THE CRITICAL ROLE OF THE UPPER TROPOSPHERE AND STRATOSPHERE IN CLIMATE AND AIR QUALITY

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Points[1] (c) and (d)

Question 1: *What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*

Anthropogenic influences on atmospheric composition are the main drivers of global change[2] and have major impacts on human and ecosystem health.[3] Links between composition and physical climate, as seen, for example, in the relationships between stratospheric ozone depletion/recovery, subtropical precipitation, ocean salinity, and polar ice cover[4–6] further demonstrate the broad impact of atmospheric composition on the Earth system. Beyond basic research, atmospheric composition and air quality are vitally important for the human and ecosystem health applications communities.

One of the foremost challenges in Earth System Science is the need to improve predictive capability for atmospheric composition on both the decadal timescale associated with climate forcings and feedbacks and the weekly timescale required for accurate air quality forecasts. Prominent among the impediments to meeting this challenge is the fact that state-of-the-art models at all scales still poorly represent key processes controlling water vapor, composition, and clouds in the upper troposphere and lower stratosphere[7–9] (UT/LS), where the radiative impact of water vapor (the strongest greenhouse gas) and ozone is greatest.[10,11] Rapid lofting of near-surface air by deep convection strongly influences the UT/LS, and the fast winds and long chemical lifetimes characterizing this region promote global pollution transport. In addition, the stratosphere, which is inextricably linked to surface climate,[12,13] continues to undergo severe ozone destruction induced by unnaturally large abundances of chlorine.[4,14] Furthermore, long-term trends and substantial but poorly understood variability[15] in stratospheric water vapor strongly influence surface climate[16,17] and the ozone layer.[4]

The atmospheric composition community has identified critical questions[18–20] whose resolution is essential for improving our predictive capability, including:

- How will UT/LS water vapor and ozone and associated chemical processes evolve in a climate with increased greenhouse gases (GHGs) and changing ozone depleting substances (ODSs)?
- Given their strong radiative impact, how will changes in UT/LS water vapor and ozone feed back on climate?
- How do deep convection and cirrus clouds interact with upper tropospheric water vapor?
- To what degree is the Brewer-Dobson Circulation (BDC) accelerating, and what are the implications of this change?
- What are the relative roles of various stratosphere troposphere exchange (STE) mechanisms (e.g., deep convection, monsoon circulations, intrusion events) in establishing stratospheric and tropospheric composition and air quality? How will those roles change in an evolving climate?
- How is tropospheric ozone changing globally and regionally, and what drives that variability on all timescales (emissions, chemical processing, convective lofting, long-range horizontal transport, STE)?

Question 2: *Why are these challenges/questions timely to address now, especially with respect to readiness?*

Resolution of the key questions outlined above is particularly timely given that the coming decade will be a pivotal period for the upper troposphere and stratosphere (UT/S), with signs of ozone layer recovery in response to declining ODSs expected to emerge in some regions,[4] concurrent with ongoing increases in GHGs. Although the past record of composition measurements has proven invaluable for addressing major societal issues (e.g., stratospheric ozone destruction), an extended data record, including improved precision/resolution and additional species, is required for further progress in advancing the state of the art in model realism;[18] indeed, an impending lack of relevant measurements (see below) represents the greatest obstacle to our readiness to move the science forward. Recent studies have exploited available multi-sensor multi-year UT/S records for attribution of changes in Earth system variables,[21] underscoring the value of extended long-term global measurements. A framework such as that recently recommended by the National Academies[22] can be used to establish the optimal balance between "continuity" and new measurements. In addition, interest is growing in "geoengineering" approaches to tackling climate change,[23] including injection of aerosols into the stratosphere, any serious consideration of which demands comprehensive understanding of the UT/S and its sensitivities.

The processes affecting atmospheric composition take place in different domains (boundary layer, mid troposphere, upper troposphere, stratosphere), and no single measurement technique is capable of probing them all. Research needs in *tropospheric* composition over the next ten years can be met *in part* by planned nadir-viewing sensors (in both low-earth and geostationary orbits) that will or could provide uninterrupted measurements of tropospheric composition. Compan-

