Space-Based Observations of Upper Tropospheric and Lower Stratospheric Water Vapor Profiles

Karen Rosenlof[1], Amin Nehrir[2], Thierry Leblanc[3], Troy Thornberry[4], Dale Hurst[4], Richard Ferrare[2], Glenn Diskin[2]

[1]National Oceanic and Atmospheric Administration
[2]NASA Langley Research Center
3 Jet Propulsion Laboratory
4CIRES/NOAA

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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?

Atmospheric water vapor plays both a radiative and chemical role. An increase in stratospheric water vapor will radiatively cool the lower stratosphere and affect the frequency of occurrence of polar stratospheric clouds, thereby impacting stratospheric ozone chemistry. Enhanced levels of stratospheric water vapor strengthen ozone loss in the presence of ozone depleting substances (ODSs). Hence, a climate with increased stratospheric water vapor will have a delayed ozone recovery even while ODSs are reduced. Changes in stratospheric water vapor also can be a significant radiative forcing for surface climate. A ~10% drop in stratospheric water vapor levels near the tropopause at the end of 2000 has been estimated to have contributed a radiative forcing of -0.1 W/m^2; this may have slowed the amount of warming from CO_2 increases over the 2000-2009 period by 25%. Decadal variations of stratospheric water vapor concentrations also likely contributed to an enhanced rate of surface warming in the 1990s.

Stratosphere water vapor is important because the amount of water vapor determines important aspects of the planetary radiative energy balance through the strong cooling to space from water vapor. This contributes to determining the temperature of the stratosphere, which then affects the dynamical circulation of the upper atmosphere and can affect stratospheric chemistry through temperature dependent reaction rates. Moreover, water vapor provides the source of the hydroxyl radical, OH, which takes part in several stratospheric chemical processes. An understanding of how the distribution of water vapor is controlled, and of how this distribution might change in future, is therefore important for understanding certain aspects of climate change.

The 2014 NASA Science Mission Directorate workshop on Outstanding Questions in Atmospheric Composition identified future trends of stratospheric water vapor as a key priority for stratospheric composition research over the next few decades. At that workshop, it was also emphasized that trend detection for stratospheric species requires observations of profiles of these species continue with at least current spatial and temporal resolutions. To address both the chemical and radiative role of stratospheric water vapor to changes in climate, long term global data records are critically needed. Space-based observations are ideal for monitoring stratospheric water vapor as much of the interfering tropospheric water vapor signal resides in the lower troposphere. Complementary ground based and aircraft based measurements are also required for targeted process studies that are on the scale of the processes doing the dehydration. Therefore, both coarse global measurements and fine scale measurements are needed.

The key mechanisms that contribute to control of stratospheric water vapor concentrations are stratospheric photochemistry and transport, tropical tropopause dehydration and polar dehydration. Additionally, transport from the troposphere to stratosphere at mid latitudes also appears to impact stratospheric water vapor. Because we don't fully understand control of stratospheric water, it is difficult to assess how it will change with increasing greenhouse gases. There have been trends noted in past measurements, in particular stratospheric water vapor has been noted to have increased since 1980, but the reason for that increase is not understood. In particular, we don't know what is natural variability and what is forced. Although overshoots of ice into the stratosphere have been observed, we don't know how much they contribute to the overall stratospheric budget. There has been much work looking at impacts of the summer time Asian anticyclone circulation on stratospheric water vapor, but those impacts have not been quantified. Other measurements related to processes, such as temperature, aerosols, and cloud parameters, as well as measurements that can help deduce relevant processes, such as those related to stratospheric transport, are also needed.

To summarize, the key questions to address are:

1) How will stratospheric water vapor and its associated radiative forcing change with increasing greenhouse gases?
2) What is the driving mechanism behind past observed changes in stratospheric water vapor?
3) What is the contribution of overshooting cloud ice to the stratospheric water budget?
4) How does the summertime Asian anticyclone circulation contribute to the stratospheric water vapor budget?
5) What are the key microphysical processes controlling the input of water to the stratosphere?

2. Why are these challenge/questions timely to address now especially with respect to readiness?

Passive infrared and microwave sensors such as the Atmospheric Infrared Radiance Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), Microwave Limb Sounder (MLS), and the Advanced Microwave Sensor Unit (AMSU) have provided a unique opportunity to sample global water vapor distributions in the UTLS. Passive infrared measurements of water vapor typically have a vertical resolution of 1-2 km and their relative error range in the 15-25%, resulting from radiances contaminated by aerosols and clouds. Microwave profilers can provide humidity measurements in regions of non-precipitating clouds, however, they can suffer from underlying biases resulting from uncertainties in the microwave surface emissivity of land. When the current fleet of stratospheric chemistry satellites exceeds their useful lifetime, we will no longer have vertically resolved stratospheric water vapor measurements. Therefore, we need to plan now for a new space based platform for more accurate measurements of stratospheric water vapor profiles. Current space based passive remote sensing platforms provide relatively coarse vertical resolution profiles of water vapor measurements in the upper troposphere and stratosphere. Furthermore, the continuity of the data record is jeopardized as the current suite of measurements are aging and no follow on missions are currently planned.

