Eos, Vol. 95, No. 27, 8 July 2014

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 95 NUMBER 27

8 July 2014

PAGES 245–252

Another Drop in Water Vapor

PAGES 245–246

In 2000 a sudden severe drop in stratospheric water vapor levels interrupted the supposed long-term increase of this greenhouse gas, an important contributor to global warming and climate variability. Satellite sensors observed a recovery in the following years, hidden behind a large variability. More recently, during 2011 and 2012, measurements revealed another severe drop in stratospheric water vapor concentrations.

Similar abrupt changes have likely occurred previously but were not observed because of the lack of adequate satellite measurements before the 1990s. In addition, future changes may remain unobserved, with present-day limb-sounding satellites well beyond their design lifetimes and no new missions planned to continue the observation record.

Long-Term Trend of Water Vapor

During the 1980s and 1990s, researchers observed a long-term increase of water vapor in the lower stratosphere (at altitudes between 16 and 26 kilometers). The measurements, made using balloon-borne cryogenic frost point hygrometers launched from Boulder, Colo. (40°N, 105°W), indicated a rate of increase of about 1% per year [*Rosenlof et al.,* 2001], later revised to 0.6% per year [*Scherer et al.,* 2008].

This long-term increase concerned scientists who study climate change because water vapor is one of the most prominent greenhouse gases that effectively absorbs light (terrestrial radiation) at infrared wavelengths [e.g., *Forster and Shine,* 2002]. Sensitivity studies with climate models demonstrated that even small changes in lower stratospheric water vapor can lead to notable changes of radiative forcing and the temperature at the surface [*Solomon et al.,* 2010].

The strength of a water vapor feedback mechanism—a warmer climate increases stratospheric water vapor, which causes further warming—was recently estimated at about +0.3 watt per square meter per Kelvin temperature change in the midtroposphere [*Dessler et al.,* 2013]. In addition, climate models uniformly predict that stratospheric water vapor concentrations will continue to increase in the future [e.g., *Gettelman et al.,* 2009].

Sudden Drops in Water Vapor

In 2000 a severe drop in stratospheric water vapor levels interrupted the supposed long-term trend, surprising observers (see Figure 1, middle and bottom). Satellite measurements showed a recovery in subsequent years, and scientists first considered the drop to be a singular perturbation in the long-term water vapor time series, attributed to an abrupt strengthening of the residual circulation (the slow circulation in the stratosphere transporting air masses from the tropics to higher latitudes), leading to stronger upwelling and lower temperatures in the tropical tropopause region [e.g., *Randel et al.,* 2004; *Randel et al.,* 2006; *Dhomse et al.,* 2008; *Rosenlof and Reid,* 2008; *Fueglistaler,* 2012].

However, several independent satellite sensors observed a large variability with several highs and lows of water vapor concentrations during the past decade. Just recently, during 2011 and 2012, a strong drop in stratospheric water vapor concentrations similar to the one observed in 2000 was measured, again accompanied by a sudden decrease of tropical tropopause temperatures.

Stratospheric water vapor concentrations followed roughly the evolution of the tropical tropopause temperature (Figure 1, top), and observations show that temperature and water vapor increased again in 2013. It can be expected that similar abrupt changes will also occur in the future and have occurred earlier in time (for example, in 1983–1985, as suggested by *Fueglistaler et al.* [2013]) but were not observed because of the lack of satellite measurements of lower stratospheric water vapor of sufficiently good quality before the 1990s.

Explaining the Water Vapor Changes

Water vapor in the stratosphere is governed by two major processes. One is the entry through the tropical tropopause, where the lowest temperature (the so-called cold point temperature) determines how much water vapor continues on its upward path into the stratosphere and how much is removed by a freeze-drying process. The other is the oxidation of methane, which is the only important chemical source of water vapor in the stratosphere. The increase in stratospheric water vapor concentrations during the past century cannot fully be explained by changing tropopause temperatures—cold point temperatures decreased while water vapor overall increased—or increasing levels of the greenhouse gas methane. Observed methane increases leveled off in the second half of the 1990s [*Rinsland et al.,* 2009] before the gas started to increase again in 2007 [*Dlugokencky et al.,* 2009; *Angelbratt et al.,* 2011].

The drop in water around 2000 and the following recovery, however, seemed to be consistent with tropopause temperatures going down and rising again. The recent drop during 2011–2012 was again accompanied by low tropopause temperatures.

Scientists believe that the variability of tropopause temperatures is dominated by modulations of the stratospheric residual circulation, with periodicities corresponding to the stratospheric quasi-biennial oscillation and the El Niño–Southern Oscillation.

