# LOng-LIved greenhouse gas PrOducts Performances (LOLIPOP)

# User Workshop

# Final Report

# (UWS_FR)

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# Contents

# 1 Executive Summary

The ESA CCI LOLIPOP Workshop was held on 18/19 November 2025 in Bologna, hosted by the Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR). The event featured 22 presentations and attracted 28 on-site participants, with an additional 28 joining remotely (see Appendix A). The programme included presentations by the LOLIPOP team on project activities, as well as contributions from the Other Long-Lived Greenhouse Gases (OLLGHG) science community, representing the perspectives and interests of the intended data users (see Appendix B).

The LOLIPOP team brings together 11 research groups/institutions from six countries. The project aims to advance understanding of the Earth's climate by closing knowledge gaps about atmospheric gases that either have a strong greenhouse effect or play a significant role in ozone layer depletion.

The focus is on Other Long-Lived Greenhouse Gases (OLLGHGs)—minor atmospheric constituents that are sparsely measured by satellites and for which user requirements remain largely undefined.

The main objective of LOLIPOP is to assess the state of the art in OLLGHGs satellite measurements and to evaluate whether the current suite of satellite observations is sufficiently mature to support climate science and services. Based on the outcomes of a comprehensive literature review and a users' needs survey, $N_2O$, $SF_6$, CFC-11, and CFC-12—retrieved from both limb and nadir observations—were initially selected for harmonisation and validation using measurements acquired after 2002. For nadir $N_2O$ observations, the dataset includes missions such as TES, CrIS/AIRS-CLIMCAPS, TANSO-FTS-FOCAL, and IASI. Instead, limb measurements are provided by ACE-FTS, HIRDLS, MIPAS, MLS, and SMR.

The validation team introduced the harmonised satellite limb and nadir OLLGHG datasets, developed by extracting priority parameters and other instrument-specific variables, in a unified data format. The features of these harmonised datasets were assessed through inter-comparison and validation against independent reference datasets from ground-based networks and balloon/flight measurement campaigns.

The LOLIPOP project and these inter-comparison/validation activities, in particular, enabled a better understanding of the available satellite OLLGHGs data and their quality. One of the main recommendations from this activity, and from the discussions held during the workshop, is to continue harvesting information from existing and heritage satellite missions and to assess and further develop techniques to ensure consistency and traceability. This includes exploring the feasibility of producing merged and homogenised time series, especially given significant gaps in the temporal coverage of OLLGHG-related observations. At the same time, it is essential to start exploring the exploitation of new datasets and future missions to extend OLLGHG retrieval capabilities. On this topic, the status of Europe's operational space-based monitoring of atmospheric composition, which integrates multiple components and draws on EU, ESA, IGACO, and EUMETSAT activities, was presented. Greenhouse gas monitoring is a central element of this system, with particular emphasis on carbon dioxide and methane, but it also provides essential constraints on less observed or indirectly inferred components, such as the OLLGHGs. Key geophysical products from the TROPOMI instrument on board Sentinel-5P were recalled, along with those from upcoming missions, with a focus on Sentinel-4, IASI-NG, Sentinel-5, CO2M, and the TANGO mission. Despite these upcoming missions, limb-viewing instruments remain essential for stratospheric monitoring and related applications, but are currently scarce. The LOLIPOP project could play a strategic role in demonstrating and reinforcing the need for sustained limb observations in future mission planning. On the one hand, the LOLIPOP project aims to assess the quality of satellite limb and nadir OLLGHG datasets; on the other, it encourages their use within the model community. To emphasise this objective and the opportunities introduced by the use of OLLGHGs satellite data, some user case studies were carried out within the project and presented during the workshop. These studies aimed to emphasise how models' simulations or methodologies based only on model data can benefit from the exploitation of OLLGHGs satellite observations. One of the studies focused on exploiting N2O limb satellite climatology rather than hardcoded climatology in climate models to assess the sensitivity of historical climate model simulations to the OLLGHGs climatology, in particular, the impact of different climatologies on longwave radiative fluxes and heating rates. Other user cases include the study of stratospheric chlorine levels over recent decades, the computation of the atmospheric lifetimes of some OLLGHGs, exploiting model simulations or observational data, and the use of hybrid methodologies that leverage the strengths of separate approaches. Another user case study focused on enhancing understanding of the effects of changes in the stratospheric circulation on the observed distributions of long-lived trace gases and inferring stratospheric circulation changes from observed changes in long-lived trace gases. In this study, different methods to compute the age of air, a proxy for the Brewer-Dobson circulation, were explored, some of which were based on limb-satellite observations of tracers. Still on Age of Air and Brewer-Dobson circulation topics, during the workshop, two external studies based entirely on satellite data were presented. The first, based on the ANCISTRUS method, exploits zonal means of several tracers and, by inverting the continuity equation and parametrising sources and sinks, computes the mean meridional and vertical transports. The second, mainly based on ACE-FTS SF6 retrieved abundances, focuses on the computation of the Age of Air, a proxy for the Brewer-Dobson Circulation, suggesting an acceleration of its shallow branch. Another innovative application of OLLGHGs satellite data is Space Weather, in particular, the assessment of the possible impact of Solar energetic particle emissions on Earth's atmospheric chemistry and climate. Some studies have demonstrated that N2O is efficiently produced during frequent energetic particle precipitation. In this kind of study, observational OLLGHGs datasets play a key role in verifying these hypotheses and validating model simulations.

A key factor, strictly related to the quality of OLLGHGs data retrieved from satellite observations (in particular, for halocarbons such as HCFC-132b), is the underlying spectroscopy and the computation of their absorption cross-sections. This aspect has already been emphasised throughout the LOLIPOP project as critical. During the workshop, innovative experimental measurements and techniques (e.g., quantum-chemical predictions) were presented, and these studies demonstrated a significant improvement in the accuracy of radiative efficiency and global warming potential calculations.

The workshop enabled a better understanding of users' needs, emphasising the results of the literature review on OLLGHGs and the survey conducted at the beginning of the LOLIPOP project, but also having the opportunity to interact with representatives of GCOS and CMUG, two key entities closely connected to the CCI. GCOS advocates for sustained, continuous, and reliable long-term time series to adequately support climate monitoring and decision-making. Throughout the years, it has defined 55 ECVs (37 of those can be measured from space) across atmospheric, oceanic, and terrestrial domains, selected based on feasibility, cost-effectiveness, and relevance. Recently, a rationalisation process started to assess coherence, identify gaps, and re-evaluate whether all current ECVs remain essential. The revised ECV list will enter into force with the next implementation plan, expected in 2028. Instead, CMUG, through a broad range of activities, interfaces, and initiatives, aims to foster the exploitation and assessment of the quality and impact of CCI ECV products, especially by bringing together climate-modelling expertise from across Europe. The growing number of ESA CCI ECVs makes it increasingly challenging for users to track and assess product consistency. In this context, CMUG serves as a coordinating body to review dataset consistency and provide structured feedback to CCI teams. Leveraging these experiences, to maximise the project's scientific impact and facilitate effective use of OLLGHG satellite data, stronger user engagement is essential. On this point, the team aims to strengthen outreach activities to showcase project results, datasets, and key findings, while also improving user support and information sharing.

The presentations and this report are made available at the ESA CCI LOLIPOP project website: https://climate.esa.int/en/projects/long-lived-greenhouse-gas-products-performances-lolipop/lolipop-workshop/.