High accuracy water vapor profile measurements in the upper troposphere and stratosphere are critical for climate research and are essential to form an absolute standard between existing measurements; changing humidity of only a few percent in the upper troposphere and lower stratosphere can influence the upwelling long-wave radiation by an amount similar in magnitude to that caused by doubling of carbon dioxide. Space based water vapor lidars are ideal for high accuracy measurements of water vapor throughout the troposphere and lower stratosphere as they are self-calibrating and not prone to bias resulting from aerosol and cloud contamination. Furthermore, they can retrieve water vapor profiles during day and night, at all latitudes, and during all seasons. There is also a need for highly accurate ground and airborne based remote and in situ measurements of upper tropospheric and stratospheric water vapor profiles for satellite validation and to use as a transfer standard to combine satellite data sets if there is a gap in global measurements. Additionally, the ground based and airborne lidars and aircraft and balloon based in situ measurements will be vital for process-based studies looking at detailed microphysical processes associated with water vapor and its transport into the stratosphere. What is critical is that we make continued measurements of highly accurate, vertically resolved, water vapor in the upper troposphere and stratosphere.

3. Why are space-based observations fundamental to addressing these challenges/questions?

A space based water vapor lidar mission concept study was carried out by DLR (Gerard et al., 2004) to assess the performance of a space based water vapor differential absorption lidar (DIAL) in relation to passive measurements such as IASI. The results of the study indicated that for a fixed error threshold, a water vapor DIAL would extend the water vapor measurement to a greater altitude than for IASI and would have approximately twice the vertical resolution. The study also indicated that the water vapor measurements would extend from the lower stratosphere down to the surface which would have significant positive impacts in determining the background error covariance used in national weather prediction (NWP) analysis, as well as for providing a stable absolute reference for calibrating other passive sensors.

Advances in laser and lidar technologies leveraged from successful space based lidar missions such as CALIPSO have enabled a new class of airborne water vapor DIALs that serve as prototypes for future satellite missions. NASA and DLR have been flying airborne water vapor DIALs for targeted process studies for over two decades, however, recent advances have made the prospect for a space based DIAL more feasible. NASA is currently developing an airborne DIAL to fly on high altitude platforms for profile measurements of water vapor and aerosols and clouds from the surface to the UTLS. This development will serve as the prototype for future space based water vapor DIAL missions. NASA has also been making continuous ground based lidar measurements of water vapor profiles in the upper troposphere and stratosphere in support of the network for the detection of Atmospheric Composition Change (NDACC). The use of airborne and ground based water vapor lidars in addition to highly accurate in situ sensors for targeted process studies are critical to advancing our knowledge of the impact of water vapor in the upper troposphere and stratosphere to long term changes in our climate. Airborne process studies will also pave the way for the next generation space based water vapor DIAL measurements required to overcome existing measurement deficiencies and lack of measurement continuity. The implementation of a space based DIAL targeting profile measurements of water vapor will provide distinct advantages with respect to current observational capabilities. Amongst these are:

- High accuracy, low bias, and high vertical resolution profiles extending from the surface to the lower stratosphere.
- Low sensitivity to bias resulting from lack of a priori knowledge of surface emissivity and temperature profiles, other interfering molecules, and contamination from aerosols and clouds.
- Capability to resolve above cloud tops as well as through and below low optical depth clouds as well as in between broken clouds.
- Increased vertical extent and resolution.
- Simultaneous information on aerosol distributions and optical depths from the surface to the lower stratosphere, boundary layer height, cloud top height, distribution, and phase, and surface reflectance and canopy height.

4. Impacted Science Communities

Water vapor is the most dominant greenhouse gas and plays a vital role in both the climate and weather communities. Water vapor profile measurements with improved accuracy and vertical resolution would benefit many major research programs including the World Climate Research Programs (WCRP), the Stratosphere-troposphere Processes and their Role in Climate (SPARC) program, the Network for the Detection of Atmospheric Composition Change (NDACC), and the Global Energy and Water Cycle Experiment (GEWEX) program. In addition to providing stratospheric profiles, the DIAL approach can provide simultaneous high accuracy and high vertical resolution water vapor profiles in the lower troposphere that are needed for numerical weather prediction initializations for improving predictions of severe weather and convective initiation and aggregation spanning from local to global scales.