13th International Atmospheric Limb Workshop

Monday, June 2, 2025 - Friday, June 6, 2025

Schloss Karlsruhe

Book of Abstracts

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SAGE III/ISS: Status Update, Science, and New Data

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The Stratospheric Aerosol and Gas Experiment (SAGE) III on the International Space Station (ISS) has now completed 8 years of successful operation. Performing solar and lunar occultation measurements that provide vertical profiles of aerosol extinction and key trace gases such as ozone and water vapor, the SAGE III/ISS data record has proven invaluable for assessing the impact of volcanic eruptions and large wildfires on the stratosphere and upper troposphere as well as contributing to the long-term monitoring of the health of the ozone layer. This talk will give an update to the health and status of the SAGE III/ISS instrument, focus on key science highlights over the past few years, discuss the changes associated with the recently released version 6.0 data products, and talk about the future of SAGE measurements.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Using MIPAS Tracer Measurements to Investigate the Quasi-Biennial Oscillation and Mean Meridional Circulation

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This study investigates the Quasi-Biennial Oscillation (QBO) influence on the mean meridional circulation during the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) operational period (2002-2012). We employ ERA-Interim, JRA-55, and ERA5 reanalysis data alongside MIPAS tracer-derived 2-dimensional velocities. Following the SPARC Reanalysis Intercomparison Project (S-RIP) methodology, we deseasonalize and composite QBO-W onsets at 20 hPa. This allows for comparisons of zonal-mean vertical and meridional velocities derived from MIPAS tracers with reanalysis data.

To derive effective transport velocities within the 2-dimensional atmosphere, we leverage a direct inversion technique based on MIPAS tracer measurements, called ANCISTRUS. This method, as detailed in Clarmann et al. (2016), integrates the continuity equation over time to determine mean velocities that replicate observed trace gas distributions. This approach offers observation-based insights into the mean meridional circulation independent of dynamical models. We analyze various atmospheric layers for the tracers CH4, CO, H2O, and N2O, and supplement them with SF6 and CCl4 to mitigate uncertainties.

Our analysis reveals distinct QBO patterns in tracer-retrieved velocities, demonstrating good qualitative agreement with ERA5, ERA-Interim, and JRA-55 reanalysis results. However, comparisons also expose differences, potentially highlighting areas for improvement in current models or limitations inherent to tracer-based continuity equation inversions. In particular, MIPAS-derived velocities are considerably smaller than those from reanalyses. These inconsistencies are under further analysis.

Our findings emphasize the significance of MIPAS tracer measurements for enhancing our understanding and modelling of the mean meridional circulation in Earth's atmosphere.

von Clarmann, T. and Grabowski, U.: Direct inversion of circulation and mixing from tracer measurements –Part 1: Method, Atmos. Chem. Phys., 16, 14563–14584, https://doi.org/10.5194/acp-16-14563-2016, 2016.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Transcontinental stratospheric and upper tropospheric measurements with the new GLORIA-Lite instrument

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The Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) is a cooled limb-imaging Fourier-Transform spectrometer (iFTS) providing mid-infrared spectra with high spectral resolution. A newly developed, compact and uncooled version of GLORIA (called GLORIA-Lite) is significantly smaller and lighter thanks to state-of-the-art infrared sensors, tailored electronics and innovative manufacturing technology. The development of this instrument enabled the first transcontinental balloon flight from northern Sweden via Greenland to Canada, which took place in June 2024. The objectives of observation have been primarily its technical qualification and the provision of a first imaging hyperspectral limb-emission dataset (spectral sampling 0.2 cm-1 in the wavelength range 700-1550 cm-1) from 5 to 40 km altitude as well as the retrieval of key stratospheric and tropospheric species (level-2 data).

In this contribution we will demonstrate the performance of GLORIA-Lite with regard to level-2 data, consisting of retrieved altitude profiles of a variety of trace gases. We will show examples of selected results together with uncertainty estimations, altitude resolution as well as comparisons to atmospheric model simulations.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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EPP-climate link by reactive nitrogen polar winter descent: Science studies for the EE11 candidate mission CAIRT

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Polar winter descent of NOy produced by energetic particle precipitation (EPP) in the mesosphere and lower thermosphere affects polar stratospheric ozone by catalytic reactions. This, in turn, may affect regional climate via radiative and dynamical feedbacks. NOy observations by MIPAS/Envisat during 2002–2012 have provided observational constraints on the solar-activity modulated variability of stratospheric EPP-NOy.

ESA's Earth Explorer 11 candidate Changing Atmosphere Infra-Red Tomography (CAIRT) will observe the atmosphere from about 5 to 115 km with an across-track resolution of 30 to 50 km within a 500 km wide field of view. CAIRT will provide NOy and tracer observations from the upper troposphere to the lower thermosphere with unprecedented spatial resolution. We present the science studies using WACCM-X high resolution model runs simulating a Sudden Stratospheric Warming event to assess its potential to advance our understanding of the EPP-climate link and to improve upon the aforementioned constraints in the future.

Topic:

Upcoming Earth observation limb and occultation instruments

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Aerosols, Trends, and Recent Results for the Atmospheric Chemistry Experiment (ACE)

Author: Chris Boone[1]

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The Atmospheric Chemistry Experiment (ACE) is an ongoing satellite mission for remote sensing of the Earth's atmosphere. It is comprised of a Fourier transform spectrometer (ACE-FTS) operating in the infrared with broad spectral coverage (750 –4400 cm-1) and high resolution (0.02 cm-1), a UV-Visible-NIR spectrophotometer (ACE-MAESTRO, Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation) with wavelength coverage 280 –1030 nm and resolution 1 –2 nm, and a pair of imagers measuring at 525 and 1020 nm, respectively. Collecting solar occultation measurements since February 2004, ACE provides over 21 years'worth of atmospheric profiles for pressure, temperature, and the volume mixing ratios of more than 30 molecules, as well as volume mixing ratio profiles for more than 20 subsidiary isotopologues. Removing the contributions of gas phase molecules from ACE-FTS measurements yields infrared spectra for aerosols, providing valuable composition information for the aerosols. Trends derived from the long-term ACE measurement set will be described, along with recent results and retrievals for new molecules (C2H4 and HFC-125) developed in preparation for the next processing version.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Global and Vertical Distribution of Ozone Isotopic Ratios in the Stratosphere and Lower Mesosphere Observed by the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)

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The oxygen isotope ratio of ozone can provide insights into the oxygen cycle. Due to observational challenges, understanding the global behavior of the stratosphere and lower mesosphere has been difficult. In this study, we derived the isotopic abundance ratios of 18OOO and 17OOO in ozone using the ultra-high-sensitivity observations of the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) onboard the International Space Station (ISS). We clarified the global distribution and vertical profile of ozone isotope ratios in the stratosphere and lower mesosphere.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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ALTIUS Primary Species Retrieval Algorithms in Solar Occultation Mode Validated using SAGE III-ISS Observations.

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The Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) is the European Space Agency's (ESA) future ozone mission, part of ESA's Earth Watch Programme. The mission is set to launch in 2027 from Kourou, aboard the Vega-C launcher.

ALTIUS is designed to perform measurements in various geometries to optimize global coverage. This includes observing limb-scattered solar light during the day, solar occultations at the terminator, and stellar, lunar, and planetary occultations during the night. The primary mission objective is to obtain high-resolution stratospheric ozone concentration profiles. Given its diverse measurement geometries, ALTIUS is considered a necessary successor to ESA's SCIAMACHY and GOMOS instruments, which were retired after the decommissioning of ENVISAT in 2012.

The ALTIUS payload, which will be mounted on a PROBA platform, comprises three imagers: UV (250-355 nm), VIS (440-675 nm), and NIR (600-1040 nm) channels. Each imager can independently capture images at desired wavelengths and acquisition times, allowing for optimal wavelength and acquisition time selection. This feature enhances vertical resolution, enabling the retrieval of vertical profiles of various chemical species, including but not limited to Ozone, NO_2, and aerosols.

The focus of this work is on simulating the ozone retrieval algorithm in the Solar Occultation configuration, using data from the Stratospheric Aerosol and Gas Experiment (SAGE-III) on board of the ISS. Since 2017, SAGE-III on ISS has been producing Solar Occultation measurements in the UV/VIS spectrum, providing spectral coverage from 280nm to 1040nm with a spectral resolution of ±1.2nm, and includes an additional 1550nm channel for aerosols and clouds.

Owing to its similar measurement geometry, large dataset, and theoretically high spectral resolution, SAGE-III serves as a valuable data source for simulating ALTIUS's Solar Occultation mode. The objective of this work is to adapt SAGE-III data to align with ALTIUS's Solar Occultation configuration by creating so-called "Altiusified stimuli." These stimuli are then used to validate ALTIUS's Level 2 algorithm and to verify the performance of its Ozone, NO_2, and Aerosol products by comparing the results against the corresponding SAGE-III Level 2 dataset.

During this work, several technical challenges were addressed that impacted the stimuli generation process, including but not limited to:

1. Gaps in spectral data within SAGE-III's Level 1 product,
2. Noise present in the Aerosol and NO_2 data of the SAGE-III Level 2 product,
3. The need to determine a best-fitting effective radius for the aerosol profiles.

As a result of these challenges, alternative measurement vectors need to be used in the L2 processing of this Altiusified data.

End-to-end simulations were conducted using our System Performance Simulator (SPS), which models the actual ALTIUS performance based on the most recent instrument characterizations available at the time of this study.

Topic:

Upcoming Earth observation limb and occultation instruments

11

Anomalous transport in the Northern Hemisphere in the stratosphere as diagnosed by nitrous oxide in meteorological and chemical reanalyses

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In early 2019, anomalously large concentrations of nitrous oxide (N2O) developed in the Northern Hemisphere (NH) with a very particular pattern. Specifically, a "tripole"structure can be distinguished: positive N2O anomalies over the tropical upper stratosphere (above 10 hPa), large negative anomalies in the mid-upper stratosphere (between 10 and 20 hPa) over the subtropics and equally large positive anomalies in the mid-stratosphere (around 50 hPa) over the whole NH. Given the long chemical lifetime of N2O in the stratosphere, these anomalies are caused by anomalies in the stratospheric transport. We use the Dynamical Linear Model (DLM) tool to separate the impact of different physical processes: the QBO with a lag of 4 months, the de-seasonalized Eliassen Palm Flux divergence (as a measure of the anomaly in the wave activity), the solar cycle, the seasonal variations, and the autoregressive term. We consider several datasets: the merged satellite dataset SWOOSH, the reanalysis of Aura MLS driven by the MERRA2 meteorology (M2-SCREAM), together with several CTM simulations: the GMI model driven by MERRA2 (M2-GMI), and the BASCOE model driven by ERA5 (BASCOE-ERA5), by JRA3Q (BASCOE-JRA3Q) and by MERRA2 (BASCOE-MERRA2). These datasets compare remarkably well in terms of the patterns and magnitudes of the N2O anomalies. The results with the DLM also show very good agreement between the datasets, with a considerable impact of the QBO with a lag of 4 months. In particular, the tripole structure in the N2O anomalies is well reproduced by the 4-months lag QBO regressor across most of the stratosphere. These patterns indicate that the N2O anomalies are generated by the QBO-induced secondary circulation developed 4 months before and were transported and stretched towards the higher latitudes by the transport due to the Brewer Dobson Circulation (BDC). Over the polar region, the positive impact of the de-seasonalized Eliassen-Palm flux divergence suggests the effect of a sudden stratospheric warming that allowed transport of N2O above the Arctic. The contribution of the seasonal cycle reflects the climatological seasonality of the BDC. In order to better understand the role of the transport via the BDC, we also investigated the N2O TEM budget. In particular, we considered the impact of the residual advection on the N2O concentrations. We show that the anomalies of the residual advection term correspond in magnitude and sign to the N2O anomalies. This suggests that the anomalous residual advection generates the N2O anomalies. We applied the DLM to the residual advection term and the DLM confirms that the lagged QBO is the main process generating the residual advection anomalies. This implies that the lagged impact of the QBO generated an anomalous residual advection in the NH that ultimately created the N2O anomalies. We highlight how valuable is N2O to study extreme events of transport and that diagnostics like the DLM and the TEM budget help to better understanding these processes.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Trends in upper stratospheric temperatures and in the stratopause from satellite limb instruments

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Stratospheric cooling and contraction are projected to occur in response to increasing anthropogenic greenhouse gas emissions. However, temperature changes in the upper stratosphere, particularly above ~45 km, are difficult to quantify and model due to a deficit of observational data in this region. The recently developed v7.3 upper stratospheric (35–60 km) temperature data product from the Optical Spectrograph and InfraRed Imager System (OSIRIS) includes over 22 years of observations that can be used to estimate temperature trends. The trends in OSIRIS temperatures over 2005–2021 are compared to those from two other satellite limb instruments: Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) and the Microwave Limb Sounder (MLS). We find that the stratosphere cooled by ~0.5–1 K/decade during this period. Results from the three instruments are generally in agreement. We also consider trends at the stratopause: both SABER and OSIRIS observations suggest that the tropical stratopause moved lower during 2005—2021, a sign of middle atmospheric contraction.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Chemical Processing and Ozone Loss in the Southern Hemisphere Stratosphere Following the Eruption of the Hunga Volcano

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The 2022 eruption of the submarine Hunga volcano injected an unprecedented amount of water vapor directly into the stratosphere. In this talk, we use measurements of gas-phase constituents from the Aura Microwave Limb Sounder (MLS) and the Atmospheric Chemistry Experiment-Fourier Transform Spectrometer (ACE-FTS), aerosol from the Suomi-NPP Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP), and polar stratospheric clouds (PSCs) from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) together with MERRA-2 meteorological reanalyses to investigate how the extraordinary hydration from Hunga affected chemical processing and ozone loss in the Southern Hemisphere polar and extrapolar lower and middle stratosphere. We review results showing widespread stratospheric chlorine and nitrogen repartitioning in the southern mid- and low-latitude stratosphere in the months following the eruption. Observed composition changes are consistent with heterogeneous processing on volcanic sulfate aerosol, in particular the hydrolysis of N_2O_5. However, the moderate enhancements in reactive chlorine did not cause appreciable chemical ozone loss, and extrapolar ozone abundances remained largely controlled by dynamics. At higher latitudes, the Hunga hydration was effectively excluded from the winter polar vortices in the first post-eruption winters in both hemispheres. While excess moisture from Hunga inside the 2023 Antarctic vortex led to unusually early and vertically extensive PSC formation and chlorine activation and intensified dehydration, by mid-winter chemical processing had essentially run to completion, as is typical in the Antarctic, preventing an exceptionally severe springtime ozone hole. The Antarctic vortex was relatively warm and dynamically disturbed through much of the 2024 season, and lower stratospheric chemical processing and ozone loss mostly followed typical patterns. The Arctic vortex in the 2023/2024 winter/spring was also unusually humid, but dynamically disturbed conditions were

unfavorable for chlorine-catalyzed ozone loss. Finally, we will also report on the 2024/2025 Arctic winter, which will have recently concluded.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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The Changing-Atmosphere Infra-Red Tomography Explorer CAIRT –a candidate mission for ESA's Earth Explorer 11

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The Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) is one of the two remaining candidate missions competing for implementation as ESA's Earth Explorer 11. 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, a Fourier Transform Spectrometer for infrared limb hyperspectral imaging, would provide continuous limb radiance measurements from the mid-troposphere to the lower thermosphere, at high spectral resolution and with unprecedented horizontal and vertical sampling. Leveraging an innovative tomographic retrieval approach, 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. With this, CAIRT would provide critical information on: (a) atmospheric gravity waves, circulation and mixing; (b) coupling with the upper atmosphere, solar variability and space weather and; (c) aerosols and pollutants in the upper troposphere and lower stratosphere.