# 2 Minutes of the meeting

## 2.1 Day 1 – 18 November 2025

The meeting opened with a presentation by **Maria Cristina Facchini**, Director of CNR-ISAC, who provided an overview of the institute's activities related to greenhouse gases (GHGs). The Institute of Atmospheric Sciences and Climate (ISAC) operates across several sites, including Bologna, and is active in three main research areas:

- Climate and Meteorology, Modelling and Earth Observation (CAMEO)
- Impacts on the Environment, Cultural Heritage and Human Health (IMPEACH)
- Atmospheric Composition, Climate Forcing and Air Quality (CAFCA)

With specific reference to GHGs and activities relevant to the LOLIPOP project, Dr. Facchini highlighted the use of satellite datasets from MIPAS for trend analyses, particularly for $N_2O$ and $CCl_4$. In addition, GHG climatologies developed at ISAC are used in climate applications, including the EC-Earth climate model. GHG measurements are also conducted at ISAC observatories:

- In-situ measurements of $CO_2$, $CH_4$, CO, $N_2O$, $SF_6$, CFCs and HFCs at the Mt. Cimone observatory (ICOS/AGAGE/GAW-WMO site), as well as $CO_2$ and $CH_4$ measurements in Bologna.
- Remote-sensing $CO_2$, $CH_4$ and CO measurements performed in Bologna within international frameworks: COCCON (operational since 2024), and NDACC and TCCON (planned from 2025).

**Bianca Maria Dinelli**, former Principal Investigator of the project (retired on 1 November 2024), welcomed participants to the Bologna research area of the National Research Council (CNR) and to the LOLIPOP (Long-Lived Greenhouse Gases: Products and Performances) User Workshop. The project team, now led by Elisa Castelli (CNR-ISAC), consists of 11 groups/institutions from six countries. By way of background, LOLIPOP aims to improve understanding of the Earth's climate by completing the picture of atmospheric gases with a strong greenhouse effect or a significant impact on the ozone layer. The focus is on Other Long-Lived Greenhouse Gases (OLLGHGs)—minor atmospheric species that are sparsely measured by satellites and for which user requirements are still largely undefined. The main objective of LOLIPOP is to assess the state of the art of satellite measurements of OLLGHGs and to evaluate whether the current suite of satellite observations is sufficiently mature for use in climate science and climate services. This assessment is a prerequisite for developing a harmonised and consistent satellite dataset. The purpose of the User Workshop is to engage potential users of harmonised OLLGHG satellite datasets, present the current status of available satellite measurements, and share the results of tests evaluating their impact across different applications. Bianca Maria Dinelli concluded by wishing everyone "*buon lavoro"* (good work) and encouraging open discussions and constructive feedback.

**Deodato Tapete**, Senior Researcher at the Italian Space Agency (ASI) and ASI Member in ESA PB-EO Data Operations Scientific and Technical Advisory Group (DOSTAG), congratulated the LOLIPOP team on the excellent work they have accomplished and the interesting outcomes achieved so far. He emphasised the importance of continuous user feedback and appreciated the organisation of this workshop to showcase the project's results and gain a better understanding of user feedback. All these elements are key factors that ASI promotes at national and international levels as part of its programmatic strategy in Earth Observation. He expressed ASI's pleasure in supporting the CCI programme and its willingness to continue this support in the future. ASI is currently developing a national program ("Innovation for Downstream Preparation" – I4DP, encompassing a dedicated line to the scientific community) aimed at demonstrating new services as part of its downstream operations, with climate change being one of the focal topics. Additionally, ASI is actively investing in and promoting the development of new Earth Observation retrieval algorithms, as well as the consolidation of existing ones. He also highlighted ASI's role in supporting the FORUM (Far-infrared Outgoing Radiation Understanding & Monitoring) mission, which has been selected as ESA's 9th Earth Explorer mission—an important achievement for the Italian national community and a result of international collaboration. ASI has actively promoted such cooperation, exemplified by the Surface Biology and Geology (SBG) mission, a joint initiative between NASA and ASI.

**Simon Pinnock** from the ESA Climate Office presented the ESA Climate Change Initiative, whose goals are to develop and deliver global satellite-based Essential Climate Variable (ECV) datasets and to promote their use in climate science. Over the past 40 years, ESA has maintained a substantial portfolio of Earth-observing satellites, greatly enhancing our understanding of the planet's complexities, particularly in the context of global change. The ESA Earth Watch programme aims *"to realise the full potential of long-term global Earth Observation archives through the development of multi-decadal, multi-satellite global Climate Data Records to support climate science."* The Global Climate Observing System (GCOS) defined 55 Essential Climate Variables, of which 36 benefit from space-based observations. ESA CCI projects are actively involved in the development and delivery of 27 ECVs. Many of these CCI ECVs have been successfully transferred to operational production by the Copernicus Climate Change Service and are available via climate.esa.int. Looking ahead, ESA has proposed a continuation of CCI to the end of 2029 and is awaiting feedback from ESA Member States.

Elisa Castelli asked how the consortium could stay informed about new initiatives and upcoming opportunities. Simon Pinnock replied that ITTs will be circulated directly to the consortium.

**Elisa Castelli** (CNR-ISAC), Principal Investigator of the project, recalled the rationale of the LOLIPOP project within the framework of CCI activities, which aim to generate satellite-based time series of atmospheric constituents (GHGs, $H_2O$, $CO_2$, $CH_4$). These activities have recently been extended to include 11 ozone-layer-related greenhouse gases (OLLGHGs; e.g. $N_2O$, HFCs) to better address uncertainty estimation. The project has developed harmonised datasets from both limb and nadir satellite measurements. Based on the outcomes of a comprehensive literature review and a users' needs survey, $N_2O$, $SF_6$, CFC-11, and CFC-12—retrieved from both limb and nadir observations—were selected for harmonisation and validation using measurements acquired after 2002. For nadir $N_2O$ observations, the dataset includes missions such as TES, CrIS/AIRS-CLIMCAPS, TANSO-FTS-FOCAL, and IASI (EUMETSAT). Limb measurements are provided by ACE-FTS, HIRDLS, MIPAS, MLS, and SMR. Harmonisation of the CRISTA-1/2 Level 2 products is currently ongoing. Further details on harmonisation and inter-comparison/validation activities, as well as on the five user case studies analysed within the project, are presented on Day 1 during dedicated contributions by the LOLIPOP teams.

**Bart Dils** (BIRA-IASB) began introducing the harmonisation of satellite nadir products. He gave an overview of the different products considered in the exercise, highlighting their heterogeneity in terms of information provided (e.g., total/partial columns, AVK), vertical coordinates, and spatial and temporal distributions. The harmonisation process aimed to extract priority parameters (e.g., latitude, longitude, vertical grid dimensions, pressure weights, concentration, uncertainty, a-priori, AVK, quality flag), and other ancillary variables needed to generate harmonised products in a unified data format in terms of structure, vocabulary and attributes. Bart Dils introduced the approach used for the intercomparison of the 8 nadir-viewing $N_2O$ satellite products, focusing on the distributions of concentration and degrees of freedom. Each product has been resampled onto a 1-degree x 1-degree regular grid and compared to the CrIS distribution. Distribution maps of the differences have been produced, reporting the median bias of each product. More generally, he highlighted that, despite a uniform strategy, the differences observed between products may simply reflect inherent property differences rather than quality differences. Bart Dils introduced the ground-based reference networks used in the validation exercise (NDACC, TCCON and AGAGE), the co-location criteria and the methodology based on the idea to compare satellite measurement with 'what the algorithm would have retrieved if the reference measurement were to represent the true state' by using a uniform *a priori* profile, if available, and applying the satellites vertical sensitivity information onto the reference measurement profile. He presented an overview of the validation results for some $N_2O$ nadir products against NDACC observations, focusing on the magnitude and latitudinal distribution of the biases. He also presented the results of the trend analyses for CFC-11, CFC-12, and HCFC-22. He also introduced some statistical parameters used to summarise the validation results to mitigate the impact of strong outliers (or outliers' stations due to high altitude/urban centres, etc.), emphasising that assessing the performance of a single dataset is not a straightforward process.

