of the ACTRIS DC to satellite calibration and validation.

A comparison of satellite and in-situ measurements of surface albedo was conducted by University of Venice. The area of interest selected is around the Thule High Arctic Atmospheric Observatory on the North-western coast of Greenland, where the measurements of downwelling and upwelling solar irradiance have been started in 2016. The used radiometers are regularly calibrated, and corrections for thermal offset are applied.

ESA presented an Announcement of Opportunity to solicit proposals for the validation of the ALTIUS mission products, namely vertical profiles of stratospheric and mesospheric ozone, aerosol extinction, NO2, H2O, OClO, BrO, NO3 and Temperature.

6 Recommendations to ESA

The following recommendations were formulated across all thematic areas, based on input from the technical sessions, and from discussions held at the end of each day of the conference:

Id	Recommendations
	General Recommendations The following section describes potential ESA actions that are not topic specific, but are cross-cutting and programmatic in nature.
R1	Continuity of funding projects is needed with longer and better funded projects to reduce proposal writing commitments, and gaps between selection and kick-off to allow for hiring.
R2	ESA should ensure consistency of the growing ecosystem of GHG satellite missions (esp. New Space & Methane) and to further develop ESA's interaction with 3rd party missions, e.g. MethaneSAT contributing to ESA projects and experiments, ensuring transparency of data as much as possible.
R3	ESA should ensure that AI/ML concepts are included in relevant future ESA training courses for atmospheric researchers
R4	ESA usually processes until L2, but recent trends of commercial satellites have included operational L3 and L4 data, ESA should provide L3 and L4 emission data as operational product for atmospheric missions.
R5	ESA should ensure that AI is embraced with its programs, but retain support for core development, notably CCI development, integrating new missions and support traditional approaches and datasets.
R6	ESA to support ground-based Cal/Val campaigns and invest in ground-based networks, European Research Infrastructures and mobile exploratory platforms capable of providing reference measurements for long-term product validation and data archiving.
R7	ESA to encourage more studies on future missions such as IASI-NG, S4, and S5 data to support various atmospheric studies.
R8	Next to operational satellite processing systems, agile pre-operational processors (e.g. S5P PAL) should be further developed to allow for easy access to value-added data products not covered by operational entities.
R9	ESA to support studies improving understanding basic physics, and basic assumptions. For example, lab spectroscopy of line parameters/absorption cross-section to improve retrieval uncertainties.
R10	ESA to implement studies that investigate if Nadir data/retrievals may have information on stratospheric species that have not been previously investigated.
R11	ESA to support the implementation of new ECVs into the CCI program, for example, stratospheric aerosols, aerosol cloud interactions , stratospheric temperature.
R12	ESA to investigate the role of volcanic eruptions on the climate, this could include studies relating to: • Ozone depletion, and the link to water vapour. • CO2 precursor emissions for detecting volcanic eruptions. • Aerosol emissions, injection into the stratosphere and cloud interactions.
R13	ESA to investigate the use of High-Altitude Pseudo Satellites (HAPS) for scientific exploitation in atmospheric physics.
R14	ESA to continue to investigate regional trends of trace gas species. For example, more focus on polar and UTLS trends (ozone and other species).
R15	ESA should support researchers in access to cloud computing facilities, in order to support the analysis and processing of the huge volumes of data to be expected from upcoming ESA missions. Research should be undertaken towards lossless data compression methods.

R16	ESA to continue the support for the exploitation of past missions (as done for CCI initiatives) in order to maximize the extrapolation of climate variables from long term datasets.
R17	ESA to develop radiative transfer models based on machine learning, to be used for multiple ESA and Copernicus satellite missions and for the retrieval of different atmospheric species, in order to reduce the computational effort of L1-L2 retrievals and the associated environmental footprint.
	Recommendations relating to Greenhouse Gases
R18	Continue on-going efforts with using a range of satellites to obtain information on important methane sources, even for challenging applications such as offshore sources or diffuse emissions like landfills and livestock. This shall be done possibly in collaboration with different operators in order to fill the gap between emission inventories and top-down estimates. This should include making combined wetlands products from EO easily available, and by developing methods for the synergistic use of modelling and observational data.
R19	Foster synergies and complementarities of instruments, retrievals, reference observations and inverse modelling setups for improving CH4 observations and reducing/characterising uncertainties. Such activities shall also consider future data availability from missions such as Sentinel 2-NG, CHIME and CO2M.
R20	Support to the few high-latitude reference sites to ensure the continuation of high-quality data. High-latitude profile analyses are recommended to be developed further to support validation of satellite and ground-based products.
R21	Support dedicated long term studies (year-around measurements are needed) to separate natural and anthropogenic CH4 emissions, with adequate observations sensitivity to the surface considering missions such as Merlin. In addition, through investigating the possibility to detect methane isotopologues from current and future missions such as CO2M, MethaneSat and GHGSat.
R22	Further studies are needed in relation to the simultaneous retrieval of CO2 and NO2 from different satellite observations or from a single mission (i.e. CO2M) to promote relevant initiative in support to the Paris Agreement.
R23	The audience highlighted the importance of continuity for the analysis of the CH4 flux trends, including sensitivity studies to improve robustness of the results, and increasing the reliability of wind data for more accurate emission estimates. The reduction of biases and uncertainties of the fluxes and of the transport models are of crucial importance to improve the accuracy of the global inversions.
R24	Regarding advancing GHG retrievals, the audience expressed the need for studies on following aspects: • Thermal IR methane retrievals are currently limited by spectroscopy of both CH4 and water vapour in the 7.9 micron band. ESA should support dedicated spectroscopic studies to fully exploit the potential for height resolved methane offered by IASI-NG in combination with Sentinel-5 on Metop-SG (as well as IASI+Sentinel5P). • Further development/improvement for high-resolution albedo and elevation maps are critically needed for improving the accuracy of GHGs observations. • Support studies for validation of aerosol properties in SWIR wavelengths.