CAIRT would thoroughly explore and elucidate the role of the middle atmosphere in climate dynamics, forcing and feedbacks. It would firmly anchor this knowledge in a more holistic understanding of fundamental processes within the Earth system, whilst equally supporting applications providing direct societal benefits and informing international policy-making and policy implementation.

CAIRT is currently undergoing Phase A feasibility studies. A broad overview of the mission and its science objectives will be given, as well as some more detailed insight into performance expectations from previous studies and on-going activities.

Topic:

Upcoming Earth observation limb and occultation instruments

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Assessment of instrument biases: ozone in the upper troposphere –lower stratosphere

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The Upper Troposphere –Lower Stratosphere (UTLS) region is a chemically and dynamically active part of the atmosphere, characterized by large spatial and temporal variability. This variability complicates studies of trace gases, and in turn analysis of trends and key processes, such as stratosphere-troposphere exchange and the impact of radiatively active species on climate. While aircraft, ground-based, balloon-borne, and satellite instruments have all been used to record composition measurements of this region, each form of measurement has inherent biases that complicate combining these measurements for integrated analysis.

The aim of this project is to assess the biases between measurement datasets, made using numerous techniques and with varying spatial and temporal resolution and coverage. To this end, climatologies are created by subsampling the high-resolution gridded MERRA-2 reanalysis dataset using measurement times and locations for a selection of aircraft, ground-based, balloon-borne, and limb-viewing satellite instruments. These sub-sampled climatologies are compared against each other to estimate inter-instrumental biases in a manner that reduces the effects of differing measurement characteristics on these bias estimates. These bias estimates are compared against more traditional coincidence-criteria estimates to examine the consistency between these two approaches. Focus within this is specifically on ozone measurement biases in the UTLS. This work is done in part to support the Atmospheric Processes And their Role in Climate (APARC) Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS) activity.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Latest Validation Results for the Atmospheric Chemistry Experiment (ACE)

Author: Kaley Walker[1]

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In August 2025, the Canadian-led Atmospheric Chemistry Experiment (ACE) mission will complete its 22nd year in orbit on board the SCISAT satellite. The more than two decades of ACE operations provide a valuable time series of composition measurements that contribute to our understanding of ozone recovery, climate change and pollutant emissions. The main instruments on board SCISAT use infrared and UV-visible spectroscopy to make their solar occultation measurements. The ACE Fourier Transform Spectrometer (ACE-FTS) is an infrared FTS operating between 750 and 4400 cm-1 and the ACE-MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation) is a dual UV-visible-NIR spectrophotometer which was designed to extend the ACE wavelength coverage to the 280-1030 nm spectral region. From these measurements, altitude profiles of atmospheric trace gas species, temperature and pressure are retrieved. The 650 km altitude, 74 degree circular orbit provides global measurement coverage with a focus on the Arctic and Antarctic regions. This presentation will describe the validation results for the newest ACE-FTS and MAESTRO data sets.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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ALTIUS Stellar Occultation Ozone and Aerosol Extinction Retrieval Algorithms

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ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere) is the upcoming stratospheric ozone monitoring mission of ESA's Earth Watch program. ALTIUS consists of three 2D high resolution imagers: UV (250-355 nm), VIS (440-675 nm) and NIR (600-1020 nm) channels. Each channel is independent of the others and takes snapshots of the atmosphere in limb geometry at requested wavelengths. ALTIUS will measure in three different observation modes to maximize the spatial coverage of the mission: limb scattering on the dayside of the orbit, solar occultation at the terminator and stellar (or planetary) occultations on the nightside of the orbit. Stratospheric ozone profiles are the mission's primary objectives. Secondary objectives include the retrieval of other species, such as NO2, NO3, aerosol extinction, BrO, OClO, temperature and H2O profiles. In stellar occultation, both ozone and aerosol extinction profiles will be retrieved.

As light coming from a star and passing through the atmosphere interacts with irregularities caused by turbulences and gravity waves, its signal fluctuates along with the air density on the optical path. This phenomenon is called scintillation and is one of the main challenges of stellar occultation measurements.

This work presents the latest updates on the expected retrieval quality using the measured instrumental functions in stellar occultation mode. The strategies considered to mitigate scintillation for both ozone and aerosol extinction retrievals are also discussed and the influence of scintillation on

retrieved profiles is assessed. Data originating from GOMOS (Global Ozone Monitoring by Occultation of Stars), an atmospheric sensor performing stellar occultations on board the ENVISAT satellite, is used to perform this study.

Topic:

Upcoming Earth observation limb and occultation instruments

18

Stratosphere Troposphere Response using Infrared Vertically-resolved light Explorer (STRIVE) Mission Concept

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The Stratosphere Troposphere Response using Infrared Vertically-resolved light Explorer (STRIVE) is a new satellite mission concept selected for a competitive Phase A Concept Study within NASA's 2023 Earth Systems Explorer Program. STRIVE includes the Advanced Limb Infrared Chemistry Experiment (ALICE), a limb-scanning infrared imaging spectrometer along with the Aerosol Radiometer for Global Observations of the Stratosphere (ARGOS), a limb-viewing dual wavelength multi-aperture near-infrared radiometer. Together they provide high vertical resolution (~1 km) measurements of temperature, ozone and other important trace gases, aerosol extinction and properties with significant daily global coverage to better understand atmospheric response.

STRIVE has the novel ability to resolve small-scale vertical structures of atmospheric composition and temperature, enabling new insights into the processes of troposphere-stratosphere interactions. In particular, the upper troposphere and lower stratosphere (UTLS) includes strong vertical gradients in many trace gas constituents along with fine scale vertical features that are more challenging to observe from space yet critical in process understanding as we move toward higher spatial (horizontal and vertical) resolution models. We will show how STRIVE will provide this higher fidelity 3D view, with a comprehensive suite of constituent and temperature measurements, in an atmosphere that is rapidly responding to changing conditions.

Topic:

Upcoming Earth observation limb and occultation instruments

19

Analyses and comparisons of the ACE-FTS and MIPAS CFC-11, CFC-12 and HCFC-22 data

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The most recent ACE-FTS version 5.3 data for CFC-11, CFC-12 and HCFC-22 are compared with the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) version 8 data for these species, processed by the IMK/IAA (Institut für Meteorologie und Klimaforschung/Instituto de Astrofísica de Andalucía) for 2005 - 2012 . Comparisons of these two datasets are carried out for the time series of zonally averaged monthly means in nine latitude bands of 20° width from 90°S to 90°N. Four types of time series are used: two from the coincident subsampled datasets of both instruments and two from the entire datasets.
Dynamical components are extracted from these time series. The mean annual cycles are derived by averaging over the data period, while the mean distributions, linear trends and quasi-biennial oscillations (QBOs) are derived from the de-seasonalized time series using multiple linear regression (MLR).
A companion analysis is applied to the MIPAS tracer-derived residual velocity data. These velocity components largely explain the mean distribution of the atmospheric species, the annual variations linked to the Brewer-Dobson Circulation, the interhemispheric asymmetry in linear trends between the Southern and Northern Hemispheric stratosphere, and the QBOs in the equatorial region.
In addition, the time series analyses of both the ACE-FTS and MIPAS data are enhanced using derived meteorological product (DMP) data, allowing comparisons between latitude/altitude and equivalent latitude/potential temperature space. Finally, 21 years of ACE-FTS data are used to derive time varying linear trends in the latitude/altitude bins, reflecting events related to compliance/non-compliance with the Montreal Protocol and its subsequent amendments.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

20

MIPAS IMK/IAA Data Version 8: An Overview of Results - A Valuable Dataset for Future Limb Sounders

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The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), onboard the ENVISAT satellite, was launched in 2002 and operated until 2012, recording infrared limb emission spectra from the middle and upper atmosphere. As a pioneering instrument, MIPAS serves as a precursor to the proposed ESA Earth Explorer 11 mission CAIRT (Changing-Atmosphere Infra-Red Tomography Explorer), which is currently under selection.

The MIPAS data retrieval software, KOPRA/RCP, developed at IMK/IAA, has demonstrated exceptional performance in deriving atmospheric vertical profiles. This advanced retrieval framework is very conducive for being adopted and used in future limb sounding missions.

To date, retrievals for 29 trace gases, upgraded to Version 8, are available: these include temperature, C_2H_2, C_2H_4, C_2H_6, CCl_4, COF_2, CH_3Cl, CH_4, $COCl_2$, ClO, $ClONO_2$, CO, CFC-11, CFC-12, HCFC-22, H_2O, H_2SO_4, HCN, HCOOH, HNO_3, HNO_4, N_2O_5, N_2O, NO, NO_2, O_3, OCS, PAN, and SF_6.
These datasets and previous versions have undergone extensive validation and have been widely used in scientific research addressing atmospheric composition, dynamics, chemistry, long-term trends, and climate change.

In this contribution, we present a collection of vertical along-track temperature and mixing ratio distributions, along with their corresponding coarse grid retrieval (CGR) results. CGR is a relatively new data product designed to facilitate comparisons between our retrievals and modelled atmospheric data, without requiring the application of averaging kernels.

We sincerely dedicate this contribution, with deep gratitude, to the memory of our late colleagues Thomas von Clarmann and Andrea Linden.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

21

The ARGOS Instrument for Stratospheric Aerosol Measurements

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Observations of aerosol distributions in the Earth's stratosphere represent a key input for Earth system models that need to characterize atmospheric heating. These aerosol measurements need good vertical resolution to capture variations in horizontal transport, dense spatial sampling to capture local structure, and regular temporal sampling to follow the evolution of aerosol injections at a specific location. We have developed the Aerosol Radiometer for Global Observations of the Stratosphere (ARGOS) satellite instrument to make these measurements. ARGOS measures scattered light from the Earth's limb in 8 directions simultaneously to provide improved spatial coverage compared to current instruments. Overlapping samples at many locations along the orbit with variable scattering geometry will help to characterize the aerosol phase function. Concurrent observations at two near-IR wavelengths (870 nm, 1550 nm) provide altitude coverage down to the upper troposphere, and enable derivation of additional information about particle size distribution. All measurements are captured on a single focal plane with an image sensor that provides < 1 km vertical resolution to enable better representation of horizontal transport processes in the atmosphere. ARGOS was launched for a technology demonstration flight as a hosted payload in March 2025. Results from on-orbit operations will be presented.

Topic:

Upcoming Earth observation limb and occultation instruments

22

Vertical and meridional stratospheric transport calculated from MLS water vapour

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The budget of stratospheric water vapour is primarily controlled by the tropical upwelling of tropospheric air masses past the cold point tropopause and into the lower stratosphere. The strength of the tropical upwelling influences the thermal characteristics of the transition region between the troposphere and stratosphere (tropical tropopause layer), constraining water vapour transport to the stratosphere through dehydration. Due to the lack of direct measurements and small magnitude of vertical velocities, it is difficult to determine interannual and long-term variability of tropical upwelling.

Here we use measurements of water vapour from the MLS (Microwave Limb Sounder) instrument to determine seasonal, interannual, and long-term changes in lower-stratospheric vertical and meridional transport for 2005-2021. This analysis is performed separately for the Northern Hemisphere and Southern Hemisphere tropics to delineate contributions from different tropical regions. Our velocity calculations make use of the propagation of the water vapour tape recorder signal and represent an effective velocity, giving an estimate for the speed of the vertical and meridional branches of the stratospheric circulation. O3 measurements from the OSIRIS (Optical Spectrograph and InfraRed Imaging System) instrument and GNSS-RO (Global Navigation Satellite System –Radio Occultation) temperatures are contrasted with the calculated velocities to better understand the variability of O3 and temperature in the tropical tropopause layer.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

23

Airborne demonstration of the CAIRT measurement geometry with GLORIA observations during the ASCCI campaign 2025

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We present trace gas measurements obtained by the airborne infrared imaging limb sounder GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) that has been operated onboard HALO (High Altitude and Long Range Research Aircraft) during the ASCCI campaign (Arctic Springtime Chemistry-Climate Investigations; March 2025) from Kiruna, Sweden. The GLORIA instrument is an airborne demonstrator for the ESA Earth Explorer 11 candidate mission CAIRT (Changing-Atmosphere Infra-Red Tomography Explorer).

During the ASCCI campaign, a dedicated flight pattern was conducted in order to mimic the anticipated CAIRT measurement geometry and spatial sampling pattern with the GLORIA airborne instrument within the ESA CAREVALAB project. We will present first results from this sophisticated flight pattern together with preliminary diagnostics. For validation, we aim to compare our retrieved temperature and trace gas concentrations with ozone and water vapour measurements from the airborne WALES lidar, which was also deployed on HALO during ASCCI. Further, we will show GLORIA measurements from other ASCCI research flights, targeting pollution and stratospheric trace gases, which we expect to measure in high latitudes.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

24

Validation of OMPS Limb Profiler Ozone Retrievals

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The Ozone Profiler and Mapping Suite (OMPS) Limb Profiler (LP) satellite instruments perform limb measurements of scattered solar radiation in the ultraviolet and visible wavelengths, which allow for the retrieval of high vertical resolution ozone profiles from the 12.5km to 57.5km with full global coverage. The first LP was launched on board the Suomi-NPP satellite in 2011 and started operational observations in April 2012. The second LP was launched on board the NOAA-21 satellite in 2022 and started operational observations in February 2023.