Although this part of the puzzle seems close to being understood [*Randel et al.,* 2004; *Randel et al.,* 2006; *Fueglistaler and Haynes,* 2005; *Jones et al.,* 2009; *Urban et al.,* 2012; *Fueglistaler et al.,* 2013; *Randel and Jensen,* 2013], inspection of Figure 1 reveals that not all of the observed variability of lower stratospheric water vapor in the tropics can be explained by changes in average tropopause temperature (see, for example, the period 2008–2011). Other zonally asymmetric or localized processes may contribute [e.g., *Fueglistaler and Haynes,* 2005]. Moreover, nobody is currently able to predict the rise and fall of tropopause temperatures and thus the future development of stratospheric water vapor.

Satellite Measurements of Stratospheric Water Vapor

Satellite limb measurements have been successfully conducted since the early 1990s with, for example, the Halogen Occultation Experiment (HALOE) on board NASA's Upper Air Research Satellite (UARS) providing a long water vapor time series of excellent quality

---

By J. Urban, S. Lossow, G. Stiller, and W. Read

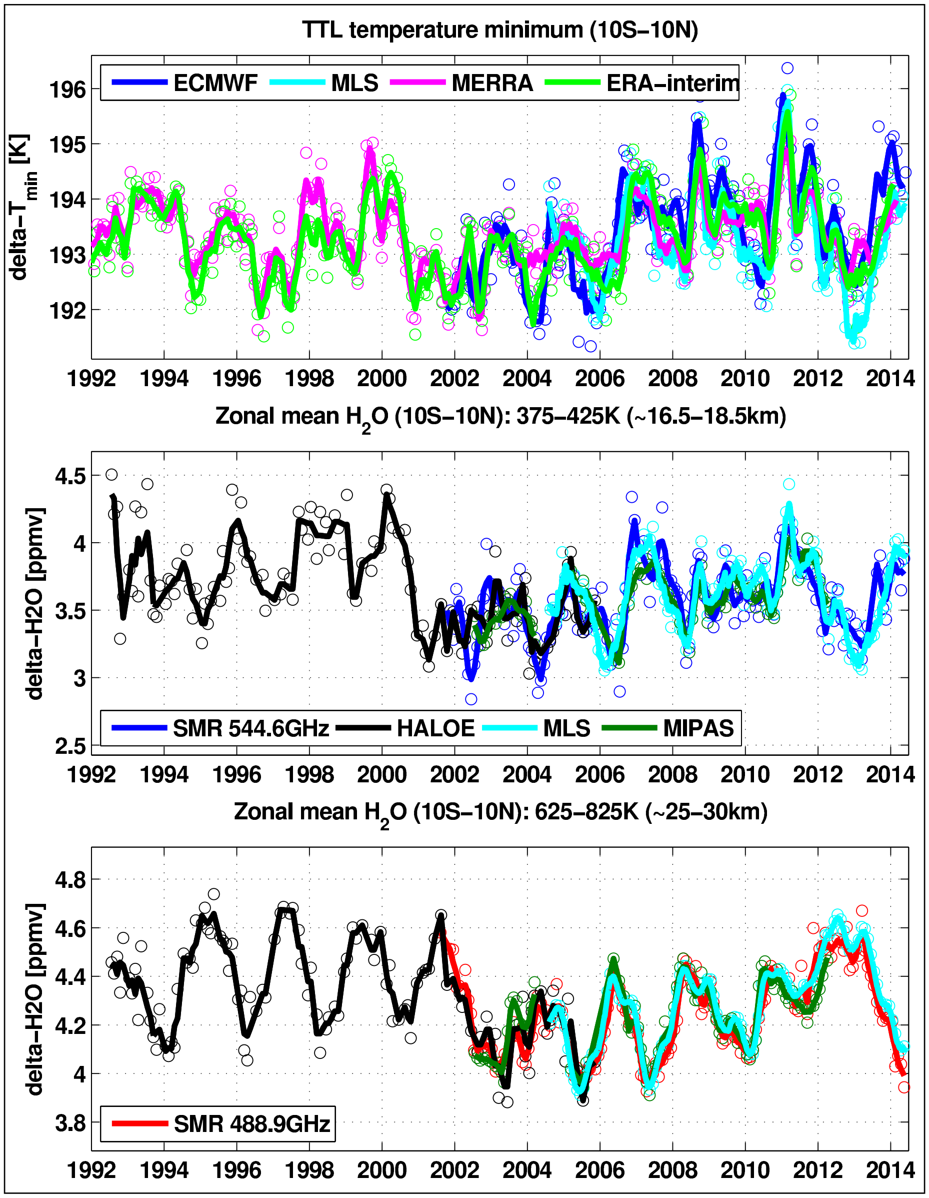

Fig. 1. Recent evolution of water vapor volume mixing ratios in the tropical lower stratosphere compared to the tropopause temperature. (top) Deseasonalized and offset-corrected changes of the minimum temperature in the tropical tropopause region (10°S–10°N) derived from different temperature data sets (European Centre for Medium-range Weather Forecasts (ECMWF) analysis, blue; ECMWF interim reanalysis (ERA-interim), green; Modern Era Retrospective-analysis for Research and Application (MERRA), magenta; Aura Microwave Limb Sounder (MLS) measurements, cyan). A 90-day running mean smoothing filter was applied (solid lines). (middle) Observed changes of monthly and zonally averaged water vapor volume mixing ratios in the tropics (10°S–10°N) within the potential temperature range 375–425 K (corresponding to the altitude range ~16.5–18.5 kilometers), derived from Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE; black), Odin Sub-Millimetre Radiometer (SMR; dark blue, 544.6-gigahertz band), Envisat Michelson Interferometer for Passive Atmospheric Sounding (MIPAS; dark green), and Aura MLS (cyan). Data sets have been deseasonalized and then offset corrected using the average mixing ratios during the overlapping periods with Odin as reference. (bottom) Same as above, but for zonally averaged water vapor (10°S–10°N) in the potential temperature range 625–825 K (~25–30 kilometers), derived from UARS HALOE (black), Odin SMR (red, 488.9-gigahertz band), Envisat MIPAS (dark green), and Aura MLS (cyan). The drop in water vapor is seen with a delay of ~1.5 years from the middle plot to the bottom plot, owing to the time it takes for air to slowly rise from the tropopause through the tropical lower stratosphere to these higher levels.

