Satellite limb observations of UTS composition

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Satellite limb observations of vertically-resolved atmospheric composition in the upper troposphere and stratosphere (UTS) from the past four decades have been of key importance for solving the science questions behind anthropogenic ozone depletion. By monitoring the state of the stratospheric ozone layer that protects human and ecosystem health, these observations have particularly underpinned the Montreal Protocol, which is widely considered the most successful international treaty for the protection of the environment. Moreover, satellite limb sounders have provided us with invaluable information necessary to study transport and dynamics and to evaluate climate variability and trends e.g., in the IPCC Assessment Reports.

Key atmosphere-related challenges for Earth System Science

Future key challenges for Earth System Science that need to be addressed over the coming decades will involve chemical and physical processes in the atmosphere and their interaction with climate change. The chemical composition of the troposphere and stratosphere, explored by a wealth of stratospheric limb observations during the past 35 years, has been found to be a critical factor determining radiative forcing and decadal-scale climate change. Future research in the field of chemistry-climate interactions will move beyond well-understood radiative forcing mechanisms and new frontiers will include the following key aspects:

1. Understanding the three-way coupling between chemical, dynamical, and radiative processes and related modulations of climate sensitivity; in particular the impact of climate change on the natural balance of the ozone layer and the stratospheric composition and chemical effects of greenhouse gases or other shorter-lived biogenic compounds,
2. Exploring the dynamical coupling between the stratosphere and the troposphere with a focus on regional variations of the atmospheric circulation and on seasonal-to-decadal climate predictions,
3. Improving weather and air pollution forecasting systems whose skills are influenced by accurate knowledge of stratospheric and mesospheric constituents, temperatures and winds.

Addressing these challenges and in particular understanding the interactive role of atmospheric chemistry in the climate system demands both new and continuing observations, along with development and validation of chemistry-climate models. A key requirement for future research tasks will be the availability of UTS data sets of temperature, wind, chemical trace gases and aerosol from limb-viewing satellite instruments. Such data sets are essential for their direct use in detailed process studies enhancing our understanding of the chemical, dynamical and radiative coupling and also in empirical studies of trends and variability. The lack of limb satellite observations, as currently faced by the atmospheric community, would threaten the capability of the WMO to fulfill its mandate to the Parties to the Montreal Protocol, namely to observe and report on the state of the ozone layer . Additionally, the evaluation of the representation of transport and chemistry in numerical models involves many trace gas data sets from limb sounders. In summary, without vertically resolved UTS satellite data sets, studies of stratospheric chemistry and climate, including stratosphere-troposphere coupling, will be severely hampered on many levels, preventing fast progress in key scientific areas.

In addition to the continuation of data sets, basic information on their availability, quality and consistency is required for all scientific applications. In particular, the evaluation of chemistry-climate models or the merging of data sets from various sources into homogeneous data records suitable for trend studies requires detailed knowledge of the availability and quality of satellite observations. The Stratosphere-troposphere Processes And their Role in Climate (SPARC) core project of the World Climate Research Programme (WCRP) initiated the SPARC Data Initiative in 2009 with the mandate to coordinate an assessment of available, vertically resolved chemical trace gas and aerosol observations obtained from a multi-national suite of space-based satellite instruments. The evaluations within the SPARC Data Initiative illustrate that there is no single best instrument that potentially covers all measurement needs, because instruments differ greatly in their measurement characteristics such as spatial and temporal sampling, viewing geometry, accuracy and precision, and measurement stability. It is only through careful comparison between the instruments that outliers can be detected, and weaknesses and strengths of instruments can be identified. For some trace gas species, good agreement between instruments is found and the atmospheric mean state distributions and variability can be considered well-known (e.g., O_3, N_2O, CH_4). However, for other species that are measured by a few instruments only and for which not many ground-based validation measurements are available, our knowledge is still limited (e.g., CO, and many short-lived species such as HO_2, OH, BrO, ClO). The overall recommendations of the SPARC Data Initiative highlight species or regions for which future observations are most needed:

- There is a general need to improve trace gas observations (especially H_2O) in the tropical and extra-tropical UTLS. Higher spatial and temporal resolution measurements that also penetrate to lower altitudes (well into the upper troposphere) are required to overcome this issue.
- Data merging, even in the case of multiple overlapping instruments, poses a key challenge and impedes our understanding of long-term changes of the stratosphere in a changing climate. For a scenario with no overlap between two instruments, the possibility to derive reliable long-term changes of atmospheric tracers such as H_2O and O_3 would be eliminated.
- The long-term monitoring of stratospheric HCl hinges on two instruments (ACE-FTS and Aura-MLS), which are both past their expected lifetimes. The abundance of HCl (scaled to yield Cl_y) in the stratosphere is an important measure to assess the effectiveness of the Montreal Protocol, which controls the use of chlorine-containing substances that lead to the destruction of ozone. New

HCl measurements are needed to fulfill the obligations to the Montreal Protocol in the future.

- At present, there is a lack of measurements that provide the necessary species to establish budgets of chemical families such as Br_y, Cl_y and NO_y. Current estimates of these families rely heavily on the use of chemical box models and hence independent validation is not possible.

The SPARC Data Initiative evaluations demonstrate clearly that there is no single instrument that can provide measurements of the full suite of needed atmospheric trace gas species with high vertical and horizontal resolution, high accuracy and precision, and dense data coverage. Only a comprehensive set of high quality instruments that are complementary with respect to data coverage and target species allows development of a global picture of stratospheric composition. In order to monitor, analyze and understand atmospheric composition, transport and chemistry in the future, multiple limb-viewing instruments as described above are required.

Capabilities of existing and planned U.S. and international programs

It has to be expected that there will be a lack of adequate limb measurements in the near future. This looming problem is due to an ageing fleet of currently still flying limb sounders (Aura-MLS, ACE-FTS, OSIRIS and SMR) along with the lack of any concrete plans to launch new instruments except for SAGE III on the International Space Station (ISS) (which offers only limited spatial coverage) and the OMPS-LP instruments (which have only limited vertical resolution, especially in the UTLS). Also, these instruments offer observations of a small number of atmospheric constituents only (both measure ozone and aerosol; SAGE III in addition measures H_2O, NO_2, and NO_3). Thus, there is an impending gap in the global observations of these essential climate variables.

Given the future key challenges in the field of atmospheric chemistry in the climate system and the impending gap, new limb satellite missions need to be planned and executed as quickly as possible. Key for the future planning of satellite limb sounders is to design measurement systems that meet specific measurement needs in terms of scientific research questions, regions of interest, resolution, accuracy and precision. Furthermore, the missions need to offer redundancy between measurements, so that irregularities, problems, and in the worst case failures can be identified early and investigated adequately.

Anticipated scientific and societal benefits

Satellite observations of stratospheric composition would allow for the investigation of outstanding science questions relating to stratosphere-troposphere coupling, future climate, and air pollution. Air quality is one of the world's biggest health risks according to the WHO with annual premature death rates of around 7 million people that are attributable to bad air quality. The stratosphere has recently been identified to play an important role in determining background ozone levels, trends, and in some cases even extreme pollution events. Future air quality policy regulations from national governments therefore would benefit from the information on ‘natural’ contributions to air pollution from the stratosphere.

Involved science communities

The importance of stratospheric observations is expressed by the broad range of potential users, which not only includes the stratospheric observation and modeling community (SPARC), but also the air quality and emissions community (IGAC, NMHCs) (with foci on stratosphere-troposphere interactions from both the observational and modeling sides), the weather prediction community (including national and international weather forecast centers such as NCEP, ECMWF, NASA/MERRA, JRA), and finally observationalists from other science communities (such as AIMES) who use stratospheric composition measurements (in particular aerosol) to constrain the retrievals of e.g. SAR instruments.