In this study we utilized ozone profile retrievals from three correlative satellite instruments, (SAGE III/ISS, ACE-FTS and Aura MLS) together with ozonesonde data, to validate SNPP OMPS LP profile measurements processed with the new NASA GSFC version 2.6 retrieval algorithm. We found that SNPP OMPS LP agrees to within 10% between 15 and 55km at all locations (except for the tropical upper troposphere/lower stratosphere) when compared to all correlative sources, and to within 5% in most cases. SNPP OMPS LP started operational observations in April 2012, and so we now have more than 12 years of data overlap with MLS, ACE-FTS and sondes, SAGE III/ISS observations started in June 2017, which provides 7 years of data overlap with OMPS LP. These overlaps provide a large source of data with which to validate OMPS LP ozone profile retrievals and allow us to determine if there are any long-term drifts between OMPS LP and correlative observations. We found that drifts relative to correlative observations are within -0.6 and +0.4 %/yr with the largest drifts (also larger uncertainties) seen relative to SAGE III/ISS which has the shortest overlap period. We also present initial comparisons of NOAA-21 OMPS LP version 1 ozone profile retrievals with the same correlative data. We found that NOAA-21 OMPS LP generally has smaller biases compared to correlative observations, in particular, the large positive bias seen in SNPP OMPS LP at around 18km in the tropics and mid latitudes is not present in NOAA-21 comparisons.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

25

The contribution of EE-11 CAIRT candidate to clouds properties retrieval

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Clouds are of great importance for climate studies. They strongly influence the Earth radiative budget, and the knowledge of their macro and microphysical properties is necessary for a correct modelling of their radiative effects. In this regard, limb sounding instruments can play an important role. Thanks to a high vertical resolution, limb observations allow to detect multiple layers cloud structures and the thinnest cirrus clouds, invisible to nadir instruments.
The Changing-Atmosphere InfraRed Tomography (CAIRT) is one of the two ESA EE-11 candidates. It is a limb-sounder imager designed to measure the atmospheric radiance across the thermal infrared spectral region from 4.55 µm to 13.93 µm, with a targeting resolution of 0.2 cm-1. Its main feature is the improved vertical and horizontal resolutions, achieved through a 2-dimensional array detector capable to simultaneously acquire an elevated number of spectra, with a nominal horizontal sampling of 50 by 50 km and a vertical sampling of 1 km.
Within the CAIRTEX project, observations of the Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) [1], a prototype of CAIRT, acquired during the HEMERA 2022 balloon campaigns (Timmins, 23-24/08/22), have been used to test the feasibility of clouds properties retrievals from CAIRT observations. Limb emission radiances acquired by GLORIA showed contamination of two clouds at two different altitudes. Six vertically aligned spectra from the same vertical sequence, representative of the cloudy scenario, have been simultaneously fitted, and an effective cloud top altitude and thickness have been retrieved for each of the clouds considered. The use of more than one vertical sequence as would be for CAIRT, will enable to independently retrieve all the cloud geometrical extents [2].
A second study has been carried out within the PerReC project to explore the application of CAIRT observations for the detection of volcanic ash clouds [3]. The radiance field of a realistic volcanic eruption as observed by CAIRT and SEVIRI has been simulated [4, 5] and used for the retrieval of ash cloud thickness and columnar abundance, respectively. CAIRT simulated radiances have also been merged to SEVIRI simulation of the same scenario to estimate the ash concentration.
These two case studies demonstrate that CAIRT measurements contaminated by clouds can be exploited to retrieve clouds properties, enlarging the expected level 2 products of the mission.
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Topic:

Upcoming Earth observation limb and occultation instruments

26

Mitigating the impact of surface reflectivity inhomogeneities on limb scattering ozone retrievals from OMPS

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The focus of this study is the investigation and the mitigation of a retrieval artefact identified in tropospheric ozone data and ozone limb profiles retrieved from OMPS-LP observations at the University of Bremen (IUP). This artefact is associated with inhomogeneities in the surface reflectivity along the satellite line of sight (LOS).
At IUP, a tropospheric ozone column (TrOC) product has been produced by exploiting the limb-nadir matching technique applied to OMPS observations. In this data set, we noticed an artefact in the tropical Pacific region, i.e. higher ozone columns in the [0°N, 5°N] latitude band, where the tropospheric ozone is expected to be fairly homogeneous. This issue was traced back to the stratospheric profiles, which show a lower ozone content at their peak altitude. This feature is also visible in the Atlantic, though less pronounced, and exceeds the typical uncertainty of the TrOC, being of the order of 5-7 DU. Other stratospheric ozone column (SOC) and TrOC data sets, e.g. the NASA OMPS and SCIAMACHY TrOC products show a similar pattern in the tropical Pacific. In preliminary studies, we associated this pattern with the semi-permanent presence of the Inter-Tropical Convergence Zone (ITCZ), a region of high surface reflectivity that crosses the satellite LOS.

The present contribution belongs to the ESA ENFORCE project, which has the aim of implementing in the radiative transfer model SCIATRAN at IUP the possibility of taking into account variations of the surface reflectivity along the satellite LOS (2D mode) to mitigate the described artefact. The final goal is the improvement of the TrOC product derived from satellite limb scattering measurements, and the outcome could be of interest to any limb scattering instrument, e.g. SCIAMACHY and ALTIUS.
We present the first results of the retrievals performed using the SCIATRAN 2D mode. First, we used simulated case studies to better investigate the impact of different idealized distributions of surface reflectivity on the retrieved profiles. Then, we compare the results obtained with the SCIATRAN 2D mode on a subset of OMPS observations with the standard 1D SCIATRAN retrievals and with collocated MLS observations. Finally, we address the impact of the implemented correction on TrOC derived using the limb-nadir matching technique.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

27

Accounting for the aerosol particle size distribution in the retrieval of stratospheric aerosol extinction coefficients from OMPS-LP measurements

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Stratospheric aerosols play a major role in determining the radiative budget of the Earth's atmosphere. They cool the troposphere by scattering the incident solar radiation back to space and warm the stratosphere by absorbing upwelling thermal radiation. Furthermore, mainly in polar regions, stratospheric aerosol particles serve as condensation nuclei to build PSC particles. Heterogeneous reactions taking place at their surfaces release halogenated compounds and convert nitrogen oxides (NOx) into inactive reservoir species. This process significantly contributes to the catalytic ozone destruction.

Space-borne measurements of the scattered solar light in limb-viewing geometry in the visible and near-infrared spectral range is one of the major sources of the information on the stratospheric aerosol on the global scale. Data from the limb-scatter instruments currently in operation (OSIRIS and OMPS-LP) are used to retrieve stratospheric aerosol extinction coefficients at one or several wavelengths. The same strategy is foreseen for the upcoming ALTIUS instrument. Measurements of this kind provide a moderately high vertical resolution and dense horizontal sampling and are extremely useful for characterization of the global behavior of the stratospheric aerosols.

A major issue related to the retrieval of the stratospheric aerosol extinction coefficients from limb-scatter measurements is the need to assume the aerosol particle size distribution. So far, all existing retrievals assume an arbitrary aerosol particle size distribution corresponding to background aerosol conditions. As a results, stratospheric aerosol extinction coefficients retrieved from limb-scatter measurements after strong volcanic eruptions (e.g. Hunga Tonga - Hunga Ha'apai in January 2022) show a strong negative bias in comparison to the data from solar occultation measurements.

In this study we investigate methods to account for the aerosol particle size distributions when retrieving the stratospheric aerosol extinction coefficients from OMPS-LP limb-scatter measurements. The measurements after the Hunga Tonga - Hunga Ha'apai eruption in January 2022 are analyzed. Results from different approaches are compared to the data from SAGE III/ISS solar occultation measurements. The latter are considered to be the reference as the corresponding retrievals do not require any information on the aerosol particle size distribution.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

28

GLORIA Observations of Dichloromethane and Peroxyacetyl Nitrate Filaments in the UTLS during PHILEAS 2023

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The limb-imaging Fourier transform infrared spectrometer GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) enables high-resolution remote sensing of trace gases in the upper troposphere and lower stratosphere (UTLS). During the PHILEAS (Probing High Latitude Export of Air from the Asian Summer Monsoon) campaign in August and September 2023, GLORIA was deployed aboard the German research aircraft HALO (High Altitude and LOng Range Research Aircraft) to investigate stratosphere-troposphere exchange processes and long-range pollutant transport from the Asian Summer Monsoon (ASM).

Observations revealed extensive filaments enriched in dichloromethane (CH_2Cl_2) and peroxyacetyl nitrate (PAN) within the free troposphere and tropopause region over the Northern Pacific, Canada, and Alaska. CH_2Cl_2, an industrial solvent and precursor chemical with reported increased emissions primarily from East and Southeast Asia, has been described as a potential contributor to stratospheric ozone depletion. Concurrently, PAN, a key tracer of pollution, was detected in similar structures. While PAN is primarily associated with biomass burning, it also forms as a secondary product of anthropogenic combustion processes. Notably, smaller filaments of both species were identified in the tropopause region.

To analyze transport mechanisms and timescales, we utilized backward trajectories computed with HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory model). Furthermore, we used ICON-ART (ICOsahedral Nonhydrostatic weather- and climate model with Aerosols and Reactive Trace gases) surface tracers to compare the measured cross sections from GLORIA to different origin regions and to follow the transport of ASM air within and into the UTLS. We discuss the vertical uplift processes in the ASM region and the fast transportation pathways across the North Pacific.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

29

Mesospheric Ozone and Temperature trends derived using the merged METEOR merged datasets

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The METEOR (MEsospheric TEmperature and Ozone climate data Record) project aims to develop a high-quality, long-term climate data record of mesospheric ozone and temperature by merging observations from multiple satellite instruments. A primary objective is to assess mesospheric temperature and ozone trends, with a particular focus on the impact of solar particle precipitation on ozone levels in polar regions.
For the merged ozone and temperature dataset, we used limb and occultation satellite instruments that provide measurements in the mesosphere and lower thermosphere. The dataset includes observations from ACE-FTS, GOMOS, MIPAS, MLS, HALOE, and SOFIE.
The initial phase involved calculating deseasonalized monthly mean anomalies using pressure as the vertical coordinate. Anomalies were computed separately for each illumination condition (daytime, nighttime, sunset, and sunrise). The merged dataset was then created by taking the median of individual instrument anomalies for each altitude, latitude band, and month. The final data record for

ozone and temperature consists of deseasonalized anomalies structured in 10° latitude bands from 90°S to 90°N, covering an altitude range from 10 hPa (~30 km) to 0.001 hPa (~95 km) for the period 1991 to 2023.
In this presentation we will show results from the data merging process and preliminary mesospheric ozone and temperature trends analysis.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

30

Seasonality of the tropical pipe position from ANCISTRUS mean velocities

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The tropical pipe is the part of the Brewer-Dobson circulation where air is transported upwards from the troposphere into the higher atmosphere. Mixing with air from higher latitudes is widely suppressed by the so-called subtropical mixing barriers. The width and latitudinal position of the tropical pipe varies with time, driven (at least) by seasonal and QBO variations.

Metrics for the latitudinal position of the subtropical mixing barriers can be separated in chemical ones (derived from tracer distributions) and dynamical ones (derived from zonal and vertical winds). Ivaniha et al. (2025) have demonstrated that the seasonal variations between chemical and dynamical metrics are subject to a phase shift.

We analyse here the seasonal variability of the latitudinal position of the tropical pipe from MIPAS tracer observations and the meridional velocities derived from the same MIPAS tracers by the inversion tool ANCISTRUS (von Clarmann and Grabowski, 2016). We find that the same phase shift occurs between the chemical metrics and the zonal mean vertical and meridional velocities.

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Topic:

Atmospheric composition (Earth and planets), chemistry and transport

31

ALTIUS: mission development status and performance

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ALTIUS is ESA's upcoming Earth atmospheric limb mission. The primary objective of the mission is to provide near-real-time and consolidated stratospheric ozone profiles. Secondary objectives include stratospheric aerosols, H2O, NO2, NO3, temperature, OClO, BrO, and mesospheric ozone. The mission is in its implementation phase, with both the space and ground segments having reached the critical design review (CDR). The launch is foreseen on a Vega-C rocket in 2027.

The mission has some unique features intended to better tackle the common problems faced by previous UV-VIS-NIR limb sounders. First, it is a single payload mission on an agile platform, giving therefore many options for the observation scenarios. The baseline mission plan combines 100 limb-scatter observations on the day side, 2 solar occultations, and 5 stellar/planetary/lunar occultations in the night side (typical numbers). Second, the instrument is a three-channels spectral imager with tunable capability from 250nm to 1020nm. It comes with excellent vertical sampling (<1km at the tangent point), and allows straighforward in-flight pointing calibration, usually a key driver of the error budget of limb instruments.

The development of the scientific algorithms is ongoing, and a number of processing chains are already implemented in the payload data ground segment (PDGS). Extensive phases of verification of the mission performance have recently been completed. They are based on the best available knowledge of the instrument and spacecraft performance via the use of a simulator of the space segment. Currently, the stratospheric O3 product from the three observation modes, and aerosol extinction and NO2 in occultation modes have been studied. Aside from the pure simulations, the algorithms are also tested on existing limb sounder L1 products, such as OMPS-LP, SAGE-III, and GOMOS. An overview of the current status will be provided.

Topic:

Upcoming Earth observation limb and occultation instruments

32

Observing System Simulation Experiment of CAIRT limb profiles focusing on UTLS composition

Authors: Quentin Errera[1]; Marc Op de beeck[1]; Stefan Bender[2]; Johannes Flemming[3]; Bernd Funke[4]; Alex Hoffmann[5]; Michael Höpfner[6]; Nathaniel Livesey[7]; Gabriele Poli[8]; Piera Raspollini[9]; Joern Ungermann[10]; Björn-Martin Sinnhuber[6]

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The Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) is a candidate for ESA's Earth Explorer 11. This mission has been proposed in order to achieve a step change in our understanding of the coupling of atmospheric circulation, composition and regional climate. The CAIRT concept proposes to perform limb infra-red tomography of the atmosphere from the troposphere to the lower thermosphere (about 5 to 115 km altitude) with a 400 km swath to provide a three-dimensional picture of atmospheric structure at unprecedented scales.
This contribution investigates the capability of CAIRT to analyse Upper Troposphere Lower Stratosphere (UTLS) composition using an Observing System Simulation Experiment (OSSE). In this effort, a reference atmosphere –the nature run in the OSSE terminology –is built based on the Copernicus Atmosphere Monitoring Services (CAMS) control run (horizontal resolution ~40 km and a vertical resolution ~500 m in the tropopause region) between October 2021 and March 2022 (5 months). The nature run is used to generate CAIRT level 2 (L2) profiles of ozone (O3), water vapour (H2O) and carbon monoxide (CO), along with a CAIRT orbit simulator and a simulator to account for CAIRT instrumental errors as well as vertical and along track smoothing. Simulated CAIRT L2 profiles are then assimilated by the Belgian Assimilation System for Chemical ObsErvations (BASCOE) to provide analyses of O3, H2O and CO –the assimilation run. In order to measure the added value of CAIRT data in the assimilation run, a BASCOE control run without CAIRT assimilation, is also done. We have also simulated and assimilated Aura Microwave Limb Sounder (MLS) O3, H2O and CO profiles in order to measure the added value of CAIRT against this instrument.