from 1991 to 2005, and the Stratospheric Aerosol and Gas Experiment II (SAGE II) on the Earth Radiation Budget Satellite (ERBS).

The number of satellite limb observations of the stratosphere increased starting in 2001 with the launch of the Swedish-led Odin satellite, which was followed by several other satellites carrying limb-sounding sensors capable of measuring stratospheric water vapor on a global scale. These include the European Space Agency's Envisat in 2002, the Canadian SCISAT in 2003, and NASA's Aura in 2004. However, Envisat's observations ended unexpectedly in 2012 because of a failure of the satellite.

Several limb-sounding missions are currently operating with the required sensitivity and resolution to make profile measurements of stratospheric water vapor. However, all these missions are already far beyond their scheduled lifetimes. Although regular balloon-borne observations at Boulder [*Hurst et al.*, 2011], measurements collected through the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) [*Seidel et al.*, 2009], and data from ground-based networks such as the Network for the Detection of Atmospheric Composition Change (NDACC; http://www.ndacc.org) are contributing to the monitoring of stratospheric water vapor, their geographical coverage and temporal sampling frequencies remain sparse, in particular in the tropics [*Fujiwara et al.*, 2010].

In the absence of a long-term global observation strategy of the space agencies, there are at present no future space missions scheduled for launch that can provide vertically well resolved measurements of lower stratospheric water vapor on a longer time scale, despite the importance of humidity for the climate system.

References

Angelbratt, J., et al. (2011), A new method to detect long term trends of methane (CH_4) and nitrous oxide (N_2O) total columns measured within the NDACC ground-based high resolution solar FTIR network, *Atmos. Chem. Phys., 11*(13), 6167–6183, doi:10.5194/acp-11-6167-2011.

Dessler, A., M. Schoeberl, T. Wang, S. Davis, and K. Rosenlof (2013), Stratospheric water vapor feedback, *Proc. Natl. Acad. Sci. U. S. A., 110*(45), 18,087–18,091, doi:10.1073/pnas.1310344110.

Dhomse, S., M. Weber, and J. Burrows (2008), The relationship between tropospheric wave forcing and tropical lower stratospheric water vapor, *Atmos. Chem. Phys., 8,* 471–480.

Dlugokencky, E. J., et al. (2009), Observational constraints on recent increases in the atmospheric CH_4 burden, *Geophys. Res. Lett., 36,* L18803, doi:10.1029/2009GL039780.

Forster, P., and K. Shine (2002), Assessing the climate impact of trends in stratospheric water vapor, *Geophys. Res. Lett., 29*(6), 1086, doi:10.1029/2001GL013909.

Fueglistaler, S. (2012), Stepwise changes in stratospheric water vapor?, *J. Geophys. Res., 117,* D13302, doi:10.1029/2012JD017582.

