Eyring, V., *et al.,* (2006), Assessment of temperatures, trace species, and ozone in chemistry-climate simulations of the recent past, *J. Geophys. Res.*, in press.

Gray, L.J. (2003), The influence of the equatorial upper stratosphere on stratospheric sudden warmings, *Geophys. Res. Letts.*, 30, doi:10.1029/2002GL016430.

Gray, L. J., *et al.,* (2001a), Model studies of the interannual variability of the northern hemisphere stratospheric winter circulation: The role of the Quasi-Biennial Oscillation, *Q. J. R. Meteorol. Soc.*, 127, 1413—1432.

Gray, L.J., *et al.,* (2004), Solar and QBO influences on the timing of stratospheric sudden Warmings, *J. Atmos. Sci.*, 61, 2777-2796.

Gray, L. J., *et al.,* (2001b), A data study of the influence of the equatorial upper stratosphere on northern hemisphere stratospheric sudden warmings, *Q. J. R. Meteorol. Soc.*, 127, 1985--2003.

Haigh, J.D. (1996), The impact of solar variability on climate, *Science*, 272, 981--984.

Haigh, J.D., *et al.,* (2005), The Response of Tropospheric Circulation to Perturbations in Lower-Stratospheric Temperature, *J. Climate,* 18, 3672-3685.

Kodera, K., and Y. Kuroda (2002), Dynamical response to the solar cycle, *J. Geophys. Res.*, 107, 4749, doi:10.1029/2002JD002224.

Kodera, K., *et al.,* (2003), Solar impact on the lower mesospheric subtropical jet in winter: A comparative study with general circulation model simulations, *Geophys. Res. Lett.*, 30 (D6), 1315, doi:10.1029/2002GL016124.

Labitzke, K., and H. van Loon (1988), Associations between the 11-year solar cycle, the QBO and the atmosphere, Part I: The troposphere and stratosphere in the northern hemisphere in winter, *J. Atmos. Terr. Phys.*, 50, 197-206.

Lean, J., *et al.,* (1995), Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lett.*, 22, 3195-3198.

Lopez-Puertas, *et al.,* (2005), Observation of NOx enhancement and ozone depletion in the Northern and Southern Hemispheres after the October – November 2003 solar proton events, *J. Geophys. Res.*, 110, A09S43, doi:10.1029/2005JA011050.

Mann, M. E., *et al.,* (1998), Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, 392, 779-787.

Matthes, K., *et al.,* (2003), GRIPS solar experiments intercomparison projects: Initial results, *Pap. Meteorol. Geophys.*, 54, 71-90.

Matthes, K., *et al.,* (2004), Improved 11-Year solar signal in the FUB-CMAM, *J. Geophys. Res.*, 109, doi:10.1029/2003JD004012

Matthes, K., *et al.,* (2006), Transfer of the Solar Signal from the Stratosphere to the Troposphere: Northern Winter, *J. Geophys. Res.*, 111, D06108, doi:10.1029/2005JD006283.

Matthes, K., *et al.,* (2007), Modeling the Influence of the 11-Year Solar Cycle and the QBO with the NCAR Whole Atmosphere Community Climate Model, manuscript in preparation.

McCormack, J. P., and D. E. Siskind (2006), Simulations of the ozone response to the 11-year solar cycle and QBO in a zonally averaged photochemical-transport model of the middle atmosphere, manuscript in preparation.

Palmer, M. A. and L. J. Gray (2005), Modeling the atmospheric response to solar irradiance changes using a GCM with a realistic QBO. *Geophys. Res. Lett.*, 32, L24701, doi:10.1029/2005GL023809.

Wang, Y. M., *et al.,* (2005), Modeling the sun's magnetic field and irradiance since 1713, *Astrophysical Journal*, 625, 622-538.

A note on an AGU spring meeting discussion of the role of atmospheric water vapour in climate and atmospheric composition

23-26 May 2006, Baltimore, Maryland, USA

N.G. Andronova, University of Michigan, USA (natand@umich.edu)
S. Sherwood, Yale University, USA (Steven.Sherwood@yale.edu)
R. Fu, Georgia Institute of Technology, USA (rong.fu@eas.gatech.edu)
I. Folkins, Dalhousie University, Canada (Ian.Folkins@dal.ca)
K. Rosenlof, NOAA ESRL Chemical Sciences Division, USA (Karen.H.Rosenlof@noaa.gov)
M. Joshi, Hadley Centre, Met Office, United Kingdom (manoj.joshi@metoffice.gov.uk)
A. Caboussat, University of Houston, USA (caboussat@math.uh.edu)
A. Stenke, Institut fuer Physik der Atmosphaere, DLR Oberpfaffenhofen, Germany (Andrea.Stenke@dlr.de)