Gabriele Stiller asked whether there is an explanation for the stronger negative trends observed in IASI compared to those observed in AGAGE. Bart Dils said this could be due to different regions of the atmosphere being sampled by the different instruments.

Elisa Castelli highlighted that new nadir products (a new version of the NOPIR products from BIRA and new CFC-11 products from IASI, developed by UNIBAS) will be developed within this project. She added that an assessment of the quality of the different datasets needs to consider also the different applications for which they are used.

Simon Pinnock asked whether trends retrieved from satellite observations provide additional or complementary information to that computed from in-situ observations. Bart Dils commented that we need to keep in mind that different instruments sample different portions of the atmosphere. For example, if a species is sensitive to the stratosphere, you will see similar effects but delayed due to dynamics and chemical processes.

**Kaley Walker** (University of Toronto) introduced the satellite limb datasets that have been harmonised (ACE-FTS/SCISAT, HIRDLS/Aura, MIPAS/ENVISAT - both ESA and IMK-IAA retrieval processors, MLS/Aura and SMR/Odin) and the gases of interest, starting from $N_2O$, CFC-11, CFC-12 and $SF_6$, and now moving to CFC-113, $CCl_4$, $CF_4$, HCFC-22, HCFC-141b, HCFC-142b, HFC-23 and HFC-134a. As for the nadir part, she explained that the harmonisation process aimed to extract priority parameters and other instrument-specific variables, generating harmonised products in a unified data format adapted from the HARMOZ (harmonised ozone) files (Sofieva et al., ESSD, 2013). She explained that the team developed a script to find and save the indices of coincidences between two instruments using the harmonised files, and another code that uses the harmonised files combined with the coincidence files to generate a variety of figures. After testing different ones, the team adopted a final co-location criterion of 300 km and 6 hours. Kaley Walker showed examples of the median VMR and median absolute deviation of the VMR for each instrument and different latitudinal bands for a specific season (September-October-November). For the same months and latitudinal bands, she showed a plot reporting the median relative differences between SMR/Odin and the coincident measurements from each other instrument. She also showed some examples of summary plots that report absolute bias and relative bias between reference limb satellite products and each other instrument providing an overview of bias distribution over time (season) and altitude. Regarding the validation exercise, Kaley Walker introduced the independent reference datasets adopted (GLORIA, MIPAS-B and MarkIV) and the coincidence criteria selected: within 72 hours (except for ACE-FTS, which is within 720 hours) and within 5° latitude, checking that profiles were on the same side of the polar vortex edge. She presented a couple of examples reporting the mean VMR profiles from the reference and satellite instrument dataset and the corresponding mean relative difference profiles. As made for the inter-comparison, the team produced summary plots that report absolute bias and relative bias between the reference profiles and each other instrument providing an overview of bias distribution features in altitude. In general, she highlighted the significant effort put into finding a visual method to show agreement across different datasets. She concluded reporting that ACE-FTS v5.2, MIPAS V8, and SMR v3.0.0 perform well across all comparisons (with only minor biases found in some regions), HIRDLS v07 has variable performance and MLS $N_2O$ profiles have a kink centred near 32 hPa (24 km).

Bianca Maria Dinelli asked whether the bias in the MLS $N_2O$ profiles could be due to spectroscopy, since the instrument operates in a different spectral range than other references. Kaley Walker answered that since the kink is so specific to a certain altitude, it is probably caused by something else.

Federico Fabiano asked whether it would make sense to create an aggregated dataset that combines the advantages of the various datasets included in the exercise.

Simon Pinnock commented that this is an aspect to face in the following phases of the project. He also added that the validation teams, both for nadir and limb, provided many interesting validation and inter-comparison results, and he asked the audience to explain if anything else should be interesting from the user point of view. Federico Fabiano answered that, as a user, he needs to understand from the data provider which data to use, so a sort of executive summary with indications and suggestions would be helpful. Tiziano Maestri asked whether there is a threshold/value/range within which we can consider a product good enough. Gabriele Stiller commented that this is strongly dependent on the application and, especially, on the precision the application requires.

**Federico Fabiano** (CNR-ISAC) started a series of presentations covering the use cases developed by different teams within the contract. He introduced the User Case Study 1 titled ‘Sensitivity of historical climate model simulations to the OLLGHGs climatology’, whose objectives were to evaluate the sensitivity of the simulated climate to changes in the distribution of minor GHGs, and to implement an updated climatology of GHGs in the EC-

Earth climate model. He introduced EC-Earth3, a Coupled Atmosphere-Ocean General Circulation Model that participated in the last CMIP6 project. In this model, the latitude/height distribution of the minor GHGs is hardcoded, taken from the MOBIDIC model (Cariolle and Brard, 1984). The hardcoded climatology of $N_2O$ and CFC-11 has been extracted from the code and compared with a simple parametrisation in Meinshausen et al. (2017) and with a climatology from the CESM-WACCM AerChemMIP historical simulation (1990-2014). First, an offline sensitivity test was performed using a set of idealised vertical distributions of $N_2O$ to assess the impact on longwave radiative fluxes and heating rates. Then, two (control and sensitivity) 10-member ensembles of 2000-2015 AMIP simulations were performed to test the impact of the CESM-WACCM climatology. The perturbed (CESM-WACCM climatologies) ensemble shows significant warming in the low- to mid-stratosphere up to stratopause and a slight increase in the OLR global mean at TOA. The team continued exploiting the $N_2O$ limb satellite climatologies provided by the validation team, highlighting that the limb datasets from different instruments are heterogeneous but agree substantially on the average climatology and (apart from MLS) also agree on the global-average vertical profile of $N_2O$. Federico Fabiano commented that the MIPAS dataset is a promising candidate for an updated climatology of $N_2O$ due to its regular coverage of all months and regions, well-defined seasonal dynamics, and good agreement with the CESM-WACCM climatology.

Gabriele Stiller asked whether the 10-year temporal coverage of the MIPAS mission could be a problem. Federico Fabiano acknowledged that this might be a concern but emphasised that having a robust monthly climatology with homogeneous temporal coverage is more important. He added that, for example, ACE-FTS provides a longer observational record, but shows a systematic lack of observations during certain months. Kaley Walker commented that although ACE-FTS has regular sampling, its temporal coverage is not homogeneous, resulting in fewer months being covered.

Bianca Maria Dinelli commented that one of the needs for the future is to develop a methodology to fill any mission’s gaps by leveraging other instruments or missions. More generally, she invited ESA to take this problem into account, particularly given the possible future lack of limb missions.

Kaley Walker commented that the validation team is working to find a suitable methodology to combine the MIPAS and ACE-FTS time series to address the possible lack of some of the missions.

**The User Case Study 2: “Study of the radiative forcing of OLLGHGs” was not presented during the workshop.**

**Antonio Giovanni Bruno** (NCEO) introduced the third user case study within the LOLIPOP project, focusing on stratospheric chlorine levels over the recent decades and their impacts on ozone recovery. He presented the three data sources used in this study: observational data (ACE-FTS), chemical transport model data (TOMCAT), and a merged dataset produced by a machine-learning data assimilation approach (TCOM; Dhomse et al., 2021). Exploiting these datasets, the team determined trends in HCl, CFC-11, and CFC-12 across different atmospheric regions over recent decades and estimated, through bespoke model simulations with constant Cl at peak levels (the era of peak halogens in the mid-1990s), the changes in HCl trends. HCl, CFC-11 and CFC-12 ACE-FTS data had been temporally interpolated using a cubic spline to fill the gaps, and the signals were de-seasonalized using empirical mode decomposition (EMD). Trends are calculated as the linear regression of the de-seasonalized signal. The team evaluated trends in CFC-11, CFC-12, and HCl over 2005-2024, computed from three different data sources, against published ACE-FTS trends (Schmidt et al., 2024). The newly computed trends showed a decrease expected under the Montreal Protocol regulations and good agreement with those reported by Schmidt et al. (2024). Antonio Giovanni Bruno continued with the second part of the study, where the team demonstrated the TOMCAT model's sensitivity of stratospheric chlorine loading to source gas emissions. To do this, they compared two model runs, performed in two different configurations: a control run reproducing the observed decline in chlorine and a bespoke run with chlorine source gas concentrations fixed to their 1995 peak values. The comparison between the control and constant-Cl runs confirmed that changes in chlorine source gas concentrations directly influence the modelled HCl trends with the increasing trend related to ozone loss.

