SPARC workshop "The UTLS: current status and emerging challenges"

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Organisers:
Peter Hoor, Daniel Kunkel, (Johannes Gutenberg University, Mainz, Germany)

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Institute for Atmospheric Physics, Johannes Gutenberg University, Mainz, Germany

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Although the knowledge on the Upper Troposphere / Lower Stratosphere region (UTLS) increased substantially over the last decade, important uncertainties remain on key topics of long-term variability and trends, feedback mechanisms between dynamics and chemistry, and mechanisms of two-way stratosphere troposphere coupling. Trend estimates of e.g. ozone (Ball *et al.*, 2018, Steinbrecht *et al.*, 2017) or water vapour (e.g. Hegglin *et al.*, 2014) are under debate illustrating gaps of our current understanding of the UTLS. The effect of mixing on radiatively active species in the UTLS is difficult to quantify in current state-of-the-art climate models (Riese *et al.*, 2012), since the distribution of the relevant species crucially depends on parameterizations of sub-grid processes.

The goal of this workshop was to summarize the current knowledge, to identify gaps of current understanding, and to provide directions for future UTLS research. The last UTLS community workshop was in Boulder (2009) and the current workshop in Mainz can be seen in the tradition of previous workshops in Mainz (2005) and Bad Tölz (2001). It comprised keynote talks, contributed talks, and a poster session over three days. During the four day workshop at the Johannes Gutenberg University in Mainz, Germany, more than 110 scientists from different fields linked to, and thus with different perspectives on, UTLS research discussed the current status of ongoing UTLS research.

The workshop was subdivided into six major topics starting with (1) aerosol and ice clouds, (2) the TTL region (3) dynamics and circulation changes (4) the extratropical tropopause including gravity waves, (5) composition and trends as well as (6) future perspectives. **Peter Hoor** opened the meeting and gave an overview on the developments since 2009 focusing on key improvements, but also addressing the major uncertainties.

Aerosol and Ice clouds

The regular part of the meeting was opened by **Dan Murphy,** who showed that the aerosol in the lowermost stratosphere is a mixture of organic and sulfate particles and that the radiative forcing of the stratospheric aerosol is larger than previously thought. Presenting new measurements from two WB57 campaigns (POSIDON, Guam 2016 and VIRGAS, California, 2015), **Andrew Rollins** showed the importance of aerosol formation in the TTL for the stratospheric sulfate, with typically 10-200pptv of SO_2 below the tropopause at 17 km.

At mid-latitudes meteoric material contributes significantly to the UTLS aerosol composition as shown by **Johannes Schneider** presenting single particle analyses from the ML-CIRRUS campaign (Western Europe, spring 2014). He also highlighted the different composition of cirrus residuals from liquid and in-situ origin. **Christiane Voigt** summarized key results from ML-CIRRUS indicating larger numbers of small ice particles in contrail cirrus compared to the natural background and pointing out the importance of vertical transport in warm conveyor belts for the cirrus formation. The afternoon session continued the aerosol topic, initially focusing on processes related to the Asian summer monsoon (ASM) and presenting results from the STRATOCLIM campaign in Nepal in summer 2017. **Stephan Borrmann** confirmed the outstanding role of the ASM as the most significant aerosol source for the summertime UTLS up to 420 K, also including new particle formation events and the role of non-volatile particles which make up about half of the sub-micron aerosol mass. **Martina Krämer** reported on the occurrence of high number concentrations of ice particles at very cold tropopause temperatures and altitudes in the ASM and of supersaturated cirrus up to 400 K which potentially moisten the UTLS. In addition to the airborne measurements, balloon measurements inside the ASM revealed the importance of convection for water vapour and supersaturation in the region above the monsoon tropopause, but still inside the anticyclone (**Simone Brunamonti**). **Troy Thornberry** then came back to POSIDON showing compact histograms of ice water content above 16.5 km in the TTL and their link to tropical convection. The first session ended with a talk by **Stefan Fueglistaler** who presented a new approach to determine water fluxes to better understand the moisture content of the lower stratosphere based on theoretical considerations and CALIOP observations.