R25	ESA to promote in collaboration with other authorities such as IMEO, CEOS, CH4 controlled releases experiments to validate the emission estimates from high spatial resolution satellite observations.
R26	ESA studies on GHGs are mostly only related to CH4 and CO2. There is a need to promote more studies on different GHGs such as N2O, CFCs, HFCs and water vapour.
R27	ESA should increase efforts for trace gas retrievals with high-resolution hyperspectral missions focusing on CO2, and NO2, considering the existing large data archives from EnMAP, PRISMA and EMIT, and the upcoming SBG and CHIME global missions, also taking into account synergies with Sentinel-2 NG. This should include efforts for future instruments (e.g. Sentinel-2NG, CHIME) to optimise channels and develop retrievals for methane observations.
R28	Tailored high latitude methane products should be developed for upcoming missions including CO2M, CHIME and Sentinel2-NG and tropospheric column retrievals using SWIR-TIR synergy of IASI-NG and S5 (on MetOp-SG). The developments should be supported by sufficient validation campaigns. by making easy available to methane community combined wetlands products from EO and by developing methods for the synergistic use of modelling and observational data.
R29	Improve the availability of data for profile validation, required to adequately validate satellite height-resolved retrievals. Potentially achieved through regular AirCore launches coordinated with satellite overpasses. Such launches should target areas with limited instrumentation for validation (e.g. high lats, Tropics).
R30	Putting high priority on providing TROPOMI CH4 Near Real Time (NRT) data, the scientific community are asking for quicker access to TROPOMI CH4 super emitter data. Which could be solved through Level 2 CH4 TROPOMI in NRT.
R31	ESA to develop studies on improving the ability to measure the OH radical. More information is needed on OH trends, and what are the abilities of satellites to provide this information.
	Recommendations relating to Air Quality
R32	ESA should support studies on methods less dependent on any a-priori information fostering the use of Level 4 data. As well as develop synergistic/complementary trace gases products combining wavelength ranges (UV-VIS and IR) from instruments on the same platforms such as Sentinel5-IASI-NG and Sentinel 4-IRS.
R33	ESA should explore possible observational approaches to improve the capabilities for NH_3 remote sensing detection at high spatial resolution.
R34	ESA should support dedicated activities on the impact of wildfires on air quality: • Increased validation efforts over wildfire-affected areas to understand atmospheric processes better. • Further developing and exploring the HONO products and its impact on atmosphere's oxidizing capacity • Foster studies on aerosol products under optically thick plume conditions to improve UV-VIS trace gas retrievals for smoke plumes. • Improving the monitoring of burnt areas through developing synergies between diverse data sources such as atmospheric and land products. • Create a longer and consistent Fire Radiative Power dataset, potentially all the way to the 1990's.
R35	ESA to trigger studies on global monitoring of Volatile Organic Compounds (VOCs):