This study reveals that CAIRT (1) O3 profiles are able to constrain BASCOE down to 7 km of altitude, a few km lower (thus better) than MLS; (2) H2O profiles are able to constrain BASCOE down to the tropopause region, with a slightly better performance than MLS at high latitudes; and (3) CO profiles are able to constrain BASCOE in the UTLS region while MLS providing a much better constraint above 10 km.

Topic:

Upcoming Earth observation limb and occultation instruments

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Aerosol transport of a stratospheric streamer towards high latitudes in spring 2017

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The stratospheric polar vortex varies in strength and spatial characteristics during winter in the Northern Hemisphere. If the polar vortex is shifted towards the equator as a result of breaking planetary waves, air masses from the subtropics can be transported towards the pole in so-called tropical-subtropical streamers. These large-scale structures are areas of low potential vorticity and high pressure, containing dry air with a high ozone mixing ratio. The presence of these streamers can also be seen using satellite instruments such as OMPS-LP, which can detect an increase in the aerosol extinction coefficient in the middle stratosphere at the edge of the vortex. Following a displacement and deformation of the vortex, aerosol transport to high latitudes occurred in the Northern Hemisphere in spring 2017. The additional stratospheric aerosol of around 0.6 kT at an altitude of 25–35 km remained at middle and high latitudes for just under a month this year.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

34

Ozone trends in the stratosphere derived using merged Ozone_CCI datasets

Author: Viktoria Sofieva[1]

Co-authors: Monika Szelag [1]; Carlo Arosio [2]; Alexey Rozanov [2]; Doug Degenstein [3]; Adam Bourassa [3]; Daniel Zawada [3]; Michael Kiefer ; Alexandra Laeng [4]; Gabriele Stiller [5]; Kaley Walker [6]; Patrick Sheese [6]; Robert Damadeo [7]; Daan Hubert [8]

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This presentation is dedicated to evaluation of global and regional trends in ozone profiles using the updated merged datasets developed in the framework of ESA Climate Change Initiative for ozone project.
For trend analyses, two long-term merged datasets of ozone profiles have been created. One is the SAGE-CCI-OMPS+ climate data record of monthly zonal mean ozone profiles. This dataset covers the stratosphere and combines measurements by nine limb and occultation satellite instruments – SAGE II, OSIRIS, MIPAS, SCIAMACHY, GOMOS, ACE-FTS, OMPS-LP, POAM III, and SAGE III/ISS, from 1984 to present. Another dataset is the MErged GRIdded Dataset of Ozone Profiles (MEGRIDOP) with a resolved longitudinal structure, which covers the period from late 2001 to the present. MEGRIDOP is derived from data by OSIRIS, MIPAS, SCIAMACHY, GOMOS, MLS, and OMPS-LP; it contains monthly mean ozone profiles in the altitude range from 10 to 50 km in bins of 10° latitude x 20° longitude. SAGE-CCI-OMPS+ and MEGRIDOP have been actively used in various assessments of ozone trends, including their regional and seasonal dependence.
In the presentation, we will show the obtained results of analyses of stratospheric ozone variability,

including updated analyses of stratospheric ozone trends. In addition, we will discuss new developments: a new merged daily gap-free 1° x 1° dataset of stratospheric ozone profiles (HIRES-LIMB) and a tropopause-referenced dataset of ozone profiles.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

35

Stratospheric Aerosol Perturbations Caused by the 2024 Ruang Eruption

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On April 18, 2024, the Ruang volcano in North Sulawesi, Indonesia, erupted, sending volcanic materials up to 20 km altitude and drifting west of the Island. On April 29, Ruang erupted again, this time reaching an altitude of 21 km and following a similar trajectory to the earlier eruption. OMPS-NM UV measurements indicated that the volcanic clouds were primarily composed of sulfur dioxide (SO2), with estimated amounts of 0.25 and 0.16 Tg for the two eruptions, respectively.
This study utilized space-based observations of SAGE III onboard ISS, OMPS LP on board the Suomi NPP and NOAA-21 satellites to monitor the evolution and transport of the Ruang volcanic plume as it circulates the globe. Initially, the two volcanic plumes remained separate for the first ten days. Over time, the volcanic aerosol began to mix, making it increasingly challenging to distinguish between them.
For the first two months following the eruption, the primary aerosol layer was confined within the tropical pipe. Subsequently, there was a gradual poleward and downward transport to the Southern Hemisphere (SH), which intensified during the SH winter.

Topic:

Aerosols and clouds

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The ALI Aerosol Retrieval Algorithm with Application to OMPS-LP and OSIRIS

Author: Daniel Zawada[1]

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The Aerosol Limb Imager (ALI) instrument is currently being developed as part of the HAWC mission, which will include three Canadian instrument contributions to the NASA Atmosphere Observing System (AOS) mission. ALI will measure limb scattered radiances in the VIS-NIR spectral region at high vertical resolution and will include polarization information to better determine aerosol particle size and discriminate high-altitude clouds. An aerosol retrieval algorithm is currently being developed that will simultaneously retrieve aerosol extinction as well as particle size information. To test the algorithm, a version of the retrieval with the particle size retrieval disabled is being consistently applied to measurements from the Optical Spectrograph and InfraRed Imager System (OSIRIS) and the Ozone Mapping and Profiler Suite - Limb Profiler (OMPS-LP). The full algorithm (including particle size) is also being applied to both instruments to determine if particle size information can be obtained from these instruments in certain viewing conditions. In this presentation we describe the current state of the ALI aerosol retrieval algorithm and show the results obtained from applications to OSIRIS and OMPS-LP.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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A machine learning approach to retrieving stratospheric water vapor from OMPS LP measurements

Author: Michael Himes[1]

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Stratospheric water vapor (SWV) plays an important role in atmospheric chemistry and dynamics. The Aura Microwave Limb Sounder (MLS) instrument has provided a daily near-global record of SWV for around two decades. After the Aura mission ends later this year, SWV measurements will be mostly limited to occultation measurements by the Stratospheric Aerosol and Gas Experiment III (SAGE III) and Atmospheric Chemistry Experiment (ACE) instruments, which have significantly reduced geographical coverage. While not designed to measure SWV, the Ozone Mapping and Profile Suite Limb Profiler (OMPS LP) shows weak sensitivity to SWV, potentially enabling it to continue the MLS SWV record until a successor instrument is launched. We present our neural network approach to retrieving SWV from OMPS LP measurements and compare with MLS, SAGE, and ACE. We also discuss the challenges and limitations of our methodology.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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The SASKTRAN Radiative Transfer Framework Version 2

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For over twenty years the SASKTRAN radiative transfer model has been used in the inversion of limb radiance observations from the OSIRIS instrument. SASKTRAN has since seen numerous upgrades that make it ideal for use in a variety of measurement scenarios across the UV, visible, and infrared spectral regimes. The next generation of the model, SASKTRAN2, is now available and has been completely rewritten with significant performance improvements and a simple yet powerful user interface. Here, we describe the main features of SASKTRAN2, such as the ability to model radiances in spherical or plane-parallel model geometries, and the inclusion of analytic weighting function calculations. We highlight the easy installation process and provide an overview of the user interface. Additionally, we discuss recent developments and applications of SASKTRAN2, including an investigation into the modelling of upwelling radiative fluxes at the top of the atmosphere.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Long-term changes in mean age of air and stratospheric chlorine

Author: Susann Tegtmeier[None]

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Stratospheric trace gases like HCl and N2O show a hemispheric asymmetry, with trends over the last two decades having opposing signs in the Northern Hemisphere (NH) and Southern Hemisphere (SH). Some of this difference is due to hemispherically asymmetric changes in the rate of transport by the Brewer–Dobson circulation (BDC). Mean age of air (AoA) is a common proxy for the transport rate by the BDC in models; however, it cannot be directly measured. Long term changes in transport, and thus AoA, also complicate the analysis of trends in stratospheric chlorine when compared to changes in surface emissions of ozone depleting substances (ODSs) regulated by the Montreal Protocol.

Here we use N2O as a proxy for the stratospheric circulation to calculate long-term trends in trace gases and AoA. First, N2O observations from ACE-FTS are combined with results from CLaMS simulations driven by 4 different reanalyses to derive AoA anomalies. We find that, irrespective of which reanalysis is used, air in the NH aged by up to 0.3 years per decade relative to the SH over 2004–2017. The maximum hemispheric difference in aging occurs in the middle stratosphere, near 30 hPa.

We also show that the aging rate in the NH becomes smaller when the analysis is extended to 2021. Furthermore, we use the N2O proxy to analyze how much of decrease in stratospheric chlorine is related to transport variations and how much is driven by the reduction in chlorinated long-lived ODSs. We show that the observed decrease in stratospheric chlorine is 25%–30% smaller than expected based on trends of long-lived ODSs alone. This can be explained by the increase in chlorinated very short-lived substances, which offsets the long-term reduction of stratospheric chlorine by up to 30%.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

40

Understanding ozone-sonde trends and variability in UTLS: Using dynamical coordinates for consistent analysis of UTLS composition

Author: Irina Petropavlovskikh[1]

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One of the goals for the SPARC OCTAV-UTLS (Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere) activity is to quantify long-term changes in the UTLS ozone variability and identify the driving processes. The determination of atmospheric composition trends in the UTLS remains highly uncertain due to large atmospheric variability driven by chemistry, mixing, and dynamics (reflected in the tropopause and jet variations). Analyzing data in conventional coordinates (e.g. on pressure and latitude grids) does not account for the local and regional variability near the jets and tropopause that serve as the natural barriers for atmospheric composition distributions. Dynamical coordinates, which account for the variability of transport barriers, can be used to separate observed data into different atmospheric regimes before analyzing them for trends. This approach reduces the impact of short- and long-term atmospheric variability represented in the NOAA ozonesonde records. This presentation will assess reduction in trend uncertainty in ozonesonde records after an appropriate meteorological coordinate system is used for all data. The ozonesonde trends in traditional and dynamical coordinates will be compared. To test the advantage of using dynamical coordinates for the regionally combined records, we will compare trends derived from the NOAA ozonesondes from the Trinidad Head and the Tropospheric Ozone Lidar (TMTOL) from JPL's Table Mountain Facility in California.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Stratospheric composition changes due to extreme events: insights from satellite limb and nadir observations

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Extreme events such as explosive volcanic eruptions and major wildfire outbreaks can produce persistent perturbations of stratospheric aerosol and gaseous composition. Volcanic eruptions, injecting ash and sulphuric aerosol precursors into the stratosphere, have historically been recognized as the primary source of large-scale perturbations of stratospheric aerosol load. An emerging source of stratospheric aerosols is wildfires and associated pyroCbs, which are increasing in frequency and intensity in a warming climate and have proven capable of altering stratospheric composition, dynamics, and ozone chemistry on annual timescales. In the last three decades, the most significant events in terms of their stratospheric impact are the Australian New Year (ANY) "Black Summer" wildfire outbreak in 2019/20 that produced the largest-ever Smoke-Charged Vortex (SCV) rising up to 35 km and the eruption of Hunga submarine volcano in January 2022 that led to an unprecedented hydration of the global stratosphere. Each of them provided unique natural testbeds for studies of climate sensitivity to strong change in stratospheric gaseous and particulate composition.

Here we use a combination of limb scattering/sensing (OSIRIS, OMPS-LP, MLS), solar/stellar occultation (SAGE II/III, ACE-FTS, GOMOS) and active nadir sounding (CALIOP, Aeolus, EarthCARE) observations to review the character and the magnitude of stratospheric perturbations induced by the most significant events in the XXI century.

Topic:

Aerosols and clouds

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OSIRIS on Odin: The End of an Era

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Co-authors: Daniel Zawada [1]; Doug Degenstein [1]; E.J. (Ted) Llewellyn [1]; Kimberlee Dube [1]; Nick Lloyd [1]; Taran Warnock [1]

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OSIRIS is a Canadian spectrometer that was launched on the Swedish Odin satellite in 2001 for a two-year mission to explore the composition and coupling of the stratosphere and mesosphere. OSIRIS was designed to measure the spectra of scattered sunlight from the ultra-violet to the near-infrared to derive vertical profiles of trace gases and aerosols, a largely untested technique at the time. Almost 25 years later, the mission is nearing its end; at the time of writing, orbital projections show rapid

descent is imminent. This talk will highlight several key scientific results of the OSIRIS mission, and discuss challenges in the production of the official data products over the past few years due to operational constraints toward of the end of the satellite lifetime.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Aerosol extinction coefficients retrieved from OMPS limb scattering observations: Tackling the differences between three data products (NASA, USASK, UB)

Author: Christine Pohl[1]

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Due to its long time series and dense spatial coverage, the aerosol extinction coefficient (Ext) obtained from OMPS limb scattering observations is a valuable data record for observing the temporal aerosol evolution in the stratosphere after strong volcanic eruptions and wildfires. The OMPS limb scattering data set is a promising candidate for use in GLOSSAC and already used in CREST climate data record. Three OMPS data sets are currently available, retrieved by algorithms from NASA, the University of Saskatoon (USASK) and the University of Bremen (UB). Each algorithm is individual, the single algorithm specifications imply various advantages for the retrieved Ext. Accordingly, each retrieval algorithm provides good results but there are certain differences between the Ext products from NASA, USASK, and UB, especially in regions where retrievals are highly challenging: During strong aerosol perturbations following volcanic eruptions and wildfires, the upper troposphere-lower stratosphere (UTLS) region, and in the southern extratropics. The intercomparison of all three OMPS Ext products provides the potential to understand the causes for these differences. Independent data from SAGE III/ISS and balloon-borne observations are used as a reference in this study. Impacts of the assumption of a particle size distribution (PSD), the surface albedo, the single scattering angle, and the tangent height normalization on the retrieved OMPS Ext are studied. The strongest driver for the differences between the OMPS data sets is the PSD assumption. It can explain the different magnitudes of Ext in volcanic/wildfire plumes, different saisonalities, and even affects the impact of the surface albedo. Understanding the causes of the differences between the Ext products helps to correctly evaluate and analyze the comparison of the OMPS Ext with other data products. It also supports the improvement of the retrieval algorithms. If more accurate satellite data products can be made available, they will be of a great importance for use in GLOSSAC and CREST, the essential input data records for global climate simulations.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Arch effects and retrieval artifacts below the Hunga Tonga plume: Estimating the uncertainties in the OMPS aerosol extinction coefficient using CALIOP data

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Due to its high spatio-temporal sampling coverage, the aerosol extinction coefficient (Ext) obtained from OMPS Limb scattering observations is excellently suited for observing the temporal aerosol evolution in the stratosphere after strong volcanic eruptions and wildfires. The record of Ext has been recently improved by the University of Bremen (UB), successfully validated with SAGE III/ISS observations (Rozanov et al., 2024) and is currently beeing compared with other existing OMPS Ext products. The UB retrieval algorithm shows a good performance. Especially the vertical extent of the stratospheric aerosol plume is well represented by the UB OMPS Ext product. However, the Ext values below strong aerosol plumes can be subject to higher uncertainties due to the arch effect and retrieval instabilities. Both effects can occur regularly when strong aerosol plumes are observed in the limb-viewing geometry. While arch effects cause an increase in Ext, retrieval instabilities can cause both too high and much too low Ext values. We estimate these uncertainties by comparing Level 2 OMPS Ext and CALIOP data after the 2022 Hunga eruption.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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The impact of particle size on OSIRIS aerosol retrievals after the Hunga eruption

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Stratospheric aerosols play an important role in atmospheric processes through their cooling effect on the surface and their role in cloud formation. Though aerosols have been widely studied for decades, there still exists a large gap between measurements and models. More refined measurements of aerosol size, shape, concentration and composition are required to close this gap to improve climate modelling. Many instruments provide measurements of aerosol, such as the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument currently flying aboard the Swedish Odin satellite. Launched in 2001, OSIRIS measures vertical profiles of limb scattered sunlight. With its lifetime far exceeding its initial mission length of 2 years, OSIRIS has provided measurements over last 24 years. The Hunga Tonga eruption in 2022, one of the largest volcanic eruptions in recent history, injected large amounts of water and sulfur into the stratosphere. When compared to aerosol retrievals from other instruments such as SAGE III/ISS and OMPS-LP, there appears to be a strong low bias in the OSIRIS aerosol during and after the Hunga Tonga eruption. It is plausible that this low bias is due to the assumed particle size distribution used in the retrieval process- the v7 retrievals use the same particle size distribution across all years of data, but this is not representative of the distribution after the Hunga Tonga eruption. A new retrieval approach will be presented, using the OSIRIS measurements in conjunction with the SAGE particle size distributions, which are used to constrain the particle size in the retrieval forward model. This approach shows promising results, with OSIRIS retrievals performed post-Hunga Tonga showing notable improvement in their agreement with the SAGE retrieved aerosol extinction.