Dynamics and chemistry related to the Asian Summer Monsoon

The last session on the first day was started by a talk of **Mohamadou Diallo** on the impact of volcanic aerosol on the strength of the Brewer Dobson circulation (BDC). In a series of talks further studies on the impact of the ASM on the composition of the lower stratosphere were presented. **Michael Volk** showed new insights on horizontal and vertical transport processes within the ASM based on in-situ measurements of long-lived trace species during STRATOCLIM. A large scale overview about the chemical composition of the UTLS inside the ASM was presented by **Michael Höpfner**, based on airborne remote sensing measurements with the GLORIA instrument. Two main transport time scales characterize export of air from the ASM into the stratosphere as shown by **Felix Plöger**. Short timescales dominate transport into the extratropical lower stratosphere, but long time scales for export into the tropical pipe. The session was concluded by two talks about the impact on the chemical composition of the extratropical UTLS after the break-up of the anti-cyclone. First, **Christian Rolf** reported on enhanced concentrations of water vapour and methane in the lower stratosphere during TACTS (Western Europe, 2012). Here, water vapour increased by about 0.5 ppmv and methane by 24ppbv during the break-up phase of the ASM. Finally, **Jörn Ungermann** showed an example on how water vapour anomalies in the extratropical UTLS can be linked to multiple Rossby wave breaking events and long range transport along the subtropical jet during the WISE campaign.

Tropical tropopause layer

Tuesday morning started with tropical tropopause layer (TTL) and water vapour topics. In the first talk, **Laura Pan** highlighted the importance of horizontal transport in the tropics for the interpretation of dehydration and the relation to the Lagrangian Cold point and the lapse rate tropopause. The anomalously dry stratosphere during 2016 was addressed by **Dale Hurst** who concluded that this was caused by a synchronization of the exceptional stratospheric QBO and ENSO which led to cold tropical tropopause, except over the tropical central Pacific (moderately cold and dry). With the goal to better understand the large spread in TTL temperatures in the CCMVal2 model simulations **Thomas Birner** then showed how the interaction of upwelling and water vapour and ozone radiative feedbacks affect the temperature and altitude of the tropical tropopause. **Alison Ming** also addressed TTL temperatures using ERA Interim data and three different methods to estimate tropical upwelling. She concluded that the seasonal cycles of temperature and upwelling are well related, but with large quantitative differences between the various methods. Causes for the variability of tropical upwelling in CMIP5 models were presented by **Kohei Yoshida**. He pointed out that the upwelling mainly depends on tropical planetary-scale and extratropical synoptic-scale waves but also on parameterized gravity wave drag with strong implications for future scenarios.

Stratosphere-troposphere coupling

The late morning session started with **Ted Shepherd** talking about open issues on stratosphere-troposphere coupling (STC) and the impact on the tropospheric circulation on various time scales. In particular, he stressed the lack of understanding in the processes leading to STC as well as the application of methods to detect the coupling and the impact on e.g., the European climate. **Chaim Garfinkel** highlighted the non-linearity of coupling between ENSO and lower stratospheric temperatures and water vapour with the main conclusion being that strong ENSO events lead to warming and moistening. ENSO also affects the ASM anticyclone with a weaker circulation associated with strong El Nino events but a stronger Hadley circulation and stronger in-mixing of ozone into the tropics following La Nina (**Xiaolu Yan**). The effect of ozone on the TTL temperature structure was shown by **Ed Charlesworth** using a simple radiative and photochemical equilibrium model. As a final talk on Tuesday morning **Mengchu Tao** emphasized the role of isentropic mixing to explain lower tropical tropospheric ozone concentrations.

A central part of the meeting was the poster session on Tuesday, which constituted of more than 50 posters. These were on display from Monday to Wednesday to allow for sufficient time for discussions.

Stratospheric circulation

The afternoon session started with **Marta Abalos**, who discussed the importance and consequences of future climate change on transport and mixing and the tropopause location using an e90 tracer. Trends of tropical upwelling in the lower branch of the BDC were presented by **Hella Garny** showing agreement between reanalysis and climate models for historical periods with strongest increases in upwelling at 70 hPa in DJF and 100 hPa in JJA. **Dieter Peters** presented a link between the NAM150 index and a downward propagating signal and tropospheric impact 8-50 days after the event, potentially enhancing climate predictability. Juan Anel (talk by **Petr Sacha**) compared the expansion of the tropics in reanalyses and WACCM simulations using isentropic PV fields and age of air showing large variability of the expansion signal. New possibilities of observations of stratospheric age of air were presented by **Andreas Engel**. He introduced the new balloon borne AIRCORE sampling, which provides an inexpensive opportunity to extend the measurement time series in the mid stratosphere. A way of deriving age spectra from realistic tracers was presented by **Frauke Fritsch**, showing differences between pulsed and linear tracer experiments and passive SF6.