	• Foster the global monitoring of VOCs using multi-instruments approaches focusing on UV-VIS data to assess the global atmospheric oxidizing power. • Investigate the role of VOCs in the ozone formation process merging atmospheric observations with different data sources such as land and vegetation products.
R36	ESA to promote studies on the tropics with focus on the deforestation and environmental changes fostering the synergetic exploitation of atmosphere and land products.
R37	There is a need to promote scientific activities linked to the policies in order to understand how the science can impact the societal benefits. This could include: • Health impact of AQ emissions • Satellite monitoring of the impact on air quality of underrepresented economic sectors, for example shipping and aviation.
R38	ESA to continue to support studies on the retrieval of water vapour isotopologues to better understand the coupling between atmospheric circulation and moisture pathways.
R39	ESA should consider projects to apply the same L1b-to-L2 algorithm to Sentinel 4, GEMS and TEMPO, especially for long-lived air quality species which can flow around the Northen Hemisphere, such as aerosols from increasing in strength and duration seasonal fires. Similarly for total ozone and water vapour, from the climate change aspect.
	Recommendations relating to Aerosols
R40	ESA should trigger studies on the harmonization of lidar missions spanning over the last 20 years, to build a 3D multi decadal climate data record on aerosol vertical distribution and extinction coefficients, leveraging over EarthCARE to reconstruct historic datasets (e.g. CALIPSO, CATS, Aeolus).
R41	Regarding the synergies between different satellite instruments the audience expressed the needs for studies on the following aspects: • Develop advanced aerosol products (such as composition, CCN, absorption properties) combining different sensor combinations e.g. passive/passive (e.g. GEO and LEO), and passive/active (e.g. EarthCARE with passive). • Develop observations of spectral aerosol optical properties (such as complex spectral refractive index) covering spectral range from VIS to TIR. • Explore the possible combinations of passive and active satellite observations with information from model forecasts for the retrieval of 3D aerosol properties. • Explore synergies of FORUM with other missions, for example Metop-SG with Sentinel 5, or EarthCARE, for the purpose of developing new scientific products.
R42	Regarding the aerosol models the audience raised the needs to foster studies on: • Improve optical models of non-spherical particles (i.e. desert dust and high latitude dust) for accurate modelling of both passive and active remote sensing (including multi-angular polarimetric data and spectral backscatter, lidar ratio, and depolarisation), to unlock the synergistic potential of passive/active remote sensing synergies and respective retrievals.

	• Improve dust optical models to reproduce spectral lidar parameters based on dust mineralogy to account for accurate modelling of passive observations. • Improve the interface between modelling and aerosol satellite observations (e.g. support data assimilation experiments through accurate operators, improve studies on aerosol impact on numerical weather predictions) in order to reduce uncertainties in climate projections. • Promote studies on the harmonization of aerosol modelling in remote sensing and climate models.
R43	ESA to foster fundamental studies on the aerosol microphysics for different aerosol types and spectral refractive index in a wide spectral range from VIS to FIR by means of laboratory measurements and surface/airborne in situ/remote sensing observations.
R44	ESA to promote a dedicated scientific strategy for stratospheric aerosols that are not covered by specific programs, e.g. promoting the development of limb sounding missions.
R45	Investigate multi-spectral lidar observation for gaining sensitivity to vertical variability of aerosol size distribution.
	Recommendations relating to Clouds
R46	With respect to clouds the participants recommended activities in the following thematic areas: • Invest in satellite studies on cloud microphysical processes • Explore high resolution (~50m) multi-angle cloud polarimetry for cloud 3D shape and microphysical process studies. • Explore cloud-bow retrieval application to CO2M-MAP. • Cloud shadow products should be exploited for correcting biases in NO2 retrieval and potentially other gases. • Explore the potential for using the Oxygen band for cloud properties retrieval. • Further studies on the impact of the changing radiative forcing due to contrails over different periods and seasons. • Explicit treatment of 3D cloud effects on radiation is important, example is the use of Monte Carlo, which is effective alternative for homogeneous atmosphere radiative transfer • Invest in exploring validation of new methods and products related to clouds, in the context of EarthCARE.
	Recommendations relating to the Thermal Infrared and Far Thermal Infrared
R47	ESA to fund studies relating to improving retrievals in the Far Thermal Infra Red, relating to the up-coming FORUM mission. The following non-exhaustive aspects should be addressed: • Can H2O and O3 observations be improved by FTIR observations? • Can cloud and dust observations be improved FORUM FTIR observations? • Improving spectroscopic parameters in the FTIR.
R48	ESA to investigate new products focusing on the capabilities of MTG-IRS during both day and night, such studies could include NH3, C2H4, C2H2 and VOCs, or others.
	Recommendations relating to Methods

R49	Instrument calibration: Importance of developing approaches to deal with stray light, both before launch and in orbit.
	Recommendations relating to Dynamics
R50	ESA to develop consistence long term measurements and records of global surface-pressure measurement from space.
	Recommendations relating to Ozone
R51	ESA to instigate and generate more measurements of ozone and Ozone Depleting Substances and related chemical species with a high vertical resolution. • This should include investigating methods for mitigating the impact from the gap of satellite observed height-resolved chemical species involved in ozone chemistry after end of MLS and before the launch of ALTIUS. • Studies into improving redundancy in satellite stratospheric ozone observations. This has been found to reduce uncertainties in long–term trends (more effective than increasing long-term stability in individual systems). • ESA to investigate how to support more high-altitude airborne campaigns to support this effort, in collaboration with campaigns for other species. • ESA to support the further harmonization of tropospheric records. • ESA to fund studies on the effects of the emissions of banned ozone depleting substances focussing also on the role of bromine and iodine chemistry and on very short-lived halocarbons not controlled from Montreal Protocol.
R52	ESA to fund studies to investigate and resolve drifts and biases apparent in the long-term ozone datasets.
R53	ESA to foster the assimilation of ozone profiles data from nadir and limb instruments into ECMWF and other CTM for the attribution of chemical and dynamic processes.