**Jeremy Harrison** (NCEO) presented the user case study 5 on the atmospheric lifetime of OLLGHGs. He explained that understanding the lifetimes of these species is essential to predict future abundances, infer emissions, and calculate global warming potentials or ozone depletion potentials. He reported a literature review of $N_2O$, CFC-11 and CFC-12 lifetimes and introduced the 2013 SPARC assessment of atmospheric lifetimes for ozone-depleting substances, their replacements, and related species that included the ACE-FTS analysis from Brown et al. (2013), an essential work that reported reference methodologies to calculate atmospheric lifetime and that stated as the "best" lifetimes were taken as weighted averages of lifetimes calculated from observations and models. The team aims to determine the stratospheric lifetimes of selected key species using ACE-FTS v5.2 data and the method of Volk et al. (1997), and to investigate the variability in lifetimes across different atmospheric regions over the ACE-FTS time period (almost 20 years). In addition, they will investigate whether there is evidence for a decrease in the atmospheric lifetimes of species such as CFC-12 and determine the implications for future abundances and ozone recovery. He introduced Volk's method 1 to compute stratospheric lifetimes based on correlations with age-of-air at the extratropical tropopause, where transport across the tropopause is extremely slow, meaning that the correlation of the species there will depend only on lifetime and not on atmospheric transport. He continued presenting Volk's method 2 to calculate the relative stratospheric lifetime using tracer-tracer correlations at the extratropical tropopause. He also introduced the approach the team adopted for calculating the slopes. Jeremy Harrison presented slope and lifetime time series for ACE-FTS and TOMCAT CFC-11 and CFC-12 across different regions and periods. These preliminary results showed that the ACE-FTS and TOMCAT slopes differ significantly, and the ACE-FTS lifetimes are too low compared to those reported in the literature. He also highlighted that there is no evidence of a decreasing trend in CFC-11 or CFC-12 between 2004 and 2024, even though ACE-FTS data are not precise enough to infer such a trend. He highlighted that this user case study will continue in the coming months, and that further analysis will be performed to improve the computation of the slopes and better explain the results.

Bianca Maria Dinelli asked what is causing the trend in the lifetime of CFC-11 and CFC-12. Jeremy Harrison answered that the positive trend is likely due to changes in the dynamics of the stratosphere (Brewer-Dobson circulation).

Gabriele Stiller stated that the correction term (C) in the equations for the computation of the lifetime is crucial for this calculation. Jeremy Harrison confirmed that this correction factor is extremely important, and it was derived from aircraft observations from the mid-90s.

**Felix Plöger** (FZJ) started presenting the user case study 4, titled "CLaMS stratospheric circulation estimates", introducing the stratospheric Brewer-Dobson circulation (BDC), the mechanism that controls the distribution of trace gases, also affecting radiation and climate. He explained that, despite models' simulations predicting a BDC strengthening in global warming scenarios, observations do not indicate such strengthening so far (Garny et al., 2024). In this context, the main objectives of this user case study were to enhance understanding of the effects of changes in the stratospheric circulation on the observed distributions of long-lived trace gases and infer stratospheric circulation changes from observed changes in long-lived trace gases. Felix Plöger presented the Chemical LAgrangian Model of the Stratosphere (CLaMS) used to simulate long-lived trace gases ($N_2O$, $CH_4$, CFC-11, CFC-12, $SF_6$) over the past 40 years. He highlighted that this model is particularly advantageous for simulating gradients and structures in the stratospheric composition. As a preliminary assessment, the team evaluated the uncertainty in the representation of the stratospheric circulation across current reanalysis datasets (ERA5, ERA-Interim, JRA55, MERRA-2). For example, he presented differences in the behaviour of the CLaMS simulations for Age of Air (AoA), a proxy for the BDC, across different reanalyses. Felix Ploeger introduced the work by Voet et al. (2025) on the mean AoA from multiple mixing ratios as a proxy for the BDC. The objective of that work was to reduce uncertainty in mean age estimates from satellite observations by exploiting multiple tracers. Voet et al. (2025) represented a "proof of concept" for CLaMS model tracers; in this user case study, the objective is to apply this method to ACE-FTS observations. He introduced the technique adopted for the computation of the mean AoA from ACE-FTS multi-tracers combined and ACE-FTS $SF_6$-only (Garny et al. 2024a, 2024b) and showed a couple of examples of mean age of air profiles computed with the different methods (CLaMS tracers combined, CLaMS ideal clock tracer, CLaMS SF6-only, ACE-FTS tracers combined, ACE-FTS SF6-only), highlighting a significantly reduced uncertainty range for age of air from multiple trace gases. He concluded by presenting the zonal means of the age of air for DJF and JJA 2005, computed with the different methods, highlighting that the model multi-tracers-derived AoA is in good agreement with the actual model AoA methods. For JJA 2005, he also presented the differences between the actual model AoA and AoA from both model multi-tracers combined and $SF_6$-only. The preliminary results showed better agreement and lower standard deviations between the actual model AoA and the AoA from model multi-tracers combined.

Bianca Maria Dinelli asked how the AoA is linked to the lifetime presented by Jeremy Harrison in the previous presentation. Florian Voet (FZJ) explained that at high altitude, AoA and lifetime are closely correlated, but this becomes less and less prononuced as altitude decreases.

**The expected presentation by Florence Bockting (Climate Resource) was cancelled for unavailability of the presenter.**

**Belén Martín Míguez** (WMO) from the GCOS Secretariat presented key insights into GCOS's mission. She began by recalling the steps that led to the creation of the Global Climate Observing System (GCOS) in 1992, established to support climate observations that enable climate science and services. These observations shall provide evidence of climate change and support mitigation and adaptation strategies, as well as climate risk assessment. GCOS does not conduct observations itself; rather, it integrates in situ and space-based contributions from a wide range of organisations and observing networks. It therefore functions as a "system of systems." GCOS plays a key role along the decision-making pathway by identifying observational priorities—most notably through the definition of Essential Climate Variables (ECVs)—and is widely recognised as the leading reference for defining climate observation requirements. To date, GCOS has defined 55 ECVs across atmospheric, oceanic, and terrestrial domains, selected based on feasibility, cost-effectiveness, and relevance. These variables are critical for characterising the Earth's climate system. GCOS is mandated to report to the UNFCCC and, on a five-year cycle, publishes a Status Report and an Implementation Plan (most recently in 2022). These documents set priorities for addressing observational gaps and needed improvements and are followed by coordinated responses and actions from space agencies. After 20 years, GCOS has initiated a rationalisation process to assess coherence, identify gaps, and re-evaluate whether all current ECVs remain essential. This process includes a public review involving a broad range of stakeholders. The revised ECV list will enter into force with the next Implementation Plan, expected in 2028. Currently, 37 ECVs can be measured from space; however, for most variables the observing system remains sub-optimal. GCOS therefore continues to advocate for sustained, continuous, and reliable long-term time series to adequately support climate monitoring and decision-making.