Fueglistaler, S., and P. Haynes (2005), Control of interannual and longer-term variability of stratospheric water vapor, *J. Geophys. Res., 110,* D24106, doi:10.1029/2005JD006019.

Fueglistaler, S., et al. (2013), The relation between atmospheric humidity and temperature trends for stratospheric water, *J. Geophys. Res., 118*(2), 1052–1074, doi:10.1002/jgrd.50157.

Fujiwara, M., et al. (2010), Seasonal to decadal variations of water vapor in the tropical lower stratosphere observed with balloon-borne cryogenic frost point hygrometers, *J. Geophys. Res., 115,* D18304, doi:10.1029/2010JD014179.

Gettelman, A., et al. (2009), The tropical tropopause layer 1960–2100, *Atmos. Chem. Phys., 9,* 1621–1637, doi:10.5194/acp-9-1621-2009.

Hurst, D., S. Oltmans, H. Vömel, K. Rosenlof, S. Davis, E. Ray, E. Hall, and A. Jordan (2011), Stratospheric water vapor trends over Boulder, Colorado: Analysis of the 30 year Boulder record, *J. Geophys. Res., 116,* D02306, doi:10.1029/2010JD015065.

Jones, A., et al. (2009), Evolution of stratospheric ozone and water vapour time series studied with satellite measurements, *Atmos. Chem. Phys., 9,* 6055–6075.

Randel, W., and E. Jensen (2013), Physical processes in the tropical tropopause layer and their roles in a changing climate, *Nat. Geosci., 6*(3), 169–176, doi:10.1038/ngeo1733.

Randel, W., F. Wu, S. Oltmans, K. Rosenlof, and G. Nedoluha (2004), Interannual changes of stratospheric water vapor and correlations with tropical tropopause temperatures, *J. Atmos. Sci., 61,* 2133–2148.

Randel, W., F. Wu, H. Vömel, G. Nedoluha, and P. Forster (2006), Decreases in stratospheric water vapor after 2001: Links to changes in the tropical tropopause and the Brewer-Dobson circulation, *J. Geophys. Res., 111,* D12312, doi:10.1029/2005JD006744.

Rinsland, C., L. Chiou, C. Boone, P. Bernath, E. Mahieu, and R. Zander (2009), Trend of lower stratospheric methane (CH_4) from atmospheric chemistry experiment (ACE) and atmospheric trace molecule spectroscopy (ATMOS) measurements, *J. Quant. Spectrosc. Radiat. Transfer, 110*(13), 1066–1071, doi:10.1016/j.jqsrt.2009.03.024.

Rosenlof, K., and G. Reid (2008), Trends in the temperature and water vapor content of the tropical lower stratosphere: Sea surface connection, *J. Geophys. Res., 113,* D06107, doi:10.1029/2007JD009109.

Rosenlof, K., et al. (2001), Stratospheric water vapor increases over the past half-century, *Geophys. Res. Lett., 28*(7), 1195–1198, doi:10.1029/2000GL012502.

Scherer, M., H. Vömel, S. Fueglistaler, S. Oltmans, and J. Staehelin (2008), Trends and variability of mid-latitude stratospheric water vapour deduced from the re-evaluated Boulder balloon series and HALOE, *Atmos. Chem. Phys., 8,* 1391–1402.

Seidel, D., et al. (2009), Reference upper-air observations for climate: Rationale, progress, and plans, *Bull. Am. Meteorol. Soc., 90,* 361–369, doi:10.1175/2008BAMS2540.1.

Solomon, S., K. Rosenlof, R. Portmann, J. Daniel, S. Davis, T. Sanford, and G.-K. Plattner (2010), Contributions of stratospheric water vapor to decadal changes in the rate of global warming, *Science, 327*(5970), 1219–1223, doi:10.1126/science.1182488.

Urban, J., D. Murtagh, G. Stiller, and K. Walker (2012), Evolution and variability of water vapour in the tropical tropopause and lower stratosphere region derived from satellite measurements, in *Proceedings of the ESA Atmospheric Science Conference: Advances in Atmospheric Science and Applications, 18–22 June 2012, Brugge, Belgium,* edited by L. Ouwehand, *Eur. Space Agency Spec. Publ., ESA SP-708.*

Author Information

J. Urban, Department of Earth and Space Sciences, Chalmers University of Technology, Gothenburg, Sweden; email: joaurb@chalmers.se; S. Lossow and G. Stiller, Karlsruhe Institute of Technology, Karlsruhe, Germany; and W. Read, Jet Propulsion Laboratory, California Institute of Technology, Pasadena