Topic:

Aerosols and clouds

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Stratospheric Aerosol and Gas Experiment observations of stratospheric nitrogen dioxide

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An important component of the reactive nitrogen (NO_X) budget of the stratosphere is nitrogen dioxide (NO_2), which participates in key reactions influencing the life cycle of stratospheric ozone. For example, it can limit the availability of reactive chlorine by forming chlorine nitrate ($ClONO_2$), but is also directly involved in catalytic cycles destroying ozone. A major source of stratospheric NO_2 is photolysis and oxidation of nitrous oxide (N_2O), which has been shown to have a decreasing lifetime [1], but increased tropospheric emission. Using the solar occultation technique, the Stratospheric Aerosol and Gas Experiment (SAGE) family of instruments have measured profiles of NO_2 concentration 1984-2005 (II), 2002-2005 (III/M3M) and 2017-present (III/ISS). Here these data sets are examined for a range of time scales: diurnal, seasonal, biennial, etc.; as well as following episodic increases in stratospheric aerosol amount from volcanic eruptions or extreme wildfire smoke. Comparisons are made with contemporaneous measurements by the Atmospheric Chemistry Experiment –Fourier Transform Spectrometer (ACE-FTS) and the Optical Spectrograph and Infrared Imaging System (OSIRIS). With the possible extension of the III/ISS record through this decade it is important to understand the linkage of the newest data product version (v6) to other NO_2 datasets.

[1] Prather, M. J., Froidevaux, L., and Livesey, N. J.: Observed changes in stratospheric circulation: decreasing lifetime of N_2O, 2005–2021, Atmos. Chem. Phys., 23, 843–849, https://doi.org/10.5194/acp-23-843-2023, 2023.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Inter-comparison study of stratospheric particle size distribution parameters derived from SAGE III/ISS extinction measurements

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Two methods of deriving monomodal particle size distribution (PSD) values from SAGE III/ISS extinction measurements have recently been produced. Wrana et al. (2021) using SAGE III/ISS measurements at 449, 756, and 1544 nm construct a lookup table of extinction ratios to retrieve monomodal lognormal PSD parameter values. Knepp et al. (2024) likewise uses seven of the SAGE III/ISS aerosol channels to construct lookup tables based on extinction ratios to derive monomodal lognormal PSD parameter values. Both methods are attempting to constrain the aerosol PSDs that underlie SAGE III/ISS measurements.

We present here a comparison of those two methods among the many different aerosol loading events (Hunga-Tonga, australian wildfires, raikoke, etc.), the low aerosol "background" periods, and at the various latitudes and altitudes. Shown, as well, are the two methods performance against NOAA POPS derived PSD values.

Topic:

Aerosols and clouds

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ALTIUS Ozone Retrieval Algorithm in Bright Limb Mode Validated using OMPS LP Observations

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ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere) is an atmospheric limb mission being implemented in ESA's Earth Watch program and planned for launch in 2027.

The instrument consists of three imagers: UV (250-355 nm), VIS (440-675 nm) and NIR (600-1040 nm) channels. Each channel is able to take a snapshot of the scene independently of the other two channels, at a desired wavelength and with the requested acquisition time. The agility of ALTIUS allows for series of high vertical resolution observations at wavelengths carefully chosen to retrieve the vertical profiles of species of interest.

ALTIUS will perform measurements in different geometries to maximize global coverage: observing limb-scattered solar light in the dayside, solar occultations at the terminator, and stellar, lunar, and planetary occultations in the nightside. The primary objective of the mission is to measure high-resolution stratospheric ozone concentration profiles.

This work concerns the bright limb mode and the validation of the ALTIUS L2P algorithm using the Ozone Mapping and Profiler Suite Limb Profiler (OMPS LP) L1 data. The OMPS LP instrument measures solar radiation scattered from the atmospheric limb in ultraviolet and visible spectral ranges between the surface and 80 km and these data were used to retrieved ozone profiles from cloud top up to 55 km.

We performed end-to-end simulations to examine the robustness of the L2P limb-scatter algorithm using L1 OMPS LP data. The data were re-formatted to feed the simulator of the ALTIUS mission, enforcing the ALTIUS signal characteristics (and flaws) in the simulations. We compare our retrieved ozone profiles with the ones from the OMPS algorithm and we discuss the causes of the potential disagreements and biases in the results.

Topic:

Upcoming Earth observation limb and occultation instruments

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Issues with the retrieval of particle size information of noctilucent clouds from optical remote sensing measurements

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Noctilucent clouds (NLCs) are optically thin ice clouds occurring near the polar mesopause in the summer hemisphere. Our understanding of the particle size of NLCs is to a large extent based on optical measurements in different observation geometries and optical NLC particle size retrievals are always based on a priori assumptions on the shape of the particle size distribution. The actual shape of the particle size distribution is generally not well known and can be assumed to be highly variable. In addition, the scattering cross section of NLC particles depends strongly on particle size. This leads to effects that have until now not been considered properly in the literature, i.e. if the assumed shape of the particle size distribution differs from the actual one, NLC size retrievals based on different measurement techniques will be associated with different biases. These differences can be quite substantial, for the retrieved particle number density in particular. In this study we carry out NLC particle size retrievals based on simplified synthetic forward simulations for the following observation techniques: satellite occultation, satellite limb-scatter, ground-based lidar and satellite nadir measurements. For the forward simulations we assume a bi-modal particle size distribution, while for the size retrieval a mono-modal distribution is assumed - which is typically the case in the literature. We assume both normal and log-normal particle size distributions, but the main results of this study are independent of the specific assumption on the shape of particle size distribution. We find that even for small deviations from the assumed shape of the particle size distribution, relatively large differences in retrieved size estimates occur between the different observation geometries considered. The retrieved median radii can differ by up to a factor of 2, while retrieved particle number densities can differ by more than a factor of 10 between the different observation geometries. These results need to be considered when comparing NLC size retrievals from different optical techniques.

Topic:

Aerosols and clouds

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Did the 2022 Hunga eruption impact the noctilucent cloud season in 2023/24 and 2024?

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In January 2022, the Hunga Tonga - Hunga Ha'apai volcano emitted approximately 150 Tg H2O into the middle atmosphere. This water vapour reached the upper polar mesosphere in the Southern Hemisphere in the beginning of 2024 and increased the H2O mixing ratio in January by about 1 ppmv between 70°S - 80°S up to an altitude of 83 km. However, no clear perturbations were found in the noctilucent cloud occurrence frequency, except for a slight increase from mid-January to February. Half a year later, the Hunga water vapour anomaly reached the polar summer mesopause region in the Northern Hemisphere, but did not result in an extraordinary noctilucent cloud season 2024. This might be due to an anomalous polar mesosphere warming in the second half of the 2024 season, which could have hindered ice particle formation. To summerize, this study indicates that the volcanic water vapour needed two years to reach the summer polar mesopause region. This resembles the 1883 Krakatoa eruption that was possibly linked to the first sightings of noctilucent clouds two years after its eruption.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Ground-based assessment of (merged) limb ozone profile data records used by ESA's Climate Change Initiative

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Since the 1980s, limb and occultation sensors have monitored stratospheric ozone changes, requiring long-term stability better than ~2% per decade for reliable trend detection. In support of APARC/LOTUS and the 2026 WMO/UNEP ozone assessment, we evaluated bias, dispersion and stability of 17 ozone profile records against ground-based observations by ozonesonde, lidar and microwave radiometer networks (NDACC, GAW, SHADOZ). This work contributed to the quality assessment of the data records used and generated by ESA's ozone CCI project and ECMWF's operational climate change service C3S.

This presentation is an update and extension of earlier analyses of Level-2 ozone profile data (Hubert et al., 2016 and later) and includes a new sensor (OMPS-LP on NOAA-21, UBR v1.1), an additional Level-2 retrieval algorithm (UBR v4.1 for OMPS-LP/SNPP), and updated data versions (e.g., OSIRIS v7.3, Aura MLS v5.0, OMPS-LP/SNPP USASK v1.3.0, SAGE III/ISS v5.3). Another recent addition is the analysis of LIMB-HIRES v1 (FMI), a new gap-free gridded ozone profile data product by the ozone CCI team. Owing to its high sampling resolution (daily, 1° latitude by 1° longitude) and its gap-free nature it co-locates with every single ground-based observation. This allows us to take the best possible advantage of the reference data to constrain e.g. the stability of LIMB-HIRES. At the same time, such an ideal co-location sample allowed us to evaluate the lower limit of drift precision that can be achieved with ground-based networks. We conclude by reflecting on the validation needs and challenges for the planned and proposed future limb missions.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Comparison of mean age of air in ERA5, ERA-I, MERRA2 and JRA-3Q using the BASCOE chemistry transport model and observations from MIPAS, ACE-FTS and CAIRT

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We present an intercomparison of the mean age of air (AoA) derived from three recent reanalyses: the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) and its predecessor (ERA-Interim), the National Aeronautics and Space Administration's Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2), and the Japan Meteorological Agency's 3-Quarter Century Reanalysis (JRA-3Q). AoA is computed using an idealized clock tracer within the Belgian Assimilation System for Chemical Observations (BASCOE) chemistry transport model.
We examine the simulated AoA time series with a particular focus on differences between the reanalyses. Preliminary results indicate that MERRA2 and JRA-3Q show a decreasing AoA trend between 1990 and 2000, after which all three reanalyses exhibit a relatively stable AoA with no significant trends. ERA5 consistently provides the youngest AoA, suggesting a faster stratospheric transport. These findings are compared with the results of Chabrillat et al. (2018), which analyzed older reanalysis versions (ERA-Interim and JRA-55) using a previous version of the BASCOE model, and with Ploeger et al. (2019, 2021), which presented AoA from the CLaMS model driven by ERA-Interim, MERRA2, JRA-55 and ERA5. We also compare with existing limb retrievals of age of air from MIPAS and ACE-FTS, as well as mock retrievals from the future CAIRT mission, which is currently in phase A of development.
This study provides insights into the evolution of AoA estimates in successive reanalysis products and highlights key differences in stratospheric transport representations.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Assessment of trend uncertainties for long-term limb profile and total ozone datasets

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With the enactment of the Montreal Protocol in 1987 and its Amendments phasing out ozone-depleting substances (ODS), a gradual recovery of the ozone layer has been observed, particularly in the upper stratosphere. Apart from ODS, ozone is also significantly influenced by atmospheric dynamics and changes in greenhouse gases. For attribution of long-term ozone changes and variability and their uncertainties, multiple linear regression (MLR) is applied to merged satellite datasets that span a period of more than 40 years until and including the year 2024.

We assess ozone trends from four long-term ozone profile datasets (GOZCARDS, SAGE-CCI-OMPS, SAGE-SCIA-OMPS and SWOOSH) and six total ozone datasets (MSR2, GSG, GTO-ECV, SBUV NOAA, SBUV NASA and WOUDC) using the MLR with appropriate proxies accounting for dynamical variability and long-term changes in ozone. The combined assessment of total and stratospheric column trends allows us to asses the question if tropospheric ozone trend play a role in zonal mean trends of total ozone trends. In 2024 total ozone column amounts in the northern hemisphere were reaching levels, that were among the highest since 1960. The ability of the MLR to account for that year's extreme values is a good test for the appropriate choice of proxies in the regression.

Drifts between timeseries'from different datasets contribute to uncertainties in long-term trends. The spread of drifts are on the order of 0.75%/decade among the ozone profile datasets and about 0.5%/decade among the total ozone datasets before and after the middle 1990s, when stratospheric halogens from ODS reached the peak.

The merged ozone profile datasets were analysed using common ozone units (number density) and altitude (geometric altitude). Units conversion were applied to SWOOSH and GOZCARDS and it can add to trend uncertainties when the conversion is applied to monthly mean data (like in the merged datasets) rather than individual daily profiles. In most cases no additional uncertainties in

the trends from the conversion was found but in few cases uncertainties of up to 1%/decade were found.