Introduction

Since the early 1970s the study of the middle atmosphere has focused on understanding the variability of its chemical and dynamical states as driven by both natural and anthropogenic processes. Concurrent with these efforts, studies have been carried out to understand both short- and long-term climatic variations that occur naturally, as well as those due to the emissions and/or alterations of optically active gases and aerosols by humanity. In these areas of study, stratospheric and tropospheric water vapour (H_2O) has been of particular interest. Water vapour is a greenhouse gas and is important for atmospheric chemistry, as it is the source of the hydroxyl radical, OH, which regulates among others the atmospheric methane lifetime and the production and destruction of ozone. Also, water vapour plays an important role in atmospheric heterogeneous chemistry, defining the aerosol effect on climate *via* formation of the stratospheric clouds. While some progress has been made in simulating the changing atmosphere, a number of observed phenomena remain unexplained, among them the reasons for the recently observed trends in upper-troposphere/lower-stratosphere (UT/LS) water vapour and temperature.

A session entitled “Role of atmospheric water vapour for climate and atmospheric composition” at the spring American Geophysical Union (AGU) meeting presented the recent state of knowledge on processes related to the UT/LS water vapour in data analysis and modelling. The atmospheric water vapour issues discussed at the session spanned from the upper troposphere to the mesosphere in the Earth’s tropical and extratropical regions, and underlined the importance of coordinating water vapour research with issues related to other chemical compounds such as ozone, carbon monoxide and aerosol. The discussion converged into two main questions:

(1) What are the main mechanisms influencing the water vapour budget in the tropical tropopause layer?
(2) What are the water vapour trends?

The purpose of this note is to assess results presented at the session and to begin creating a base for the next steps of the ongoing research.

Tropical tropopause layer water vapour budget

The tropical tropopause layer (TTL) is a transition layer between the wet and turbulent troposphere and the dry and stable stratosphere, where tropospheric processes gradually decrease in importance. Two speakers (**Folkins** and **Sherwood**) emphasised that because the ambient vertical velocity vanishes near 15 km, air cannot enter the TTL from below except in vigorous convective updrafts originating in the lower troposphere. This probably limits the ability of upper-tropospheric constituents, including water vapour, to affect the lower stratosphere. Sherwood noted that observations, basic theory, and climate models all suggest that tropospheric humidity is not sensitive to microphysical forcings, even though such forcings are evidently able to change water vapour entering the stratosphere and probably account for some of the increases in water vapour between the 1950s and 1990s. Folkins underlined the major factors defining the water vapour budget in TTL. These factors are related to the processes associated with the convective detrainment. **Figure 1** shows Folkins’s “TTL Virtuous Circle,” which shows that to get a fair description of the water vapour evolution in the TTL, one should at least take into account (1) a vertical profile of the detrainment, (2) the water vapour mixing ratio of air parcels detraining from deep convective clouds, (3) irreversible post-convective removal of water vapour by formation and fall-out of sedimenting ice crystals, (4) the evaporation of ice crystals descending from higher altitudes, and (5) quasi-horizontal exchange with the extratropical stratosphere. He argued that a comprehensive theory of water vapour in the TTL should be based on a dynamical model that is consistent with empirical estimates of the relevant thermodynamic forcings, and should predict mean profiles of other trace species that are in agreement with observations. Since ozone affects net radiative heating in the region, the future evolution of cold point temperature will be sensitive to the convective detrainment profile.