**Amy Doherty** (Met Office) presented the Climate Modelling User Group (CMUG) perspective on the project. She started by recalling the ESA CMUG's overarching goal of fostering the exploitation and assessing the quality and impact of CCI ECV products. She outlined CMUG's broad range of activities, interfaces, and partnerships, which bring together climate-modelling expertise from across Europe. Of relevance to the project is CMUG's role in promoting data use and integration across the CCI programme, especially as the growing number of ESA CCI ECVs makes it increasingly challenging for users to track and assess product consistency. In this context, CMUG acts as a coordinating body to review consistency across datasets and to provide structured feedback to CCI teams. CMUG is expected to be extended into a further phase to support new ECVs and project teams. Beyond coordination, CMUG is also developing community tools and strategic activities, including a gap analysis and an annual Integration Meeting that brings together all CCI projects; the next meeting is planned for March 2026. CMUG supports the standardisation and uptake of CCI datasets and has produced a report with recommendations on the future evolution of Obs4MIPs (Observations for Model Intercomparisons Project). In addition, CMUG contributes to the Earth System Model Evaluation Tool (ESMValTool) by integrating diagnostics and performance metrics based on ESA CCI datasets, thereby enabling more targeted and robust model evaluation. The key takeaway is that CMUG actively facilitates exchange between users and CCI projects and that initiatives such as Obs4MIPs and ESMValTool play a crucial role in efficiently delivering CCI data to the modelling community.

**Michiel van Weele's presentation was postponed to Day 2, and Gabriele Stiller's contribution was anticipated to Day 1.**

**Gabriele Stiller** (KIT) anticipated her presentation on the middle atmospheric mean transport derived from satellite data of tracers. She introduced the Brewer-Dobson circulation, the mechanism that distributes trace gases in the middle atmosphere (10 – 80 km). So far, the standard approach is to compare the age of air from observations with that from model simulations. The main challenge with this approach is finding suitable age tracers. Currently,

$SF_6$ is the most used, but observations are rare. In addition, the exploitation of "Integral quantity" does not resolve information along the path through the atmosphere. Thus, the team would like to obtain a better-resolved picture with information along the path and develop ANCISTRUS. This method uses monthly (weekly, bi-weekly, …) zonal means of several tracers (e.g., $H_2O$, $N_2O$, $CH_4$, CO, CFC-11, CFC-12, HCFC-22, $CCl_4$, $SF_6$). Considering that chemical sinks and transport drive changes in tracer abundance within an altitude-latitude bin, and that chemical sinks can be modelled, the mean meridional and vertical transport are derived by inverting the continuity equation, solved simultaneously across all latitude-altitude bins. Gabriele Stiller showed a couple of examples of analyses that can be performed exploiting ANCISTRUS: a multi-year December-January climatology of the Brewer-Dobson circulation, and MIPAS tracer-retrieved residual 2-D velocities derived from the continuity equation. She also introduced two applications of ANCISTRUS. In the first one (Kerzenmacher et al., in preparation), time series have been analysed for the secondary circulation that is imprinted on the tropical uplift by the QBO. ANCISTRUS shows agreement in structures with reanalysis data, but hints at differences in the altitude regimes and velocities relative to each other. Another application (Brehon et al., https://doi.org/10.5194/egusphere-2025-4457) compares uplift velocities with those derived from MLS observations of the tropical water vapour tape recorder. This comparison hints at somewhat too low ANCISTRUS vertical velocities in the lowermost stratosphere (probably due to too strong regularisation); interannual variations show a QBO signal again. She concluded, highlighting that ANCISTRUS is open to further evolution and applications. In particular, the team aims to extend the analysis of mixing coefficients, apply it to other satellite data (e.g., MLS, SMR), and compare it to models.

## 2.2 Day 2 – 19 November 2025

**Keith Shine** (University of Reading) presented recent work aimed at improving the understanding of net radiative forcing from halocarbons. His talk started from the paper by Pinnock et al. (1995; https://doi.org/10.1029/95JD02323), published nearly 30 years ago, and highlighted the evolution since then. The original approach has been refined and updated multiple times. However, several open issues remain. One key uncertainty concerns halocarbon breakdown products whose contribution to radiative forcing is still not well quantified. Recent studies (e.g. Pettinari et al., 2021; Bernath et al., 2021) emphasise the central role of satellite observations in constraining these effects, while also revealing unresolved discrepancies in observed abundances (e.g. MIPAS versus ACE for phosgene). Emissions from parent species generally lead to a systematic increase in radiative forcing, typically modest (1–3%), but substantially larger for carbon tetrachloride ($CCl_4$), where increases of 5–15% have been reported but depend strongly on the satellite product used (see Thornhill et al., 2024). In addition, the definition of radiative forcing itself has evolved. The IPCC now favours the concept of Effective Radiative Forcing (ERF), which includes atmospheric adjustments —such as for clouds— based on Earth System Models (ESMs). To date, however, halocarbon ERF calculations are available only for the direct effects of CFC-11 and CFC-12. The IPCC applies a tropospheric adjustment of 12 ± 13% to these two compounds, while assuming 0 ± 13% for all other halocarbons. Further limitations arise because radiation codes in ESMs consider only a small subset of halocarbons, even though atmospheric adjustments are estimated to enhance forcing by approximately 10–20%. The net radiative forcing from ozone-depleting substances (ODSs) remains poorly constrained. It varies significantly among individual gases and involves a cascade of indirect effects: ozone depletion reduces radiative forcing, alters methane lifetime, and subsequently affects tropospheric ozone and stratospheric water vapour. Taken together, these uncertainties mean that the overall climate benefit of the Montreal Protocol is still not fully quantified.

**Michiel van Weele** (KNMI) presented the status of Europe's operational space-based monitoring of atmospheric composition, which integrates multiple components and draws on EU, ESA, IGACO, and EUMETSAT activities. The CAPACITY report dated October 2005(!) already highlighted the themes to be supported operationally by Europe (Stratospheric Ozone and Surface UV radiation; Air Quality; Climate) and addressed the needs of specific user categories, including the definition of explicit data requirements. Requirements included a limb component for the non-CO2 greenhouse gases. Key geophysical products from the TROPOMI instrument onboard Sentinel-5P were recalled, alongside the upcoming missions, with a focus on Sentinel-4 (S4), IASI-NG, Sentinel-5 (S5), CO2M, and the TANGO mission. Greenhouse gas (GHG) monitoring is a central element of this system, with particular emphasis on carbon dioxide ($CO_2$) and methane ($CH_4$). Although the operational space system primarily targets these key GHGs, it also provides essential constraints on less observed or indirectly inferred components. Short-lived precursor gases offer valuable "fingerprints" that enhance the monitoring and attribution of specific GHG emissions. The AGATE project was mentioned as an example of current efforts to estimate $NO_2$ emissions. Advanced methods are being developed to use $NH_3$ and soil $NO_x$ products to constrain surface fluxes of nitrous oxide ($N_2O$) and methane ($CH_4$) and provide comprehensive insight into the Earth system. In addition, land-use satellite observations provide further constraints, improving our understanding of $N_2O$ and $CH_4$ budgets across different ecosystems. The key message was that the combination of multi-disciplinary operational satellite data is essential for the operational attribution, monitoring, and verification of $CO_2$ and non-$CO_2$ GHG emission inventories. Finally, Michiel announced the 10th International Symposium on Non-$CO_2$ Greenhouse Gases (NCGG), to be held on 15–17 June 2026 in Utrecht (The Netherlands), focusing on methane ($CH_4$), nitrous oxide ($N_2O$), fluorocarbons, and other halogenated species.