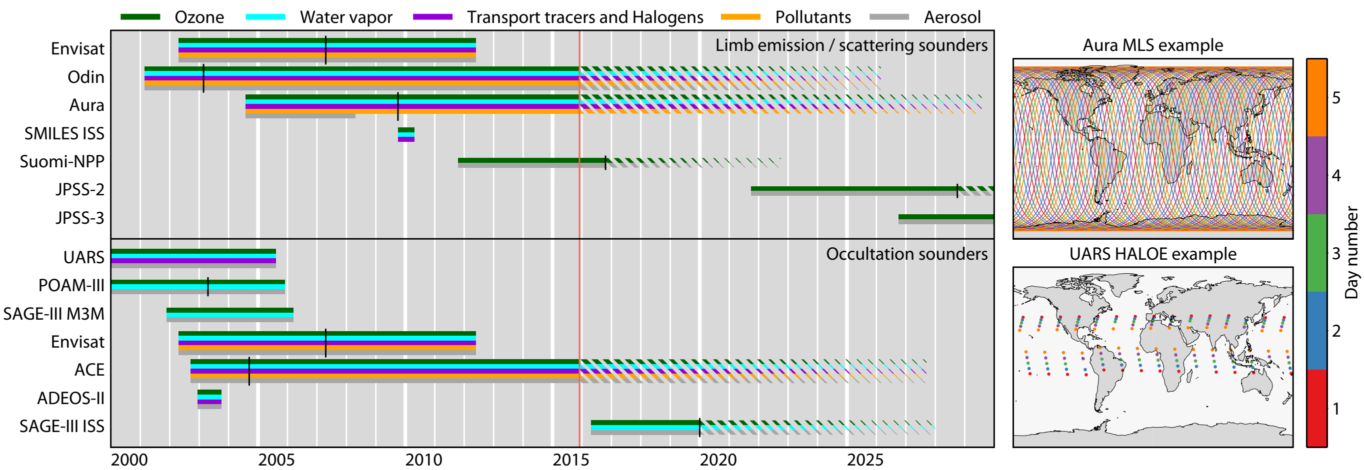

Figure 1: Left: Timeline of high vertical resolution satellite UT/S observations. Vertical bars indicate design lifetime / end of prime mission; hatching indicates potential extended mission operations. For Suomi-NPP, one year of overlap with JPSS-2 is assumed (as JPSS-1 has no OMPS-LP). SAGE-III ISS life is set by ISS extended operations (2020 – 2028, subject to negotiation). Other end dates assume a maximum 25-year mission (in compliance with international agreements on space debris). Right: Typical 5-day coverage for limb emission sounding (upper) and solar occultation (lower).

ion white papers[24] lay out the case for new programmatic opportunities to exploit or develop tropospheric composition products from existing and known future instruments, and also identify measurement priorities that will remain unmet.

In contrast, prospects for future measurements with the vertical resolution necessary to capture the strong gradients in the UT/S are meager. Suitable instruments fall into two broad categories: limb emission/scattering sounders with daily near-global coverage, and solar/lunar/stellar occultation sounders with sparser spatial coverage but typically better precision and vertical resolution. Figure 1 summarizes the capabilities of relevant current and planned instruments, illustrating the anticipated dramatic decrease in measurement assets in the coming decade. The looming cessation of such observations has been emphasized in international assessments,[25] and is expected to be heavily stressed in the GCOS[26] *Status of the Global Observing System for Climate* report[27] to parties of the UNFCCC.[28]

The past decade has been characterized as a "golden age" for space-based atmospheric research. This is particularly true for the UT/S as, at peak, twelve limb/occultation sounders were operational on eight satellites. In contrast, in the coming decade only one occultation and one limb sounding instrument are planned to be launched by any agency or country. OMPS-LP[29] scheduled for launch on JPSS-2/3[30] in 2021/2026, respectively, will measure only ozone and aerosol. Their coverage, while dense, excludes nighttime regions, notably polar night (a shortcoming that ruled out consideration of similar techniques for a European "Operational Ozone" capability[31]). Apart from that limitation, and the extended period of "blindness" that would follow any strong volcanic aerosol injection,[32] OMPS-LP will likely meet most needs for daily near-global profile observations of ozone and aerosol after 2021.

For other critical UT/S measurements, however, the outlook is bleak. Only SAGE-III,[33] to be deployed on the ISS[34] in 2016, will measure UT/S water vapor. (SAGE-III will also measure ozone, aerosol, and other minor species.[35]) The sparse SAGE-III sampling, however, hinders its applicability to key scientific studies. For example, rising bands of moist and dry air in the tropical lower stratosphere (the "tape-recorder" signature[36]) give the best observational measure of the speed of the BDC[37] and its response to climate variability. Variations in this circulation have critical impacts on polar ozone loss[38] and on the stratospheric contribution to tropospheric ozone.[39,40] The sporadic solar occultation sampling of the tropics (at best a handful of days each month) provides an inaccurate picture of these variations (see Figure 2 for HALOE[41] example).

Furthermore, neither SAGE-III nor OMPS-LP measure other key UT/S species, notably:

Tropospheric pollution tracers: Satellite observations of carbon monoxide have proven essential to studies of emissions, convection, and long-range transport.[42,43] Species such as hydrogen cyanide and methyl chloride can help differentiate industrial, biomass burning, and biogenic sources.

Long-lived stratospheric tracers: Species such as nitrous oxide and/or methane provide unique information on transport and mixing. Knowledge of their stratospheric distribution is essential to understanding their lifetimes and, thus, climate impact.[44,45] Declines in controlled ODSs raise the importance of nitrous oxide for ozone layer stability.[4]

Stratospheric chlorine and bromine species: Such measurements are needed to quantify the balance between dynamical and chemical influences on stratospheric ozone.[4,14]

Infrared and microwave limb sounders can fill these critical observational gaps. These instruments measure thermal emission both day and night, have strong heritage, and offer complementary capabilities. While infrared sounders can typically measure to slightly lower altitudes (6 – 8 km lower limit vs. 8 – 10 km for microwave sounding), microwave instruments are significantly less affected by aerosols and clouds, thus affording many more measurements of the tropical upper troposphere.