We present updated ozone trends until end of 2024 derived from both ozone profile and total ozone merged datasets and discuss contributions to trend uncertainties.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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TUNER compliant error reporting for IMK/IAA MIPAS Envisat V8 retrieval

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We present the implementation and results of the error estimation for temperature and trace gas mixing ratios retrieved with the IMK/IAA MIPAS L2 processor in the framework of the TUNER (Towards UNified Error Reporting) project. Several error sources are taken into account: spectral noise, propagated temperature and pointing noise, uncertainties of spectrally interfering species' abundances, instrument line shape errors, and spectroscopic data uncertainties (line intensities, broadening coefficients). Both the direct impact of volatile and persistent gain calibration uncertainties, offset calibration, and spectral calibration uncertainties, as well as their impact through propagated calibration-related temperature and pointing uncertainties, are considered. If a retrieval is done with non-local thermodynamic equilibrium modelling, the related kinetic constants and mixing ratios of species involved in the modelling of populations of excitational states also contribute to the error budget. Generalized Gaussian error propagation and sensitivity analyses are used to estimate the error components. Error correlations are taken into account. Some error sources contribute to both, the random and the systematic error components. The sequential nature of the MIPAS retrievals gives rise to entangled errors. These are caused by error sources that affect the uncertainty in the final data product via multiple pathways, i.e., on the one hand, directly, and, on the other hand, via errors caused in a preceding retrieval step. These errors tend to partly compensate for each other. Estimated uncertainties are calculated for 34 typical atmospheric conditions. Error budgets for T, H2O, O3, HNO3Ch4, N2O, ClONO2, CFC-11, CFC-12, HCFC-22, ClO, HNO4, C2H(2,4,6), N2O5, COCl2, and NO will be presented and discussed.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Nearly two solar cycles of ACE-FTS temperatures in the stratosphere to lower thermosphere

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In August of this year, the ACE-FTS (Atmospheric Chemistry Experiment –Fourier Transform Spectrometer) instrument will celebrate its 2^{nd} "helioversary" of being in orbit. With routine measurements of temperature profiles within 15-125 km, spanning from February 2004 to today, ACE-FTS data is well-suited to measure atmospheric cooling trends and temperature responses to solar input. This study will compare ACE-FTS temperatures to correlative data from four other atmospheric limb sounders—MLS on Aura, OSIRIS and SMR on Odin, and SABER on TIMED. The comparison results will be used to assess global, regional, and seasonal biases and drifts. These data will also be used to derive temperature trends throughout the stratosphere to lower thermosphere over the past two decades, as well as the atmospheric temperature response to the 11-year solar cycle.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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On the relationship between synoptic events and ozone changes in the Arctic using observations from satellite instruments and the MOSAiC ship campaign

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Although cyclones and anticyclones, referred to as synoptic events, strongly influence weather predictability, they are not well characterized or predicted in the Arctic region because of the sparse coverage of relevant meteorological measurements. As synoptic events at high latitudes influence the atmospheric dynamics in the region of the lower stratosphere and upper troposphere (UTLS) and the lower stratospheric ozone via tropopause changes, a potential approach to characterize these

events is the use of space-borne measurements of ozone vertical distributions and total columns. The final goal is to assess whether the satellite ozone data can be used to obtain information about synoptic events and provide herewith an additional value in the assimilation by numerical weather prediction models.

In this talk, we report our investigations of the link between synoptic events and changes in UTLS ozone by using the unique combination of ozonesonde measurements during the MOSAiC ship expedition, OMPS-LP ozone profiles, and ERA-5 data. Ozone contour levels follow changes in the tropopause height. The negative correlation between ERA5 tropopause height and ozone total columns or sub columns, retrieved from OMPS-LP observations and MOSAiC ozonesonde data can be used as an indicator for cyclonic activity. An approach to automatically identify and track cyclones with OMPS-LP ozone observations, using the lowering of the 250 ppb ozone contour level below 9 km, is proposed and discussed. The correlation between the magnitude of (anti)cyclones and the strength of the ozone change was validated using OMPS-LP data and a historical analysis of this relationship was performed using ERA5 ozone data.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Version 8 IMK/IAA MIPAS measurements of ClO

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We present global distributions of chlorine monoxide (ClO) retrieved from infrared limb emission spectra measured with the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), covering the time period 2002–2012. The retrieval was performed using spectral lines in the fundamental band of ClO around 844 cm-1. The vertical resolution of V8 ClO is 4 km at 18–20 km and 7.5–9.5 km at 40 km altitude. The considerable improvement at 40 km with respect to the previous V5 data version was achieved by extension of the spectral range for retrieval of upper stratospheric ClO. Retrieval errors are dominated by measurement noise and increase from 0.4 ppbv at 20 km to 0.8 ppbv at 50 km altitude. Thus, profile averaging has to be performed for analysis of the upper stratospheric ClO maximum. However, strongly enhanced lower stratospheric ClO amounts of more than 1.5 ppbv during polar winter can well be detected in single measurements. Along with the standard data product, an alternative coarse grid representation is provided, which can be used without consideration of averaging kernels. Due to improved modelling of the atmospheric continuum and of the instrumental offset, the high bias of upper stratospheric ClO, which had affected measurements between 2005 and 2012 in the previous data version, has disappeared. A comparison with ClO measurements of the Microwave Limb Sounder on the Aura satellite shows a fairly good agreement for the lower stratospheric enhancements observed in polar winter. With the aid of simulations by the ECHAM/Messy Atmospheric Chemistry model, deviations between the upper stratospheric maxima, especially occurring at southern mid- and high latitudes during winter, can be explained by the different local times of the measurements.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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The MATS mission: Locking back and looking forward

Authors: Björn Linder[1]; Donal Murtagh[2]; Jacek Stegman[1]; Jonas Hedin[1]; Julia Hetmanek[1]; Jörg Gumbel[1]; Linda Megner[1]; Lukas Krasauskas[1]; Nickolay Ivchenko[3]; Ole Martin Christensen[1]

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The MATS (Mesospheric Airglow/Aerosol Tomography and Spectroscopy) mission is a Swedish satellite initiative designed to investigate atmospheric gravity waves by observing structures in the O2 atmospheric band airglow and noctilucent clouds around the Mesopause. The mission employs a high-resolution telescope to capture continuous images of the atmospheric limb, allowing for tomographic analysis to reconstruct three-dimensional wave structures and provide a global map of gravity wave properties. By splitting light into six separate wavelength channels, the mission aims to extract temperature and microphysical attributes of noctilucent clouds.
In this presentation, we look back at lessons learnt from the entire MATS mission, highlighting how certain complications could have been avoided. We will briefly explain the new in-orbit calibration technique that was created due to significant uncertainties in the laboratory calibrations. Finally, we will show the first scientific results and introduce the newly released dataset. With this, we are looking forward to discussions and research collaborations.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Sub-orbital demonstration of coincident aerosol and water vapour measurements with the Aerosol Limb Imager and the Spatial Heterodyne Observations of Water instrument

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The High-altitude Aerosols Water Vapour and Clouds (HAWC) satellite mission is Canada's contribution to NASA's upcoming Atmosphere Observing System (AOS). HAWC will provide observations that will focus on aerosols, clouds, and water vapor in the Upper Troposphere and Lower Stratosphere (UTLS), with coverage extending into the middle stratosphere and lower altitudes at the poles. The mission comprises three instruments: the Aerosol Limb Imager (ALI), the Spatial Heterodyne Observations of Water (SHOW) instrument, and the Thin Ice Cloud in Far InfraRed Emissions (TICFIRE) instrument. Advancements in HAWC science and algorithm development are progressing through multiple initiatives, including sub-orbital testing of the instruments aboard NASA's ER-2 aircraft. The first of two planned measurement campaigns took place last fall and involved two extended flights carrying the ALI and SHOW instruments. These flights yielded extensive high-resolution, coincident observations of aerosol properties and water vapor. The campaign also featured coordinated underpasses of MLS, OMPS, JPSS-2, and SAGE, along with an EPCAPE overpass and co-located in-situ measurements using frost-point hygrometers and radiosondes launched from JPL's Table Mountain Observatory. This paper presents preliminary findings from the campaign, including insights into algorithm development, synergies between instruments, overall instrument performance, and key scientific objectives. Additionally, plans for the second measurement campaign, which will incorporate the TICFIRE instrument, will be outlined.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

60

Odin and Noctilucent Clouds –Thoughts about the Limb Analysis of Inhomogeneous Layers

Author: Jörg Gumbel[1]

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Odin's database of noctilucent clouds (NLCs) is approaching 25 years. NLCs are readily identified in the limb profiles of scattered sunlight measured by OSIRIS onboard Odin. However, quantitative data products are needed in order to relate NLC observations to geophysical processes or to other measurements. Unfortunately, the notoriously inhomogeneous nature of NLCs prevents an analysis of limb data in terms of vertical profiles and local cloud properties. This presentation promotes a limb analysis in terms of vertically integrated NLC properties that are representative for a defined cloud volume. This concerns e.g. cloud albedo or ice water content. Analysis ideas are tested using simulated clouds and comparisons to tomographic data.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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3-D tomography for the MATS satellite mission

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MATS (Mesospheric airglow/Aerosol Tomography and Spectroscopy) is a Swedish satellite launched in November 2022. It is a limb imager that observes O_2 A-band airglow (four different spectral channels) in near-infrared and UV light scattered from noctilucent clouds (two channels) in the 70 km to 110 km altitude range. The airglow observations can be used to obtain a 3-D tomographic temperature data product with high vertical resolution, enabling the identification and characterisation of individual gravity waves and their full 3-D spatial structure. Similarly, the UV data set can be used for 3-D reconstruction of the noctilucent clouds.

In this talk, the 3-D tomographic retrieval algorithm will be introduced and some of the first 3-D temperature data will be presented. The steps in Level 1 processing of MATS images that are particularly relevant to tomography will also be discussed.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Using ACE-FTS to assess mixing barrier strength in nudged chemistry-climate models

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Methane is a potent greenhouse gas with an increasing trend in the atmosphere due to rising emissions. Aside from its climate impacts, it is important to monitor methane because of its long lifetime of about ten years, which makes it a useful tracer of atmospheric transport. Modelled methane fields can therefore be compared with observations to evaluate transport in atmospheric models. Several methods have been proposed for assessing the strength of the subtropical mixing barrier and the polar vortex edge using long-lived tracers, but most require high data density. In addition, it is difficult to separate the effects of mixing from those of chemical production and destruction or from other aspects of atmospheric transport. In this study, we explore various methods of using methane probability density functions and time series to quantify the strength of the subtropical mixing barrier and the polar vortex edge through comparisons with relatively sparse satellite measurements from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS). ACE-FTS is a solar occultation instrument with near-global coverage and 3–4 km vertical resolution, spanning the upper troposphere to the lower mesosphere. The focus of the comparisons is on a specified dynamics run of the Canadian Middle Atmosphere Model (CMAM39-SD) for the 2004-2018 period. In general, we find that the modelled subtropical mixing barrier is too weak in the lower stratosphere and too strong in the upper stratosphere. In contrast, CMAM39-SD reproduces methane variability near the polar vortex edge very well. To provide context, we also compare ACE-FTS with the air quality model GEM-MACH, the Earth system model MRI-ESM2, and the chemical transport model GEOS-Chem.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Ozone Profile Retrievals from Suomi NPP and NOAA-21 OMPS Limb Profilers: Operational Status and Improvements

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The Limb Profiler (LP) is a limb-scattering sensor that is part of the Ozone Mapping and Profiler Suite (OMPS). The first OMPS LP onboard the Suomi NPP satellite has been operational for over 13 years, since 2012, while the second LP onboard the NOAA-21 satellite began observations in February 2023. In this study, we provide updates on the operational status of both LPs and offer an overview of some algorithmic and operational changes. Measurements from both LPs have been processed using the same retrieval algorithm (version 2.6), which combines measurements from the UV and VIS regions of the spectrum to retrieve a single vertical ozone profile between 12.5 km (or cloud tops) and 57.5 km. We will discuss ongoing improvements aimed at enhancing ozone retrievals in the lower stratosphere, including updates to the new aerosol correction scheme.
The Suomi NPP satellite experienced several GPS anomalies in 2024, which affected the pointing of the LP instrument and resulted in ozone anomalies. As a result, we have not released data from the Suomi NPP OMPS during this period of GPS anomalies. We will also discuss changes in the retrieved ozone, related to variations in ancillary meteorological data, such as pressure and temperature, which are necessary for the radiative transfer calculations.
Finally, we present comparisons between the two OMPS LPs and provide an assessment of the associated uncertainty budget.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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HAWC –The High-altitude Aerosol, Water vapour and Cloud Mission, a Canadian Contribution to the NASA Atmosphere Observing System (AOS)

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The HAWC Mission is a Canadian contribution to the NASA AOS Mission designed to answer a combination of question posed within the recent decadal survey. Two main survey topics, Aerosols and Clouds, Convection and Precipitation, were originally merged into an American concept known as A-CCP. In the early days of A-CCP, Canada expressed interest in participating with a suite of national led instruments and now that A-CCP has morphed into AOS, a fully international concept, Canada is firmly onboard with sufficient national funding to build TICFIRE, a nadir looking thermal imager designed to measure thin ice cloud properties and a standalone satellite with two instruments, ALI and SHOW, limb looking instrument designed to measure aerosol properties and water vapour respectively. TICFIRE will fly in the same orbital plane, but behind the Canadian HAWCsat, and will look down while ALI and SHOW look backward from HAWCsat simultaneously sampling the same atmosphere as TICFIRE. This talk will detail the HAWC Mission that consists of TICFIRE and HAWCsat and highlight the work already done, and to be done, by the expanding group of Canadian and international scientists and engineers who will help make HAWC a reality and use the measurements to study our ever-evolving atmosphere. This talk will focus on the individual instruments and their associated data products and highlight the advancements that are possible when measurements from all three instruments, and the international instruments that are part of AOS, are used together in a synergistic fashion.

Topic:

Upcoming Earth observation limb and occultation instruments

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Potential Advantages of the synergy between Limb and Nadir Measurement

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Limb and nadir measurements offer complementary insights into atmospheric composition. Limb observations, characterized by high vertical resolution and broad vertical coverage, primarily focus on the upper troposphere and above. In contrast, nadir measurements, with higher horizontal resolution but limited vertical resolution, provide valuable data for the lower and middle troposphere.
Recent efforts have explored how the synergy between limb and nadir measurements can enhance our understanding of atmospheric composition, particularly in the troposphere and lower stratosphere. These studies are part of the preparatory work for the CAIRT mission, which, if selected as part of the ESA Earth Explorer Mission 11 program, will fly in formation with the MetOp-SG satellite, carrying several nadir instruments.
During the CAIRT Phase 0, the benefits of the synergy between CAIRT, IASI-NG and S5 was demonstrated, particularly for ozone and other trace gases. The combination of limb and nadir data results in reduced total error and improved spatial resolution, especially in the upper troposphere and lower stratosphere (UTLS) region. Synergy between the two measurement types also shows promise for cloud studies.

This paper will present results for data from the GLORIA instrument, the CAIRT demostrator, during the CAREVALAB campaign, which performed both limb and nadir observations in a configuration that resembles CAIRT measurements.