**Lorenzo Biasiotti** (INAF-OATs) presented the impact of Space Weather on Earth's atmospheric chemistry and climate. He started from the ESA definition of space weather, which can influence the functioning and reliability of spaceborne and ground-based systems and services, with main events including solar flares, Coronal mass ejections (CMEs), and the emission of Solar energetic particles (SEPs). He emphasised that the formal definition does not mention changes in atmospheric species, but he introduced ion chemistry triggered by SEPs. High-energy protons can penetrate the polar regions where they collide with the Earth's atmospheric gases, producing fast secondary electrons that can dissociate $N_2$, producing both the electronic ground state N(4S) and the electronic first excited state N(2D) of the nitrogen atom, which in turn readily react with ambient atmospheric gases to form odd hydrogen HOx (H, OH, $HO_2$; short lifetime) and odd nitrogen NOx (N, NO, $NO_2$; longer-lived) gases, which contribute to catalytic $O_3$ destruction cycles. In addition, he mentioned the work of Airapetian et al. (2020), who showed that $N_2O$ is efficiently produced through frequent energetic particle precipitation. He continued presenting the results of his team's work on whether the latest could represent a solution to the faint young Sun paradox. They used a pipeline of models to describe different possible Archean Earth and showed that, if the initial gas mixture contained 10% $CO_2$ and 10 ppm $CH_4$, the two most abundant species produced are CO and $H_2$. However, he emphasised that this condition does not result in a significant increase in global temperature (maximum warming of only ~0.3 K) and that the contribution from nitrogen species, such as $N_2O$ and HCN, is negligible, in contrast to what has previously been proposed in the literature. He concluded that the cumulative effects on the present-day Earth of a prolonged period of intense solar activity (Carrington-like SEP events) would result in a global surface temperature decrease of nearly 4 K, due to a decrease in the concentration of minor greenhouse gases.

Gabriele Stiller and Kaley Walker remarked that, in particular for the Halloween event, many studies have analysed this type of event using MIPAS and ACE-FTS observations.

**Koffi Ayassou** (University of Lomé) presented a study on the impact of hydrofluorocarbon (HFC) emissions on global average temperature, with a focus on Togo. He recalled that HFCs were introduced as replacements for chlorofluorocarbons (CFCs) in refrigeration, air conditioning, and aerosol propellants. While HFCs do not deplete the ozone layer, they are powerful greenhouse gases, with global warming potentials considerably higher than that of $CO_2$. The Kigali Amendment to the Montreal Protocol (2016) established global phase-down schedules for HFC production and consumption. Under this framework, Togo, classified as a Group 1 developing country, is required to gradually reduce HFC use between 2024 and 2048, targeting a reduction to 15% of its reference level. In his study, Koffi Ayassou simulated the contribution of Togo's HFC emissions to global mean temperature increase. Using the Long-range Energy Alternatives Planning – Integrated Benefits Calculator (LEAP-IBC) model, the 2018 HFC emissions were projected forward to 2030. This analysis highlighted Togo's potential contribution to achieving the Paris Agreement's 1.5 °C temperature-limit goal. The results indicate a projected 305% increase in HFC emissions by 2030, driven primarily by rising demand in the refrigeration and automotive air-conditioning sectors, a trend reinforced by increasing temperatures in tropical regions. Although Togo's individual contribution is small, its cumulative effect—together with emissions from other sectors and countries—adds to the pressure on the 1.5 °C threshold identified in multiple IPCC scenarios. The key message is that, without mitigation measures, HFC emissions from Togo could contribute approximately $9 \times 10^{-5}$ °C to global warming by 2030, underscoring the urgency of action to meet national and international climate commitments. As a next step, the study recommends strengthening HFC emission inventories in Togo through the integration of satellite observations and ground-based measurements.

Keith Shine noted that the expected rise in energy demand and its impact on both fossil fuel and renewable energy sources has not been assessed in the study.

**Nicola Tasinato** (Scuola Normale Superiore, Italy) presented a study on the atmospheric reactivity, infrared absorption cross sections, and climate metrics of HCFC-132b. He recalled that the Montreal Protocol and its subsequent amendments regulate the phase-out of ozone-depleting substances (ODSs), with a full ban on CFCs implemented by 2010 globally. HCFCs and HFCs were introduced as replacement gases subject to progressively stricter phase-out requirements. Nevertheless, emissions of several ODSs are declining only slowly, or in some cases increasing, as observed for HCFC-132b. The study focuses on the degradation of halocarbons in the context of climate change. Understanding the rate and location of their atmospheric degradation is essential for assessing long-term accumulation. In addition, the work seeks to identify potentially harmful breakdown products, provide key parameters such as atmospheric lifetimes for chemical transport models, and quantify associated climate metrics, including radiative efficiency (RE) and global warming potential (GWP). This work represents the first spectroscopic investigation of HCFC-132b: infrared absorption cross sections were derived from measurements performed at Università Ca' Foscari, Venice, Italy, covering the spectral range 150–3500 $cm^{-1}$. The experimental data are complemented by quantum-chemical (QC) predictions of gas-phase atmospheric degradation pathways, including photolysis and reactions with major atmospheric oxidants (OH, Cl, $NO_3$, and $O_3$). Climate metrics for HCFC-132b, including retrieved radiative efficiency and global warming potentials, were subsequently derived. The QC workflow linking molecular properties to climate metrics—such as atmospheric lifetimes and IR absorption cross sections—achieves accuracy comparable to experimental measurements, demonstrating its suitability for screening candidate replacement compounds and supporting informed policy decision-making.

Bianca Maria Dinelli asked whether data had been shared with the HITRAN community. Nicola Tasinato answered that the data he presented had not been provided, but new data will be made publicly available.

Tiziano Maestri asked whether the team expects the effective radiative efficiency to vary with changes in temperature and pressure. Nicola Tasinato answered that, in most cases, no significant change is expected, but theoretically, in some cases, it could happen.

**Daniela Alejandra Alvarado Jiménez** (Scuola Normale Superiore, Italy) presented work on the contribution of low-wavenumber absorption to halocarbon radiative forcing. The Pinnock Curve (1995, with a 2020 update) highlights the spectral regions where weak absorbers, such as halocarbons, exert the greatest radiative forcing (RF). This curve is derived from a combination of narrow-band and line-by-line radiative transfer calculations. Halocarbon absorption cross-sections below 500 $cm^{-1}$ have been poorly characterised due to instrumental limitations (Hodnebrog et al., 2020). In this study, the first experimental measurements in this spectral region were performed at the RAL High-Resolution Spectroscopy Facility using a Bruker IFS125, over the temperature range 225–298 K. Measurements were obtained for selected molecules (HFC-236fa, HFC-245fa, and HFC-43-10mee). Integrated IR absorption band strengths below 500 $cm^{-1}$ show good agreement with quantum chemical modelling. This work complements the HITRAN database, which does not currently extend to such low wavenumbers. For all three molecules, the computational results proved reliable in predicting radiative efficiency across the full frequency range, particularly in the challenging low-frequency region. Including low-frequency absorption significantly improves the accuracy of radiative efficiency (RE) and global warming potential (GWP) calculations, supporting more robust and informed climate-mitigation assessments.

Simon Pinnock recalled that the FORUM mission will be measuring this spectral range, making coordination and information exchange between the two projects particularly important.

Bianca Maria Dinelli confirmed that the HITRAN database does not currently cover this spectral range, highlighting the need for such a dataset.

Tiziano Maestri noted the major uncertainty associated with the water vapour continuum in this spectral range and that FORUM aims to address this gap, and emphasised the important contribution of this study.