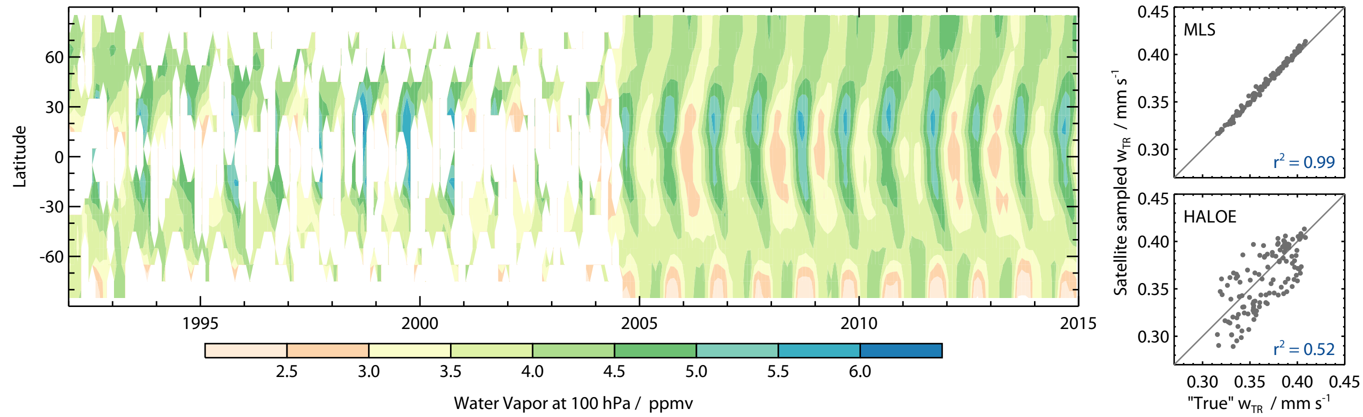

Figure 2: Left: Zonal mean timeseries of 100 hPa water vapor from GOZCARDS[46] (UARS HALOE solar occultation to 2004, Aura MLS limb emission thereafter). Right: Impact of satellite sampling on the estimation of tropical lower stratospheric ascent rates. Water vapor fields from 10 years of CMAM-30[47] output have been sampled at representative MLS and HALOE observation locations, and ascent rates estimated.[48] Plots compare "true" ascent rates (computed directly from the synoptic CMAM-30 water vapor fields) to those computed from the satellite sampled timeseries.

From a technical readiness perspective, NASA ESTO[49] has invested heavily in advancing the technologies needed for next-generation microwave limb sounders for composition and temperature. These technologies enable (1) dramatic improvements in horizontal, vertical, and temporal resolution, with coverage of the full diurnal cycle, while remaining within the same mass/power/cost envelope as previous sensors, and (2) substantial reductions in mass/power/cost/volume for instruments making "continuity" measurements.

Thanks to these investments, we expect no significant technological barriers to implementing the "advanced microwave limb sounder" identified for the Global Atmospheric Composition Mission (GACM) recommended in the 2007 Decadal Survey.[50] Approaches to providing significantly improved vertical resolution (sub 1 km) within a low-cost (e.g., "Earth Venture") mission profile are also under development.

Question 3: *Why are space-based observations fundamental to addressing these challenges/questions?*

The global impacts of atmospheric composition on climate and air quality mandate a global perspective for composition observations, necessitating a space-based vantage point. This is particularly true for the UT/S, opportunities for *in situ* sampling of which are rarer than for lower altitudes. In addition, ground-based remote sounding observations of most UT/S species lack needed vertical resolution. Vertically resolved sonde and ground-based (e.g., lidar) observations from limited fixed locations are critical to validating and establishing continuity between spaceborne sensors. For stratospheric water vapor, however, long-term trends derived from such records are unrepresentative of global variability.[51]

Process studies are increasingly capitalizing on both *in situ* and satellite composition observations.[52–54] Tools such as dynamically based coordinate systems and Lagrangian techniques can overcome the dramatic resolution and coverage differences between such measurements.

In addition to direct application to UT/S science, spaceborne limb observations of composition and temperature are important components of data assimilation systems and emerging multi-sensor retrieval approaches yielding profiles from the surface through the stratosphere with vertical resolution greater than that of individual instruments.[55,56] The unparalleled insights derived from the "A-Train" constellation's colocated observations of composition and other variables underscore the benefits that accrue from a comprehensive multi-sensor, multi-disciplinary approach to Earth observation.

1. Points addressed herein, as noted in the RFI:
   (a) Whether existing and planned US and international programs will provide the capabilities necessary to make substantial progress on the identified challenges and associated questions. If not, what additional investments are needed?
   (b) How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs;
   (c) The anticipated societal benefits; and
   (d) The science communities that would be involved
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Point (b)

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