The extratropical UTLS

Wednesday morning was dedicated to the extratropical tropopause and started with **Heini Wernli**, who highlighted the role of diabatic processes for the tropopause structure and cross tropopause exchange. Particularly, this involves sub-grid processes such as cloud formation, convection and warm conveyor belts, which lead to modification of Rossby waves and the PV structure. The role of turbulence as an important small scale process for redistributing trace species across jet streams in global models was shown by **Holger Tost. Volkmar Wirth** presented a new diagnostic to quantify the propagation of Rossby wave packets (RWP), the 'local finite amplitude wave activity', which allows diagnosing RWPs even in the nonlinear stage, where envelope methods tend to lose the RWP signal. **Andreas Schäfler** presented first results from the WISE mission, showing curtain like water vapour and ozone LIDAR observations which allow identifying different mixing states of air parcels in a tropopause fold. **Robin Pilch Kedzierski** showed the effect of planetary and synoptic waves on the lower stratospheric static stability and concluded that the tropopause inversion layer (TIL) is a result of the tropopause based average of the wave affected tropopause locations. The second part of the extratropical session was opened by **Markus Rapp**, who showed the effect of the TIL for the propagation of gravity waves (GW), which in turn may lead to mixing and trace gas exchange at the tropopause. A detailed analysis of gravity wave propagation through and interaction with the TIL was presented by **Vera Bense**, using idealized simulations to show that the transmission strongly depends on the vertical wavelength and that the waves can alter the TIL as well. As shown by **Aurelien Podglajen**, GWs play a vital role for mixing and vertical transport in the TTL which in some cases can be on the same order of magnitude as vertical upwelling. **Gergely Bölöni** presented a new approach to represent gravity waves in global models, replacing the current steady state parameterization of GWs by one that allows for a more realistic interaction between GWs and resolved flow. **Martin Riese** gave an overview over the WISE mission in September 2017, which focused on mixing processes at the extratropical tropopause, including the influences of fine-scale structures in a tropopause fold.

During the campaign, small scale mixing above a warm conveyor belt was observed. The POLSTRACC mission in winter 2015/2016 was introduced by **Hermann Oelhaf**, who showed that the lower stratosphere was strongly affected by polar stratospheric clouds down to 11km and strong ozone loss down to 400 K.

UTLS trends and composition

Wednesday afternoon started with **Michaela Hegglin**, who talked about recent updates on trend observations in the UTLS with a focus on water vapour and ozone. She pointed out the difficulty to quantify trends in the UTLS due to the strong dynamical variability, as well as the necessity of consistent and precise observations to reduce uncertainties and partly contradicting results of trend estimates. Focusing on ozone trends in the tropical UTLS, **Anne Thompson** showed reprocessed data from SHADOZ which have a higher accuracy than earlier versions. She also pointed out the substantial differences of ozone variability in the deep tropics compared to the subtropical stations. A new clustering technique to compare UTLS ozone from sondes and MERRA-2 reanalysis was presented by **Ryan Stauffer**, allowing to link extratropical ozone profiles to meteorological conditions and tropical profiles to convection and pollution events. **Krzysztof Wargan** also used MERRA-2 data to identify multi-decadal changes of ozone trends in reanalyses. He concluded that negative trends can most probably be linked to enhanced isentropic mixing in the UTLS in MERRA-2 and in M2-GMI simulations. A catalogue of stratospheric intrusions in MERRA-2 was presented by **Emma Knowland**, particularly addressing the importance of these intrusions for tropospheric ozone. **Karen Rosenlof** showed that the North American monsoon convection is not a significant driver of heterogeneous chemical ozone loss in the mid latitude stratosphere. Using MLS observations **Michelle Santee** showed the large variability of the UTLS composition due to the ASM anticyclone. Her study includes latest results from 2017, when the stratospheric moistening by the ASM started earlier, but the pollution inside the ASM was weaker compared to other years. **Rolf Müller** stressed that NO_x is more important for chemical ozone production in the UTLS than infrequent events of high water vapour and simultaneous enhanced HCl and ozone. An analysis of Arctic ozone loss during the very cold winter 2015/2016 was presented by **Björn Martin Sinnhuber**. Based on measurements during POLSTRACC and simulations by CLaMS and EMAC he concluded on ozone loss of 1.6 ppmv at 400 K. The Wednesday session on ozone and composition trends was closed by **Irina Petropavlovskhikh**, who showed results from the LOTUS initiative. Combined satellite, model and ground based data sets indicate an ozone recovery for the post 2000 period in the extratropical stratosphere, but decreasing ozone in the lower UTLS with large uncertainties.