**Laura Saunders** (University of Toronto) introduced her recent study (Saunders et al., 2025) on the Age of Air (AoA) from ACE-FTS measurements of sulfur hexafluoride ($SF_6$). Briefly introducing the Brewer-Dobson circulation (BDC), she emphasised that climate models predict the BDC will speed up due to increasing radiative forcing from greenhouse gases, and that this will, in turn, modify the distribution of atmospheric gases. Starting from the definition of AoA, the time that has elapsed since an air parcel left the troposphere, she explained that a decrease in the AoA over time would indicate that the BDC is speeding up. Laura Saunders clearly introduced the basic idea behind the calculation of AoA: tropospheric $SF_6$ increases over time and shows no seasonal cycle, making it a useful clock. For example, a stratospheric SF6 measurement of 7 pptv in 2020 corresponds to the tropospheric VMR in 2011, so **Δ**t=~9 years. ACE-FTS SF6 v3.5/3.6 dataset (February 2004-February 2021) has been used since, as expected, mean profiles decrease with altitude above 22 km (not true in v5.2). Inter-comparisons with coincident profiles from MIPAS V5R (MIPAS-IMK Version 5 - Reduced resolution) and observations from three BONBON balloon flights have been performed, showing a good agreement. She presented the ACE-FTS AoA climatology (1 month, 10º latitude, 3 km altitude bins) and explained that the mesospheric $SF_6$ sink has been corrected by applying the correction scheme developed by Garny et al. (2024). Focusing on the midlatitude lower stratosphere (40-50, 50-60, 60-70ºN and S, 14-17km and 17-20km), the climatology has been fitted with a parametric function that includes proxies for the QBO, ENSO, and the solar cycle. The trend (linear component of the parametric function) was insignificant in 8/12 regions, but negative in the others, suggesting that the shallow branch of the BDC is accelerating. A similar analysis has been performed using the MIPAS reduced resolution period (2005-2012), and the results have been compared with those from an analysis exploiting MIPAS V5R data, showing trends within 2 standard deviations of each other. She concluded, emphasising that ACE-FTS v3.5/3.6 has the highest quality global $SF_6$ product available at this time and that they have a global 17-year AoA dataset based on $SF_6$ measurements from ACE-FTS.

Anu Dudhia asked whether the team has already explored the possibility of using $SF_4$ instead of $SF_6$. Laura Saunders answered that they had not yet exploited $SF_4$ for this approach, since the products need to be validated, but they expected noisier data.

**Federico Fabiano** (CNR-ISAC) summarised the results of the literature review on OLLGHGs, highlighting their key role in anthropogenic radiative forcing (about 20%). He also stressed that many of these gases' concentrations are not decreasing as expected and, in some cases, are increasing. Federico Fabiano introduced the ongoing Coupled Model Intercomparison Project - Phase 6 (CMIP6, Eyring et al. 2016), which places significant emphasis on the use of OLLGHGs data for climate modelling. In the context of this project, models require observed or reconstructed GHG concentrations as input for the historical simulation (1850-2014). Currently, these models incorporate 43 GHGs data from NOAA ESRL and AGAGE networks (Meinshausen et al., 2017). However, since only surface data is utilised and models require 3D distributions, the vertical extension is presently based on simplified assumptions, including a well-mixed troposphere with predefined latitudinal variations. The implementation of observed 3D GHGs concentrations in these models would be immensely beneficial, particularly for radiative computations and assessing the effective Radiative Forcing (ERF). He pointed out that the model community is now moving towards phase 7 of CMIP (CMIP7), but is still focusing on ground-based observations, such as those from the Global Greenhouse Gas Reference Network (GGGRN). Federico Fabiano also introduced the Climate-Chemistry models (CCMs), which are AOGCM + chemistry modules (CCMI, Morgenstein et al., 2017; AerChemMIP, Collins et al., 2017). These models can simulate the transport and mixing of chemical species and can even be 'emission-driven'. Even this type of model could benefit from new or more comprehensive data on OLLGHGs. Then, he introduced the chemistry transport models capable of tracing back atmospheric emissions of specific constituents. Even though a new OLLGHGs dataset can be interesting for this kind of models, for them, an essential need is the high spatial and temporal resolution, which is difficult to achieve with satellite observations. Federico Fabiano also presented the results of the users' needs survey conducted at the beginning of the LOLIPOP project. There have been 42 responses (60% of them are modellers), and most of them agree on the need for new observational datasets on OLLGHGs. The survey results clearly showed that there are two distinct communities with different needs. The community interested in climate applications values datasets with high spatial/temporal coverage, but does not require high spatial resolution. On the other hand, the community engaged in emissions/transport research prioritises products with high spatial and temporal resolution.

# 3 Discussion and wrap-up

Simon Pinnock (ESA) thanked all presenters for their valuable contributions to the workshop, highlighting the clear demonstration of both user needs and existing capabilities that emerged through the numerous application examples showcased. He expressed his appreciation for the quality and relevance of the presentations. The discussion emphasised the added value that satellites can bring, including the use of merged products and supporting datasets. Several new requirements emerged from the workshop, with gap-filling identified as a key priority—recognised as a challenging yet essential task for advancing the field. The discussion also underlined the importance of long-term datasets, particularly for emission studies, and highlighted applications in the stratosphere, where dedicated limb missions are required, as in situ measurements alone are insufficient. Finally, it was stressed the need for exchange and collaboration with other projects, citing MEDUSA as an example, which focuses on methane emission monitoring.

Bianca Maria Dinelli reinforced that limb instruments are currently limited and stressed the need to merge different types of measurements to obtain coverage of the entire atmosphere. Careful identification of the most reliable datasets is thus required. Anu Dudhia suggested exploring the use of geostationary platforms for limb observations. Simon Pinnock acknowledged this point and emphasised the need to advocate for new limb measurements at the decision-making level, ensuring results are communicated effectively, particularly in policy and funding forums such as the upcoming ministerial meeting.

Jeremy Harrison added that laboratory activities should also be considered, notably to identify and validate the most appropriate spectroscopic cross-sections.

Data homogenisation proved to be one of the most demanding aspects of the project. Several lessons were learned, highlighting the importance of defining clear standards early on. In particular, establishing common data formats, units, metadata conventions, and naming rules during mission preparation would significantly reduce downstream harmonisation efforts and associated risks.

It was also noted that engaging more systematically with international climate bodies proved essential. Relevant CMUG case studies provided valuable user-driven insights, while closer coordination with GCOS would ensure readiness for the upcoming ECV reviews. Early, structured, and continuous dialogue with these bodies improves alignment with user needs, facilitates the incorporation of best practices, and streamlines review preparation.

The workshop enabled a better understanding of users' needs and of the available satellite data. One of the main outcomes was the formulation of the following recommendations.

**REC-01 – Fill gaps in existing time series through multi-mission integration.**

Significant gaps remain in the temporal coverage of OLLGHG-related observations. It is therefore recommended to harvest information from existing and heritage satellite missions, and to assess and further develop techniques to ensure consistency and traceability. The feasibility of producing merged and homogenised time series should also be investigated.

**REC-02 – Exploit new datasets and future missions to extend capabilities.**

Potential additional data sources (e.g. MTG-IRS, Sentinel-4, Sentinel-5, IASI-NG) for OLLGHG retrieval.

**REC-03 – Demonstrating the need for sustained Stratospheric observations.**

Address current observational limitations by demonstrating the added value of complementary observing geometries. For stratospheric monitoring and related applications, limb-viewing instruments are essential but currently scarce. The project could be used strategically to demonstrate and reinforce the need for sustained limb observations in future mission planning.

**REC-04 – Boost uptake of LOLIPOP data within the scientific community.**

To maximise scientific impact, a stronger engagement with users is required. Outreach activities shall be enhanced to showcase project results, datasets, and key findings. The following ideas were presented:

- Participation in major scientific conferences (e.g. NCGG, EGU, AGU), organising or contributing to specific dedicated sessions.
- Strengthen connections with other relevant CCI projects (e.g. GHGs, Water Vapour, Ozone) and with the APARC initiative.
- Identify synergies with GCOS and CMUG

**REC-05 – Strengthen User Support and Information Sharing.**

To enable effective use of OLLGHG satellite data, user support should be strengthened by improving access to clear, up-to-date documentation and practical guidance. Information sharing should be enhanced through ad-hoc meetings or workshops to encourage informed and efficient data use.