Topic:

Upcoming Earth observation limb and occultation instruments

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Synergy between atmospheric products with limb and nadir geometries: Comparison between MIPAS+IASI and MIPAS+GOME2 a posteriori fusion

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In this study, we delve into the synergy between level 2 (L2) products obtained from satellite measurements with different geometries, utilizing the Complete Data Fusion (CDF) method. Specifically, we compare the fusion of data from MIPAS with IASI and the fusion of MIPAS with GOME2. This comparison allows us to analyze several key themes, including the characteristics of the CDF method and the products it generates, the differences between the products obtained by keeping the limb sensor (MIPAS) constant and varying the nadir sensor (IASI/GOME2), and the benefits that such a study brings in terms of knowledge and quality control of the involved products.
The CDF method, based on the Optimal Estimation (OE) algorithm, integrates individual retrievals from different instruments, leveraging their complementary features to enhance the accuracy and completeness of the resulting atmospheric profiles. We examine the various challenges that arise when applying the same algorithm to data from instruments with different geometries, and the strategies used to compare initially disparate situations, with particular reference to the a priori constraints adopted in the retrieval of atmospheric products.
The comparison between MIPAS+IASI and MIPAS+GOME2 fusion highlights the peculiarities of the obtained products, showing how the combination of different measurement geometries can influence the quality and reliability of atmospheric data. This study provides valuable insights for improving data fusion techniques and optimizing retrieval processes, contributing to a better understanding and management of the quality of atmospheric products.
Furthermore, the study discusses the implications of using different nadir sensors in conjunction with a constant limb sensor, focusing on the specific advantages and limitations of each combination. By maintaining MIPAS as the limb sensor and alternating between IASI and GOME2 as nadir sensors, we can observe how each configuration impacts the retrieval accuracy and overall data quality. This approach allows us to identify the strengths and weaknesses of each fusion strategy, offering guidance for future applications and research in atmospheric data fusion.
Ultimately, the findings of this study underscore the importance of considering measurement geometry in the fusion of satellite data. The insights gained from comparing MIPAS+IASI and MIPAS+GOME2 fusion not only enhance our understanding of the CDF method but also pave the way for more effective and reliable atmospheric data products. These advancements hold significant potential for improving climate models, weather forecasting, and environmental monitoring, thereby supporting a wide range of scientific and practical applications.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Stratospheric impacts of the Hunga volcanic eruption: Overview and the importance of satellite measurements

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On January 15, the Hunga volcano in the south west Pacific erupted injecting material into the stratosphere to altitudes up to or higher than 30 km. Estimates are that it injected 0.4 Tg of sulfur dioxide into the stratosphere and 150 Tg of water vapour. The sulfur mass injected was much smaller than that from the 1991 Mt. Pinatubo eruption, but the water injection was unprecedented over the satellite era.

Achieving a solid understanding of processes and impacts of this massive eruption on the chemistry and dynamics of the stratosphere have required a multi-pronged approach, using in situ measurements, satellite measurements and global modeling. There had not previously been in situ measurements made in a volcanic plume immediately after the eruption. The location of the Maïdo climate observatory 8000 miles to the west of the eruption coupled with the prevailing winds allowed collection of fresh plume measurement by balloon instruments, enabling a further understanding of microphysical processes and chemical processes in the fresh plume. Geostationary cloud images allowed estimation of the height of the eruption, while measurements from the Microwave Limb Sounder, the Ozone Mapping and Profiling Suite and CALIOP gave a global picture of plume motion and allowed estimations of the amount of material injected. Constraining modelling efforts with those critical measurements allowed estimation of downstream climate impacts.

Current limb satellite instruments were critical to understanding both short- and longer-term impacts of the Hunga eruption. They were used both for estimating global impacts, as well as to direct timing for making in situ measurements. In this presentation I will give a brief overview of some of the wealth of information we have learned from both satellite and in situ measurements of the material injected into the stratosphere by the Hunga eruption.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Observability of the lower stratospheric perturbations caused by overshooting convections

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Deep convections overshooting the tropopause can strongly influence the lower stratosphere. Seeing such impacts with satellites however has been a challenge. We discuss what thermodynamic anomalies can be observed and what cannot with different observing techniques (nadir vs. limb), based on Observing System Simulation Experiments utilizing high-resolution atmospheric models.

Topic:

Upcoming Earth observation limb and occultation instruments

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Sensitivity of interannual and long-term changes in stratospheric ozone to predictor time series and trend model

Authors: Oindrila Nath[1]; Daan Hubert[1]

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Several 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. Another challenge is the proper statistical modelling of non-linear long-term ozone changes. In support of ongoing activities in APARC/LOTUS to improve the baseline time series analysis method, we present an investigation of whether and how different methodological approaches influence the regression results inferred from merged satellite ozone profile time series (SAGE-CCI-OMPS+, SWOOSH, and GOZCARDS). Predictors include the Quasi-biennial Oscillation (QBO), the 11-year Solar Cycle, El Niño Southern Oscillation (ENSO), and aerosols (AOD). We have used a pressure-latitude gridded lag matrix to try to infer the geographical structure of the ozone response to the delayed ENSO time-series. We also investigate how trend values and their uncertainty are affected by the lag.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Review of the stratospheric CAMS products evaluation.

Author: Marc Op de beeck[1]

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Since 2015, the Copernicus Atmospheric Monitoring Service (CAMS) provides analyses and forecasts as well as a reanalysis of the atmospheric composition globally. These products are provided by ECMWF and are evaluated every 3 months by the Evaluation and Quality Control (EQC) team using in-situ, ground based or satellite observations. Part of this effort is the evaluation of stratospheric composition using profiles from ozone sonde and satellite limb instrument, discussed in this contribution. Limb profiles are taken from ACE-FTS, Aura MLS (v5.0 while CAMS assimilate the NRT version) , SAGE-III/ISS, OMPS-LP (from Suomi-NPP and NOAA-21 satellites), MIPAS, GOMOS

and SCIAMACHY.
CAMS outputs are compared to the available observations and several statistical indicators are computed to assess the quality of the different CAMS products.We present a review of our comparison results concerning ozone (O3), methane (CH4), water vapor (H2O), nitrous and nitrogen oxides (N2O, NOx), trichlorofluoromethane (CFC-11) and aerosols extinction coefficients.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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The Novel Limb-imaging FTIR Sounder GLORIA-Lite

Author: Felix Friedl-Vallon[1]

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A new remote-sensing instrument, GLORIA-Lite, was developed by the Institute of Meteorology and Climate Research (IMK-ASF) at the Karlsruhe Institute of Technology (KIT), in collaboration with the ICE4 and ZEA2 institutes at Forschungszentrum Jülich(FZJ). It was launched within the TRANSAT2024 field campaign on board a large stratospheric balloon by a team of the Centre National d'Études Spatiales (CNES) from the European Space and Sounding Rocket Range (ESRANGE, Swedish Space Corporation), on June 22, 2024. The balloon ascended to an altitude of 40 km, traveling from Kiruna, northern Sweden, to Baffin Island, Canada, where it safely landed on June 26.
GLORIA-Lite is an advanced limb-imaging Fourier-Transform Infrared instrument, extending the decades-long legacy of its predecessors, GLORIA (airborne/balloon) and MIPAS (airborne/balloon). By leveraging state-of-the-art infrared detectors, customized electronics, and innovative manufacturing techniques, GLORIA-Lite achieves a significant reduction in size and weight compared to its predecessors. This miniaturization enables its deployment on transcontinental balloon flights, sharing a gondola with multiple other instruments. The alignment of the fully reflective optical system is performed during manufacturing, ensuring consistent performances over the wideband long wave spectral range of the infrared detector array. The quasi-monolithic design approach eases thermal constraints of instrument operation. The electronics controlling the instrument are developed towards further miniaturisation into a Multi-Processor System-on-Chip architecture, with the goal to process the data on the fly up to Level 1.
GLORIA-Lite is capable of analyzing infrared emissions of more than 20 different molecules and aerosols in the atmosphere. The instrument is designed to enhance our understanding of dynamic and chemical processes occurring from the middle troposphere deep into the stratosphere. In times of accelerating climate change, it is particularly important to study the impacts on the middle atmosphere and to monitor them through long-term measurement series. Additionally, GLORIA-Lite serves as a technology demonstrator for the CAIRT satellite project, a proposed mission developed by the European Space Agency (ESA). CAIRT aims to bring the advanced atmospheric monitoring capabilities to a global scale.
We will provide a detailed account of the instrument's technical development and characterization, along with the results obtained from retrieving geophysical parameters, such as trace-gas distributions, during its first flight.

Topic:

Upcoming Earth observation limb and occultation instruments

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Investigating possible contributions of IASI/IASI-NG for briding the upcoming gap of stratospheric water vapour limb-sounding observations

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Satellite instruments operating in limb-viewing geometry provide independent measurements of different parts of the atmosphere (e.g., stratospheric details without tropospheric interferences). Unfortunately, missions like MIPAS, ACE-FTS, or Aura/MLS have already ended or are expected to end several years before respective next-generation missions will be operative (e.g. the current ESA Earth Explorer 11 candidate CAIRT). The thermal nadir measurements of IASI/IASI-NG are guaranteed for 2006 –2040s and could bridge this gap from a temporal viewpoint; however, they represent the whole atmosphere (above the surface or dense clouds), which makes a detection of stratospheric details independently from tropospheric interferences difficult. Here we discuss to what extent IASI/IASI-NG measurements can be used to detect stratospheric water vapour (SWV) anomalies independently from tropospheric water vapour interferences, despite the aforementioned difficulties.

Firstly, we present the update of our MUSICA IASI retrieval processor, which we use for this study. We present a retrieval performance test that demonstrates the capability of IASI/IASI-NG for detecting SWV anomalies. The capability of detecting SWV anomalies with thermal nadir observations can be explained by the thermal contrast between the cool tropopause and the warm stratosphere. Secondly, we document that the anomalies seen in the IASI data following the Ha'apai volcanic eruption in 2022 is in line with the anomalies as observed in the datasets of the two limb-sounders Aura/MLS and ACE-FTS.

We conclude, that due to their long-term availability (from 2006 to the 2040s), the IASI/IASI-NG missions offer valuable possibilities for linking past/present and future limb-sounding SWV data products, thus contributing to reduce the scientific impact of the upcoming limb-sounding data gap.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Using HYSPLIT with SAGE III/ISS Aerosol Observations to Model the Hunga Tonga-Hunga Ha'apai Plume

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The January 2022 eruption of the Hunga Tonga-Hunga Ha'apai (HTHH) volcano injected unprecedented volumes of aerosols and water vapor into the stratosphere. The evolution of the plume dynamics and chemical processing of the injected constituents is a unique event and opportunity of which even with global monitoring instruments instantaneous observations of that evolution are still sparse. One such instrument, the Stratospheric Aerosol and Gas Experiment III (SAGE III) onboard the International Space Station (SAGE III/ISS), saw changes to the stratosphere caused by the eruption in the days following. SAGE III/ISS retrieves vertically resolved profiles of ozone, aerosol, water vapor, and nitrogen dioxide and observed distinct and highly enhanced aerosol layers relative to the preceding background conditions in the short window following the eruption. SAGE III/ISS offers 0.5 km vertically resolved profiles of aerosol extinction coefficient derived from direct measurement of atmospheric transmission with inherently high accuracy and precision from the high signal to noise ratio afforded by the solar occultation technique at the cost of spatial and temporal sampling. Repeat observations offer point samples of evolution that are temporally and spatially conjoined, but the highly valuable information contained therein can be joined with dynamic modeling and trajectory analysis offered by a tool such as The NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to produce more dense instantaneous analyses of plume composition. The presented research effort employs HYSPLIT to map a series of SAGE aerosol observations backwards in time to both produce a proxy for a simultaneously sampled point cloud of the injected aerosol's quantities and the following evolution of those points in time and space. The resulting analysis is an effective volumetric representation of the injected aerosol at arbitrary time intervals. The fusion of empirical observations and dispersion modelling such as with HYSPLIT can improve dynamic model accuracy and increase the utility of point measurements. Ultimately this improves our understanding of plume properties, behavior, and impacts on atmospheric composition and dynamics within sudden highly localized events. Plans to integrate data from additional satellite and in-situ instruments may further strengthen this approach.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Deciphering QBO and ENSO Influence on Stratospheric Transport with Ozone and Water Vapour from Aura MLS

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The Brewer-Dobson Circulation (BDC), stratospheric global mass circulation, influences the distribution of trace elements in the stratosphere, particularly radiatively active water vapour and ozone. The stratospheric meridional transport responds to various oscillations in the stratosphere, notably the tropical Quasi-Biennial Oscillation (QBO) and El Niño–Southern Oscillation (ENSO). QBO influences the meridional transport through the changes in zonal-mean zonal wind. An intensified meridional transport is observed during its westward QBO phase. The composite analysis of ozone and water vapour from the Aura Microwave Limb Sounder (MLS) reveal distinct QBO signatures. Additionally, ENSO-induced changes are linked to enhanced wave propagation. Despite the less periodic nature of ENSO compared to QBO, significant changes are observed in the composite analysis of ozone and water vapour in the stratosphere.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Understanding trends and variability in stratospheric inorganic chlorine in the stratosphere with the ACE-FTS and the TOMCAT 3-D CTM

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Stratospheric inorganic chlorine comprises product gases, e.g., HCl, produced by the decomposition of ozone-depleting substances (ODSs) such as chlorofluorocarbons (CFCs). Following action initiated under the 1987 Montreal Protocol, the tropospheric abundances of many long-lived ODSs have been declining as expected, leading to a corresponding decrease in total stratospheric inorganic chlorine since around the year 2000. Continued monitoring of chlorinated species is crucial to ensure that these abundances are decreasing as expected and to monitor potential factors of variability, including emissions of very short-lived substances (VSLSs), which are not regulated by the Montreal Protocol, non-compliant emissions of regulated gases, e.g., CFC-11 and CCl4 (Li et al., 2024; Montzka et al., 2018), hemispheric variability in stratospheric dynamics (Mahieu et al., 2014), and transient variability like severe wildfire smoke plumes (Bernath et al., 2022). The limb sounder able to regularly measure various chlorine species is the Atmospheric Chemistry Experiment –Fourier Transform Spectrometer (ACE-FTS), operational since 2004 and capable of observing multiple other species (Bernath, 2017).

To investigate the trends and variability of inorganic chlorine abundances over the past 20 years, the 3-D offline chemical transport model TOMCAT (Dhomse et al., 2019) has been used to compare to observations and for analysing the variability in the cited factors above. The use of TOMCAT alongside ACE-FTS measurements ultimately allows us to infer trends of chlorinated species in the stratosphere, allowing a comprehensive analysis and providing valuable insights into inorganic chlorine chemistry and the path to ozone layer recovery.

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Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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SOLSTICE, a constellation of cubesat-borne solar occultation limb sounders for atmospheric composition profiling - instrument development and qualification

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Owing to the stringent requirement on spectral resolution and line of sight pointing, hyperspectral thermal infrared (TIR) limb sounders of atmospheric composition tend to be large missions. SOLSTICE (Solar Occultation Limb Sounding Transformative Instrument for Climate Exploration) is a mission development programme supported by the UK Space Agency and the UK Centre for Earth Observation Instrumentation (CEOI) to demonstrate a cost-effective and agile way to measure high-vertical resolution profiles of atmospheric constituents, leveraging the benefits of the small satellite infrastructure.