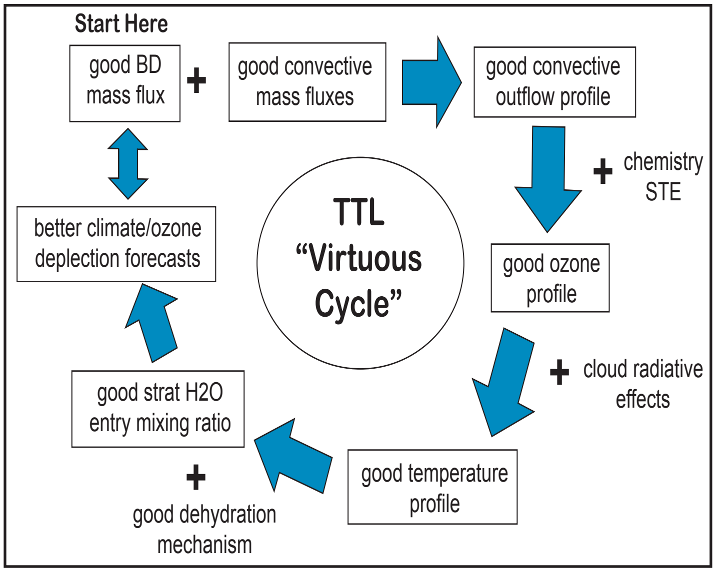


Figure 1: The TTL Virtuous Circle

Wright examined the relative roles of detrainment temperature, convective ice water content, ice cloud effective radius, and ambient relative humidity upon the efficiency of convective moistening in the tropical upper troposphere between 300 and 200 hPa by closely matching AIRS water vapour measurements with the vertical and microphysical structure of their convective sources using a trajectory model. His results show that, in a global sense, after being detrained from its convective source, water vapour is mainly controlled by temperatures during and after convective detrainment. Cloud microphysical properties appear to play a secondary role globally, although they can be more significant on regional scales. His observational results support the advection-condensation model and relative humidity control of the convective hydration/dehydration suggested by Sherwood.

John presented a method for comparing temperature and humidity profiles simulated by a dozen coupled General Circulation Models (GCMs) with observations using satellite microwave data. They showed that the models correctly predict the observed correlation between cirrus cover and atmospheric moisture, refuting a recent paper suggesting that this well-known relationship implies a missing component to the water vapour feedback.

There were a few talks at the session touching upon the question of water vapour interaction with aerosol. **Harkey** and **Hu** presented results on the role of tropical biomass burning on water vapour in the TTL. Using a regional model, Harkey predicted that changes in microphysical properties of the cirrus clouds within the TTL due to increased biomass burning caused more rapid growth of cirrus clouds and reduced water vapour content. Hu studied the influence of biomass burning aerosols on convective/cirrus cloud properties and water vapour transport to the upper troposphere. Close correlation was found among the deep/cirrus clouds, aerosols, and atmospheric constituents over these regions in the boreal summer. **Caboussat** drew attention to the role of organic aerosols in the water vapour budget of the upper troposphere. They emphasised that the chemical properties of aerosols are needed for the aerosol growth and activation and cloud formation, as illustrated in Figure 1. More precisely, organic components have an effect on the crystallization of salts in aerosols, known as the *salt-in – salt-out* effect. However, this effect is neglected in the current models and replaced by a *phase lock* between hydrophobic and hydrophilic organic components. To avoid this artifact, they proposed a model for the computation of the thermodynamic equilibrium (phase separation) and dynamics (gas-particle partitioning) of organic aerosols and the determination of the microphysical state of organic aerosols and water vapour budget. They designed an accurate method to incorporate these effects in numerical simulations of cloud formation. Results have shown that their approach is efficient and could be inserted into regional or global models. **Wang** used the CAM3 community climate model coupled to the IMPACT aerosol model to investigate how aerosol-induced increases in ice crystal number and reductions in size and settling velocity would affect water vapour in the UT/LS region. They found that a decrease in the settling velocity increased the ice flux into the stratosphere directly, but reported that a larger moistening effect occurred indirectly because the cloud cover increased, thereby increasing the radiative heating and the tropopause temperatures.

An important role of orography for the water vapour transport in the TTL region was mentioned by **Fu** *et al.* They presented evidence from multiple satellites (AURA, TRMM, AQUA) that much of the water vapour and CO entering the global tropical stratosphere in Asia is transported over the Tibetan Plateau (TP) region during the boreal summer. They showed that the tops of convection over the Asian monsoon region are mostly below the TTL (15 km), while convection over the TP can detrain water vapour directly to the tropopause level or into the lower stratosphere. In this case, the tropopause temperature is about 7K warmer and 40% less saturated than that over the Indian monsoon region. A combination of these conditions allows fast transport of water vapour into the lower stratosphere, which bypasses, or short-circuits, the “cold trap” occurring in the monsoon region.

There are three main conclusions from this part of the session:

(1) The advection-condensation model of water vapour continues to be supported in the troposphere;
(2) Model and observational studies indicate likely impacts of aerosols on TTL water vapour; and
(3) The horizontal transport is important particularly during the Asian monsoon season.

Water vapour trends

It is known that the distribution, variability, and trends of water vapour in the upper troposphere and lower stratosphere are important for understanding the Earth’s climate. Trends in stratospheric water vapour, if they can be confirmed, would cause a significant change in the radiative forcing of climate. Water vapour is the dominant greenhouse gas in the atmosphere, and also can be a cooling agent in the middle and upper troposphere. Despite the stratosphere being relatively dry, small changes in the stratospheric water content can substantially alter the stratospheric chemical composition and influence surface climate.