**REC-06 – Workshop follow-on.**

To maintain momentum and ensure continuity of dialogue with users, it is recommended to organise a follow-up event. This would provide an opportunity to confirm whether user requirements remain valid and to discuss any potential updates.

# 4 Appendix A – List of participants

The list of participants is provided in the following tables.

<u>On-site participants:</u>

| Participant | Affiliation |
|---|---|
| Alessandro Montanarini | CNR-ISAC |
| Bart Dils | BIRA-IASB |
| Bianca Maria Dinelli | CNR-ISAC |
| Daniela Alejandra Alvarado Jiménez | Scuola Normale Superiore |
| Elisa Castelli | CNR-ISAC |
| Enzo Papandrea | CNR-ISAC |
| Federico Fabiano | CNR-ISAC |
| Gabriele Brizzi | Serco Italia |
| Gabriele P. Stiller | KIT |
| Giuliano Liuzzi | University of Basilicata |
| Guido Masiello | University of Basilicata |
| Kaley Walker | University of Toronto |
| Keith P. Shine | University of Reading |
| Laura Saunders | University of Toronto |
| Lorenzo Biasiotti | INAF-OATs |
| Marco Falda | University of Bologna |
| Marco Gai | CNR-IFAC |
| Margherita Premuda | CNR-ISAC |
| Martina Taddia | CNR-ISAC |
| Massimo Valeri | Serco Italia |
| Nicola Tasinato | Scuola Normale Superiore |
| Paolo Cristofanelli | CNR-ISAC |
| Paolo Pettinari | CNR-ISAC |
| Piera Raspollini | CNR-IFAC |
| Roberto Luciani | Serco |
| Simon Pinnock | ESA |
| Stefano Della Fera | CNR-IFAC |
| Tiziano Maestri | University of Bologna |

Remote participants:

| Participant | Affiliation |
|---|---|
| Amy Doherty | CMUG |
| Ayassou Koffi | University of Lomé |
| Claire Macintosh | ESA |
| Paolo Laj | WMO |
| Sophie Vandenbussche | BIRA-IASB |
| Michiel Van Weele | KNMI |
| Antonio Giovanni Bruno | NCEO |
| Simon Whitburn | ULB |
| Deodato Tapete | ASI |
| Windy Chyntia Dewi | Oxford University |
| Daniele Minganti | BIRA-IASB |
| Sandip Dhomse | Uni. Leeds |
| Marc Op de beeck | BIRA-IASB |
| Flavio Barbara | CNR-IFAC |
| Simon Chabrillat | BIRA-IASB |
| Belén Martín Míguez | WMO |
| Pamela Wales | NASA |
| Francesco Graziosi | JRC |
| Maya George | LATMOS/CNRS |
| Cathy Clerbaux | LATMOS/CNRS |
| Felix Ploeger | FZJ |
| Florian Voet | FZJ |
| Samuele Del Bianco | CNR-IFAC |
| Francesco Pio De Cosmo | CNR-IAC |
| Luca Sgheri | CNR-IAC |
| Jeremy Harrison | NCEO |
| Anu Dudhia | Oxford University |
| Klara Gunnarsson | ESA |

# 5 Appendix B – Final Agenda


## ESA CCI - LOLIPOP User Workshop

**Understanding Satellite Observations of Anthropogenic Greenhouse Gases other than $CO_2$ and $CH_4$**

**18-19 November 2025 | Bologna (Italy)**

**DAY 1: Meeting starts at 10:30 -** Timezone: Europe/Rome

| | | | |
|---|---|---|---|
| **10:30** | 10 min | Workshop Practicalities | (Serco/CNR) |
| **10:40** | 10 min | Welcome | Maria Cristina Facchini (CNR-ISAC Director) |
| **10:50** | 10 min | Opening Remarks | Bianca Dinelli (CNR-ISAC) |
| **11:00** | 10 min | Italy's view on Space | Deodato Tapete (ASI) |
| **11:10** | 15 min | ESA CCI programme Intro | Simon Pinnock (ESA) |
| **11:25** | 20 min | Overview of the ESA CCI LOLIPOP project | Elisa Castelli (CNR-ISAC) |
| **11:45** | 20 min | Dataset harmonization and validation/inter-comparison: Nadir products | Bart Dils (BIRA) |
| **12:05** | 20 min | Dataset harmonization and validation/inter-comparison: Limb products | Kaley Walker (University of Toronto) |
| **12:25** | 20 min | **Case study 1**: Sensitivity of historical climate model simulations to the OLLGHGs climatology | Federico Fabiano (CNR-ISAC) |


| | | | |
|---|---|---|---|
| **12:45** | 20 min | **Case study 2:** Study of the radiative forcing of OLLGHGs | Reinhold Spang (FZJ) |
| Lunch break | | | |
| **14:30** | 20 min | **Case study 3:** Monitoring of stratospheric chlorine levels and their impacts on ozone recovery | Antonio Giovanni Bruno (NCEO) REMOTE |
| **14:50** | 20 min | **Case study 4**: CLaMS stratospheric circulation estimates | Felix Plöger (FZJ) REMOTE |
| **15:10** | 20 min | **Case study 5**: The atmospheric lifetimes of OLLGHGs | Jeremy Harrison (NCEO) REMOTE |
| **15:30** | 20 min | Insights into GCOS's mission for ECVs | Belén Martín Míguez (WMO) REMOTE |
| **15:50** | 40 min | Coffee break | |
| **16:30** | 20 min | Insights from the ESA CCI Climate Modelling User Group (CMUG) | Amy Doherty (Met Office) REMOTE |
| **16:50** | 20 min | Operational monitoring of atmospheric composition: current status | Michiel van Weele (KNMI) REMOTE |
| **17:10** | 20 min | Integrating Earth Observations into GHG Forcing Datasets for CMIP | Florence Bockting (Climate Resource) REMOTE |

**DAY 1: meeting ends at 17:30**

**Evening: Social dinner ( no-host ) 19:30**

**DAY 2: Meeting starts at 9:00** - Timezone: Europe/Rome

| | | | |
|---|---|---|---|
| **9:00** | 15 min | Day 1 recap | CNR-ISAC |
| **9:15** | 15 min | Halocarbon radiative forcing | Keith Shine (Uni. Reading) |
| **9:30** | 15 min | Middle atmospheric mean transport derived from satellite data of tracers | Gabriele Stiller (KIT) |
| **09:45** | 15 min | The impact of Space Weather on Earth's atmospheric chemistry and climate | Lorenzo Biasiotti (INAF-OATs) |
| **10:00** | 15 min | Simulation of the impact of hydrofluorocarbon (HFC) emissions in Togo on global average temperature | Koffi Ayassou (Uni. Lomé) REMOTE |
| **10.15** | 15 min | Atmospheric reactivity, infrared absorption cross section and climate metrics of HCFC-132b | Nicola Tasinato (SNS) |
| **10.30** | 40 min | Coffee break | |
| **11.10** | 15 min | Contribution of low-wavenumber absorption to halocarbon radiative forcing | Daniela Alejandra Alvarado Jiménez (SNS) |
| **11.25** | 15 min | Age of air from ACE-FTS measurements of sulfur hexafluoride | Laura Saunders (University of Toronto) |
| **11.40** | 30 min | Review of climate applications and user needs | Federico Fabiano (CNR-ISAC) |
| **12.10** | 50 min | Discussion and wrap up | All |

**DAY 2: meeting ends at 13:00**

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