SOLSTICE is designed from the scientific requirements established for the late CubeMAP mission [1]. It focuses on the study of the tropical upper-troposphere and stratosphere to contribute to an improved understanding of processes occurring in these regions and how they are affected by global change. Limb solar occultation is retained as the observing geometry to provide high-radiance input scenes, and self-calibration from exo-atmospheric views, both aspects enabling the design of highly miniaturized spectrometers compatible with cubesat platforms. In turns, the system miniaturization obviates the coverage drawback of limb solar occultation by enabling constellation flying.

Two scientific instruments have been developed for SOLSTICE: 1) the High-resolution InfraRed Occultation Spectrometer (HIROS), which is a highly miniaturized laser heterodyne spectro-radiometer operating in the thermal infrared, and 2) the Hyperspectral Solar Disk Imager (HSDI), which is a 16-channel visible imager. Over the last two years, the engineering models of the instruments were designed, built, characterized through thermo-vacuum testing campaign, including payload integration within a 16U Open Cosmos platform. The status of the SOLSTICE development, the results from instrument built and the associated qualification will be presented.

[1] Weidmann, D., Antonini, K., Martinez Pino, D., Brodersen, B. K., Patel, G., Hegglin, M. I., Sioris, C., Bell, W., Miyazaki, K., Alminde, L. K., Gabriele, A., Pastena, M., & Hoffmann, A. (2020). Cubesats for monitoring atmospheric processes (CubeMAP): A constellation mission to study the middle atmosphere. Proceedings of SPIE - The International Society for Optical Engineering, 11530. https://doi.org/10.1117/12.2573727

Topic:

Upcoming Earth observation limb and occultation instruments

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SOLSTICE, a constellation of cubesat-borne solar occultation limb

sounders for atmospheric composition profiling –mission simulator and processing algorithms

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In tandem with the SOLSTICE instrument development (see related abstract 'instrument development and qualification') a mission simulator has been developed to evaluate the performance of the SOLSTICE system. The simulator includes production of synthetic Level 0 data raw from the instruments, the processing of calibrated atmospheric transmission as Level 1 data, and the 'retrieval' processor generating the Level 2 vertical profiles of atmospheric constituents.

The sounding geometry is simulated from orbital dynamics using the Orekit package, implemented for constellation of limb solar occultation sounders by GOM Space Luxemburg. For each occultation event, the thermal infrared and visible radiance fields in the instruments'line of sights are calculated from the transmittance produced by the line-by-line Reference Forward Model (RFM) [1]. Two physical models of the two scientific instruments, HIROS and HSDI have been developed to produce synthetical instrument data and their associated noise, from which the Level 0 data is packaged.

The synthetic Level 0 granules are then available for input to the data processor. The Level 1 data processor includes three functions: 1) the HSDI images are processed to reconstruct the accurate knowledge of the line of sight pointing. 2) the HSDI images are processed into calibrated channel transmittance registered as function of altitude. 3) The HIROS high-resolution spectra are calibrated into transmittance on the absolute frequency grid. For performance assessment, an option to fully bypass the platform and instrument simulator has been added so that reference ideal Level 1 data can be produced.

The retrieval algorithm, producing the level 2 dataset, is based on the Multispectral Orbital Retrieval using Sequential Estimation (MORSE) developed at the University of Oxford. The sequential aspect, as implemented in MORSE, is not to solve the equation using all available measurements simultaneously but to divide the measurements into correlated subsets and solve for each in turn, updating the a priori estimate. The vertical profiles are retrieved between 6 and 50 km, on a 1 km grid. MORSE is first run on HSDI data to produce temperature, pressure, water vapour, and pointing correction vertical profiles. HIROS data are then ingested to produce and/or update profiles of temperature, pressure, pointing correction, water vapour, methane, nitrous oxide and ozone profiles. Retrieval errors, averaging kernels, and other optimal estimation diagnostic metrics are also determined.

We will present the simulator architecture and give an overview of its working, as well as a first performance assessment of the SOLSTICE products.

[1] Dudhia, A. (2017). The Reference Forward Model (RFM). Journal of Quantitative Spectroscopy and Radiative Transfer, 186, 243–253. https://doi.org/10.1016/j.jqsrt.2016.06.018

Topic:

Upcoming Earth observation limb and occultation instruments

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The Applicability of Machine Learning Techniques to Assessing the Evolution of Stratospheric Aerosol Properties

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Physics and chemistry fundamentally govern stratospheric aerosol processing and dispersion following an injection event. While a self-evident statement, the exact course of those processes which govern residence time and final yields of chemical products like sulfuric acid can have significant uncertainty in the time period shortly following these events. Forecast models have a degree of power validated by empirical observations including satellite observations. The accuracy and precision of those measurements and their underlying utility is a product of the spatiotemporal sampling frequency and the sampling technique used by each instrument. The more accurate techniques often trade sampling frequency for that increased accuracy or direct measurement of the relevant quantities as opposed to inference. Thomason et al. (2021) showed evidence for the predictability of stratospheric aerosol evolution given the initial injection conditions, and the Global Space-based Stratospheric Aerosol Climatology (GloSSAC) provides a model for stratospheric aerosol perturbations as a posterior analysis. Robust predictive tools that can fill gaps between instrument measurements or entire records can improve estimates for aerosol climatologies as well as forecasts for long-term aerosol burdens and fallout rates. This research will assess if there is promise in additional analysis tools such as machine learning techniques to improve existing understanding and modelling assimilations for the prediction of aerosol properties based on previous satellite observations.

Topic:

Aerosols and clouds

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Recent progress in spectroscopy at the NCEO

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Limb sounding has a number of advantages over nadir sounding for measuring trace gases in the atmosphere. Limb sounders measure with improved vertical resolution and can extend to higher altitudes. They measure spectra over longer pathlengths than their nadir counterparts, with an increased sensitivity to minor species. In the infrared, this increased sensitivity along with the typically higher spectral resolution provides additional challenges in interpreting the measured atmospheric spectra, principally linked to the atmospheric radiative transfer modelling and the underlying spectroscopic data. As quantitative molecular spectroscopy is the foundational basis for this field, it is crucial that we continue to improve spectroscopy through new laboratory measurements and analyses. This presentation will focus on recent laboratory measurements for a number of important trace gases, including halogenated species, carbon dioxide and ammonia, and will also cover a new laboratory at Space Park Leicester dubbed the SPectroscopy for ENvironmental SEnsing Research (SPENSER) facility.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Occultation and limb Observations of Terrestrial Atmospheres: Mars and Venus as Case Studies

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Many celestial bodies in the Solar System have been studied extensively using limb and occultation techniques, which have proven to be powerful tools for retrieving detailed information about the composition and dynamics of planetary atmospheres. These methods date back to the early 1970s, when NASA first deployed missions around Mars to investigate the planet's atmospheric components.

Since then, both limb and occultation observations have become standard techniques in planetary science, consistently revealing critical insights into atmospheric structures and constituents. In recent years, solar occultation in particular has emerged as a highly effective approach, taking advantage of the Sun as an exceptionally bright and stable light source. This method has enabled researchers to conduct unprecedentedly sensitive measurements, especially of trace gases, in the atmospheres of Mars and Venus.

One of the most notable advancements in this field comes from the European Space Agency's Trace Gas Orbiter (TGO), launched in 2016 as part of the ExoMars program. Designed to improve trace gas detection capabilities by a factor of 100 to 1000 compared to previous missions, TGO aimed initially to resolve the ongoing debate over the presence of methane on Mars. However, it far exceeded expectations. Not only did it place stringent new limits on methane, but it also achieved the first detection of hydrogen chloride (HCl) in the Martian atmosphere—a key species that had long eluded detection. Furthermore, TGO provided unprecedented insights into the behavior of water vapor on Mars, including its seasonal variability and its role in atmospheric escape processes.

This presentation will offer an overview of historical and contemporary atmospheric measurements obtained via limb and solar occultation techniques across the Solar System. It will then focus on the groundbreaking discoveries made by TGO, highlighting how this mission has reshaped our understanding of the Martian atmosphere.

Topic:

Atmospheric composition (Earth and planets), chemistry and transport

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Global Stratospheric Aerosol Watch (GSAW) –a web portal for NRT visualization and analysis of satellite and ground-based observations relevant to stratospheric aerosol

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GSAW is a new web portal conceived for quick visualization of various satellite observations relevant for the stratospheric aerosols with a specific focus on extreme events, such as wildfires/pyroCb and

volcanic eruptions reaching the stratosphere. GSAW provides visualization of Near-Real Time (NRT) data (delivered with a latency of 1-3 hours) as well as historical data dating back to 1979 for some data sets.
The portal includes several modules offering various ways of data visualization for the following purposes:
1) NRT detection of extreme events: wildfire outbreaks and explosive volcanic eruptions
2) Spatiotemporal tracking of aerosol plumes in NRT mode
3) Source attribution of aerosol plumes in the UTLS
4) Multi-scale analysis of stratospheric aerosol perturbations, their evolution and longevity
Post-KUMAR is the most advanced interactive GSAW module enabling NRT visualization of global nadir mapping and along-orbit vertical sections. The geographic maps of UV absorbing Aerosol Index (AAI) and SO2 total column are overlayed by satellite orbit ground tracks, realized as clickable objects. Clicking on the orbital track in a region of interest displays the respective vertical curtain of aerosol/clouds. Post-KUMAR comprises the following objects:
⊠ Daily maps of AAI and SO2 total column (zoomable and color-scalable)
o TROPOMI AAI 2019/01 –present (operational)
o OMPS-NM AAI 2012/02 –2018/12
o AAI merged satellite record ESA CCI 2000/01 –2012/01
⊠ Satellite ground tracks (clickable) and along-orbit cross sections
o EarthCARE ATLID 2024/08 –present (operational)
o SNPP OMPS-LP 2012/02 –present (operational)
o NOAA-21 OMPS-LP 2023/02 –present (operational)
o CALIPSO CALIOP 2006/06 –2023/06
⊠ Aerosol layer detections (color-coded by layer top altitude)
o SNPP OMPS-LP (stratospheric aerosol layer detection –SALD) 2012/02 - present
o NOAA-21 OMPS-LP (SALD) 2023/02 - present
o CALIOP (upper tropospheric smoke and SALD) 2006/06 –2023/06
⊠ Solar occultations (clickable) and vertical profiles of aerosol and gases
o SAGE II (1984/10 –2005/08) and ISS SAGE III (2017/05 –present) extinction ratio profiles
o ACE-FTS extinction, temperature, CO, H2O, O3, HCN vertical profiles (2004/02 –2023/11)
⊠ Animated GFS wind fields at 12 UT at different pressure levels (2000/01 –present)

Topic:

Applications (e.g., data assimilation, gridded products, spacecraft re-entry plumes)

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How stratospheric composition Limb observations improve weather model forecasts

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The Microwave Limb Sounder (MLS) on the Aura satellite has been providing essential observations of ozone for the upper troposphere and lower stratosphere (UTLS). The relevance of the UTLS region for key weather and climate patterns, and coupling between the troposphere and stratosphere, highlights the capacity of MLS O3 to enhance weather forecasting.

This study investigates the impact that the assimilation of MLS ozone data has on meteorological fields in NWP simulations using the European Centre for Medium-Range Weather Forecasts (ECMWF) IFS model. We will show results that focus on short- and medium-range forecasts for recent weather events that were influenced by stratosphere-troposphere interactions.

Our study also explores alternatives to be used after MLS data will stop being available. And it shows the need for new observation platforms like the ESA-CAIRT instrument, to provide atmospheric composition measurements that will enable better representation of UTLS processes and enhance stratosphere-troposphere coupling in weather forecast systems and reanalyses.

Topic:

Applications (e.g., data assimilation, gridded products, spacecraft re-entry plumes)

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Limb temperature observations in the mesosphere with OMPS

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Molecular scattering (Rayleigh scattering) has been extensively used from the ground with lidars and from space to observe the limb, thereby deriving vertical temperature profiles between 30 and 80 km. In this study, we investigate how temperature can be measured using the new Ozone Mapping and Profiler Suite (OMPS) sensor, aboard the Suomi NPP and NOAA-21 satellites. The OMPS consists of three instruments whose main purpose is to study the composition of the stratosphere. One of these, the Limb Profiler (LP), measures the radiance of the limb of the middle atmosphere (stratosphere and mesosphere, 12 to 90 km altitude) at wavelengths from 290 to 1020 nm.

This new data set has been used with a New Simplified Radiative Transfer Model (NSRTM) to derive temperature profiles with a vertical resolution of 1 km. To validate the method, the OMPS-derived temperature profiles were compared with data from four ground-based lidars and the ERA5 and MSIS models.

The results show that OMPS and the lidars are in agreement within a range of about 5 K from 30 to 80 km. Comparisons with the models also show similar results, except for ERA5 beyond 50 km. We investigated various sources of bias, such as different attenuation sources, which can produce errors of up to 120 K in the UV range, instrumental errors around 0.8 K and noise problems of up to 150 K in the visible range for OMPS.
This study also highlighted the interest in developing a new miniaturised instrument that could provide real-time observation of atmospheric vertical temperature profiles using a constellation of CubeSats with our NSRTM.

Topic:

Current and past limb and occultation instruments: algorithms, products, validation

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Keystone: Exploring the mesosphere and lower thermosphere

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Keystone is a proposed upper atmospheric limb sounding mission that would provide a comprehensive measurement of the Mesosphere and Lower Thermosphere (MLT) composition, temperature and winds, and its variability (from a diurnal to a seasonal scale). It's currently in Phase-0 study as ESA's 12th Earth Explorer satellite.

The MLT is the upper atmosphere region which goes from 70km to 120km. The MLT is subject to high energy inputs from space as solar electromagnetic radiation and energetic particles. The resulting photodissociation, photo-ionisation and high-energy collisions generate radicals and ions, often with internal excitation.

The key science objective of the Keystone mission is to gain knowledge of geophysical parameters in the MLT that will allow a better understanding of its behaviour. Keystone will improve our understanding of space weather and climate change processes, particularly their impact on the MLT region. To do this, Keystone will measure the composition, gradients and variability of the neutral atmosphere, temperature profiles, and mesospheric winds.

The Keystone concept includes a comprehensive remote sensing payload, covering spectral windows in the Terahertz (THz), IR and UV-Vis regions of the electromagnetic spectrum in order to fulfil its science objectives.

The primary instrument foreseen for this mission is a supra-THz radiometer with high spectral resolution for the retrieval of vertical distribution profiles of trace gases between 1 THz and 5 THz, including—as a world first—the key MLT species atomic oxygen, for which no global, time resolved measurements exist. The THz instrument will also retrieve temperature profiles, and mesospheric winds (through Doppler shift).

To date, atomic oxygen can only be inferred indirectly from IR and UV-Vis measurements, a process that is heavily reliant on model assumptions. Collocated measurements of atomic oxygen from the THz instrument, combined with heritage IR and UV-Vis instruments, will allow us to resolve decades old uncertainties in these photochemical models.

Topic:

Upcoming Earth observation limb and occultation instruments