According to the data presented by **Nedoluha** from the combination of WVMS, POAM, and HALOE measurements over the period 1991 to the present, it is difficult to gain any information about water vapour trends above 60 km due to a masking role of two major natural factors: the realization of the QBO and the variation of the solar cycle, of which the influences on the middle atmosphere are still not well understood or modelled. In the stratosphere an increase in water vapour was documented between 1990 and 1996, in spite of the fact that the interannual behaviour of the water vapour there is influenced by the QBO. After 1996 the upper stratosphere/lower mesosphere showed no trends, but starting in 2001 the water vapour in the lower stratosphere began to decrease in accordance with cooling of the tropical tropopause.

Rosenlof and **Reid** also showed that according to HALOE measurements the tropical stratospheric water vapour dropped dramatically at the end of 2001. This decrease has propagated upward, reaching 10 hPa within one to two years, and has persisted to the present (see **Figure 2a**, colour plate IV). It is directly correlated with a temperature decrease at the tropical cold point, obtained from UARS data (**Figure 2b**, colour plate IV), with a magnitude equivalent to 1/3 of the annual cycle peak-to-peak temperature differences. The cooling was confined to a narrow layer near the cold point. It also appears correlated to a change in the global sea-surface temperature pattern, including changes outside of the tropics. They hypothesised that a change in the amplitude of the tropical stratospheric QBO in temperatures occurs at the same time as the tropical tropopause temperature changes, possibly due to changes in the convective wave that forces motions in the UT/LS. They also mentioned an increase in the strength of the upper portion of the Hadley circulation, leading to an increased meridional mass flux in the lower stratosphere, peaking above 150 hPa, but below 60 hPa.

Dameris presented a modelling effort by Stenke *et al.* to simulate the historical evolution of the water vapour in the stratosphere. They ran an atmospheric GCM coupled with interactive chemistry, with all known climate system anthropogenic and natural forcings, including greenhouse gases, volcanoes, solar variability, observed changes in SST, ice coverage, and the QBO. These forcings were prescribed from the observed fields over the period from 1960 to 2000 and projected to 2020. The model simulation supports a relationship between water vapour changes and QBO variability for the observed period used in the model. It also simulated a reversal of the lower stratospheric water vapour trend with decreasing water vapour during the first 10 years and increasing values from 1980 on (see **Figure 3**). It did not show the decrease of the water vapour after 2001 reported by Nedoluha, Rosenlof and Reid; however, the forcings prescribed in the model from 2000 were not based on observations, but on future projections. The simulated water vapour variations, short- as well as long-term, are strongly linked to the temperature at the tropical tropopause, which controls the entry-level water vapour mixing ratio, and therefore all conclusions depend on how accurately the tropical tropopause is simulated.

Joshi presented possible consequences of the stratospheric water vapour trends for the tropospheric circulation. Based on numerical experiments with the Hadley Centre’s climate model he showed that a prescribed increase in stratospheric water vapour (in accordance with observations) changes the North Atlantic Oscillation (NAO) index, which would explain a significant portion of the observed NAO trend over 1965 to 1995. This suggests a mechanism for interannual predictability of the tropospheric circulation due to effects of large tropical volcanic eruptions, ENSO events or QBO changes using information about stratospheric water vapour change.

Zveryaev and **Alan** studied trends of the tropical column integrated water vapour (CWV) over the period 1979 to 2001, and showed that the spatial distribution of CWV is strongly determined by thermodynamic constraints, while its spatial variability is dominated by changes in the large-scale dynamics, in particular those associated with the El Niño - Southern Oscillation (ENSO). They concluded that over 1979 to 2001 the CWV trends are dominated by dynamics rather than thermodynamics.

This part of the session also had three main conclusions:

(1) Upward stratospheric water vapour trends reported prior to the late 1990s are still not explained by conventional models, and have not continued;
(2) The sudden, mysterious tropopause cooling in 2001 caused a marked and persistent drying; and,
(3) Stratospheric water vapour changes are estimated to have had significant impacts on the atmospheric general circulation.

Concluding Remarks and Outstanding Questions

We believe that the Spring AGU session on water vapour had very insightful presentations and as a result raised many important questions to be answered by future research. Among the questions are:

- Are aerosol indirect effects on water vapour significant in the stratosphere, and could they be occurring in the troposphere? If so, which aerosol types and nucleation modes are most important?
- What will happen to methane concentrations in the future?
- What caused the sudden 2001 cooling near the tropopause and what will happen to tropopause temperatures in the future?
- Are there pathways around the tropical tropopause that allow significant moisture from the upper troposphere to reach the stratosphere?
- What other natural and anthropogenic factors might have an influence on water vapour evolution in the TTL?