Thursday started with a series of talks about passenger aircraft observations from the IAGOS project. First, **Andreas Zahn** highlighted the gain from combining regular passenger aircraft observations with modelling and reanalysis data to identify e.g. pathways controlling water vapour in the UTLS. **Harald Bönisch** (presenting the contribution by Denise Assmann) addressed the aerosol abundance in the UTLS, indicating that accumulation mode particles are present above the tropopause and that WCBs may act as a source of aerosols in the tropopause region. **Yann Cohen** showed climatologies of CO and ozone in the Northern Hemisphere UTLS from IAGOS data. CO trends (2002-2013) appear to be mostly negative in the northern UT, whereas ozone increases (1994-2013) in the UT, but shows no significant trend in the LS. **Andreas Petzold** summarized findings on the long term water vapour distributions based on combined IAGOS and research aircraft data from the JULIA data base. No significant H_2O trend can be deduced over the North Atlantic, but large seasonal differences of UTLS water vapour distributions indicate significant seasonally varying transport processes affecting water vapour in the UTLS.

The session was closed by **Bill Randel**, giving a summary, outlook, and scientific challenges of the previous days. He emphasized the global view of the tropopause region including the Southern Hemisphere. Open questions concern the extratropical tropopause, which is much stronger affected by diabatic processes than previously thought, and which might substantially affect the lower UTLS composition. Important advances have been made in understanding the role of the Asian summer monsoon anticyclone and its relevance as source region for trace gases and aerosols in the UTLS. However, while the qualitative picture of the UTLS increased in the last years, quantitative estimates of the relevant transport pathways and times are still under debate. Also, the TTL, its coupling to the residual circulation, and the effects of two way mixing across the jets lacks quantitative understanding. Small scale processes, like gravity waves or turbulence, may play an important role for the composition and entry conditions to the BDC.

Figure 7: *Participants of the UTLS Workshop.* *(Photo: Philipp Reutter, University of Mainz)*

He emphasized the use of long-term measurements and observations in the UTLS to identify uncertainties in trends and link processes and large scale trends.

With this summary, and based on the input by the rapporteurs (**Marta Abalos, Hella Garny, Andreas Petzold, Daniel Kunkel, Tanja Schuck, and Felix Plöger**), the final discussion started. It was led by Peter Hoor and brought out the following questions:

- Can we better quantify trends and variability and their driving processes in the UTLS?
- What roles do diabatic (sub-grid) processes play in the tropopause region for the UTLS composition?
- Which feedback mechanisms on multiple scales affect large scale circulation and climate?
- What are the sources of UTLS aerosol, and what is their contribution to radiative forcing?
- What roles do UTLS processes play for stratosphere-troposphere coupling and extreme weather, and what are relevant coupling mechanisms?

To answer these questions further collaborations across the various sub-communities which actively work on topics related the UTLS were discussed. The community agreed on the need for a continuation of high precision and accurate measurements of ozone and water to better constrain trends. This also holds for the role of aerosols in the UTLS, which may affect the energy budget in many ways. These measurements in combination with new higher resolution reanalysis data are further needed for a quantitative understanding of processes, in particular at the tropopause, which are potentially missed by previous coarse reanalysis data sets.

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References:

Ball, W.T., *et al.* 2018: Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery. *Atmos. Chem. Phys.*, **18**, 1379-1394, https://doi.org/10.5194/acp-18-1379-2018.

Hegglin, M.I., *et al.* 2014: Vertical structure of stratospheric water vapour trends derived from merged satellite data. *Nature Geoscience*, **7**, pp. 768-776, https://doi.org/10.1038/ngeo2236.

Riese, M., *et al.* 2012: Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *J. Geophys. Res.*, **117**, D16305, https://doi.org/10.1029/2012JD017751.

Steinbrecht, W., *et al.* 2017 An update on ozone profile trends for the period 2000 to 2016. *Atmos. Chem. Phys.*, **17**, 10675-10690, https://doi.org/10.5194/acp-17-10675-2017.