We are pleased that there were a few excellent student papers presented at the session (Harkey, John, Wright, Wang). Wide involvement of student research activities in these sessions guarantees that the number of atmospheric scientists studying and solving atmospheric water vapour mysteries will grow as they graduate and move forward with their own research.

List of Talks

Caboussat A., N. R. Amundson, J. He and J. H. Seinfeld: *Modeling of Organic Effects on Aerosols Growth.*

Folkins I, P. Bernath, C. Boone, and K. Walker: *Water Vapor Budget of the Tropical Tropopause Layer.*

Fu R., Hu Y., J S. Wright and J. H. Jiang: *What are the main pathways for the cross tropopause transport of water vapor and CO over the Asian monsoon/Tibetan Plateau?*

Harkey M.K. and M. H. Hitchman: *An Evaluation of the Impact of Idealized Heterogeneous Ice Nucleation on Lower Stratospheric Water Vapor Using the UW NMS.*

Hu Y., R. Fu and J. H. Jiang: *Aerosol Impacts on Convective Transport of Water Vapor and Polluted Air in the Upper Troposphere Over the Asian Monsoon Region.*

John V. O., B. J. Soden and S. A. Buehler: *Comparison of UTH in IPCC AR4 coupled GCMs to microwave observations.*

Joshi M., A. Scaife, A. Charlton and S. Fueglistaler: *The influence of stratospheric water vapour changes on the extratropical tropospheric circulation on different timescales.*

Nedoluha G. E., R. M. Bevilacqua, R. M. Gomez, B. C. Hicks, W. J. Randel, B. J. Connor and J. M. Russell III: *Variations in Middle Atmospheric Water Vapor since 1991.*

Rosenlof K.H. and G. C. Reid: *Tropical UTLS Temperature and Water Vapor Changes.*

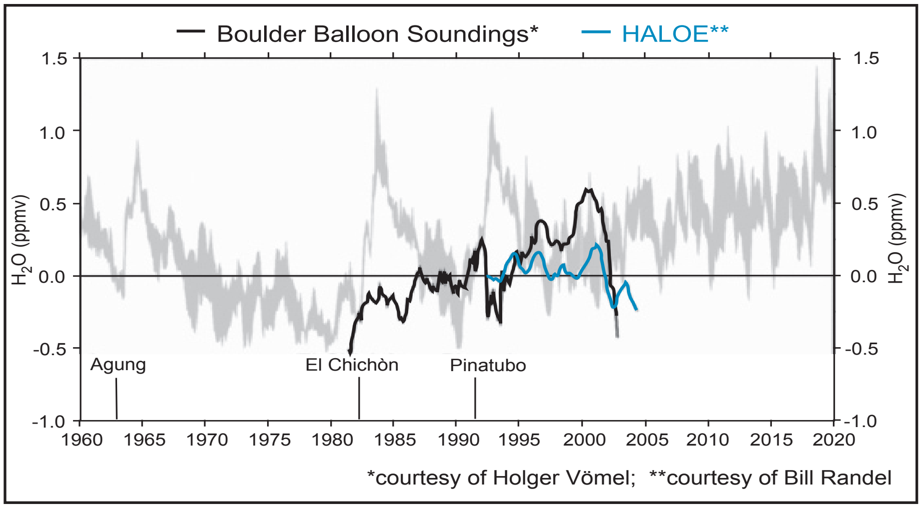
Sherwood S. C. : *Mechanisms controlling water vapor in the UT/LS.*

Stenke A, V. Grewe, M. Dameris, M. Ponater and R. Sausen: *Simulated Trends of Stratospheric Water Vapor From 1960 to 1999 and Their Impact on Ozone Chemistry.*

Wang W, Chen Y., N. G. Andronova and J. E. Penner: *Comparison of the flux of water into the stratosphere on aerosols, in cirrus clouds, and as vapor.*

Wright J.S. and R. Fu: *A Trajectory Analysis of Convective Detrainment in the Tropical Upper Troposphere Using AIRS.*

Zveryaev I. I and Richard P Allan: *Water Vapor Variability in the Tropics and its Links to Dynamics and Precipitation.*



*courtesy of Holger Vömel; **courtesy of Bill Randel

Figure 3: Deseasonalised water vapour volume mixing ratios at 40°N and 50hPa. The grey shaded area indicates the min/max values derived from three simulations for 1960-1999 and four simulations for 2000-2020. The blue and black curves show the respective time series from HALOE and Boulder balloon soundings.

◆