Workshop on Dynamics, Transport, and Chemistry of the UTLS Asian Monsoon

7-10 March 2016, Boulder, Colorado

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The upper troposphere-lower stratosphere (UTLS) of the Asian summer monsoon (ASM) region is characterized by a continental-scale anticyclonic circulation, which is dynamically active and coupled to monsoonal convection. The monsoon anticyclone exhibits anomalous chemical and aerosol characteristics, linked to the outflow of deep convection and the large-scale circulation, and strongly influences the global UTLS composition during boreal summer. Ongoing increases in regional surface emissions enhance current scientific interests. There is substantial work in the research community aimed at improving understanding of the behaviour of the UTLS monsoon region using observations and models. Key topics that are poorly understood include dynamical and chemical coupling with convection, three-dimensional transport pathways from the surface to the stratosphere, composition/reactive chemistry in the monsoon region, as well as microphysics and the tropopause aerosol layer. There are plans for aircraft-based field experiments and enhanced *in situ* sampling in the near future, which promise novel data to address these questions. To summarize current understanding and plan for future activities, a workshop was held from 7-11 March in Boulder, Colorado, USA, focused on "Dynamics, Transport and Chemistry in the UTLS Asian Monsoon". The workshop was aimed at synthesising observations from satellites, aircraft, and balloons; modelling from regional to global scales; and developing key questions for the focus of future research. The workshop was attended by ~50 scientists and students who are actively engaged in UTLS monsoon research. This summary provides a brief overview of the key topics and discussions; a list of workshop participants and the individual presentations made at the workshop can be found here: **www2.acom.ucar.edu/asian-monsoon**.

Dynamics

The ASM system plays a dominant role in large-scale climate variability influencing over half of the world's population. Monsoon-related droughts and floods, and effects of enhanced aerosols and poor air quality are serious environmental hazards. The monsoon circulation and water cycle are driven by atmospheric heating tied to convection, with complex behaviour across a wide range of space-time scales. New research is recognizing the importance of the UTLS as an integral component of the monsoon system.

Monsoon dynamics and aerosol interactions

One aspect of monsoonal behaviour emphasized over recent decades regards the feedback effects of atmospheric aerosols, especially absorbing aerosols (*e.g.,* black carbon), which regulate and interact with heat sources and influence circulation and water cycles. Deep convection and aerosol feedbacks are strongly coupled with circulations extending to the UTLS, and new work focuses on quantifying dynamical and radiative feedbacks and coupling with lower altitudes. Improved understanding of the UTLS region and its impact on dynamical, chemical, and radiative behaviour at lower levels is a major research goal (**Bill Lau**).

Anticyclone behaviour, stratosphere-troposphere exchange (STE), and the tropopause

The UTLS monsoon anticyclone is an inherently unstable circulation pattern, with sub-seasonal modulation of the anticyclone centre and 'eddy shedding' as key aspects of observed variability (in both dynamics and constituents). Discussions at the workshop focused on understanding bimodality of the anticyclone (with centres over Tibet and Iran), and quantifying the relationships between shifting of the anticyclone, large-scale

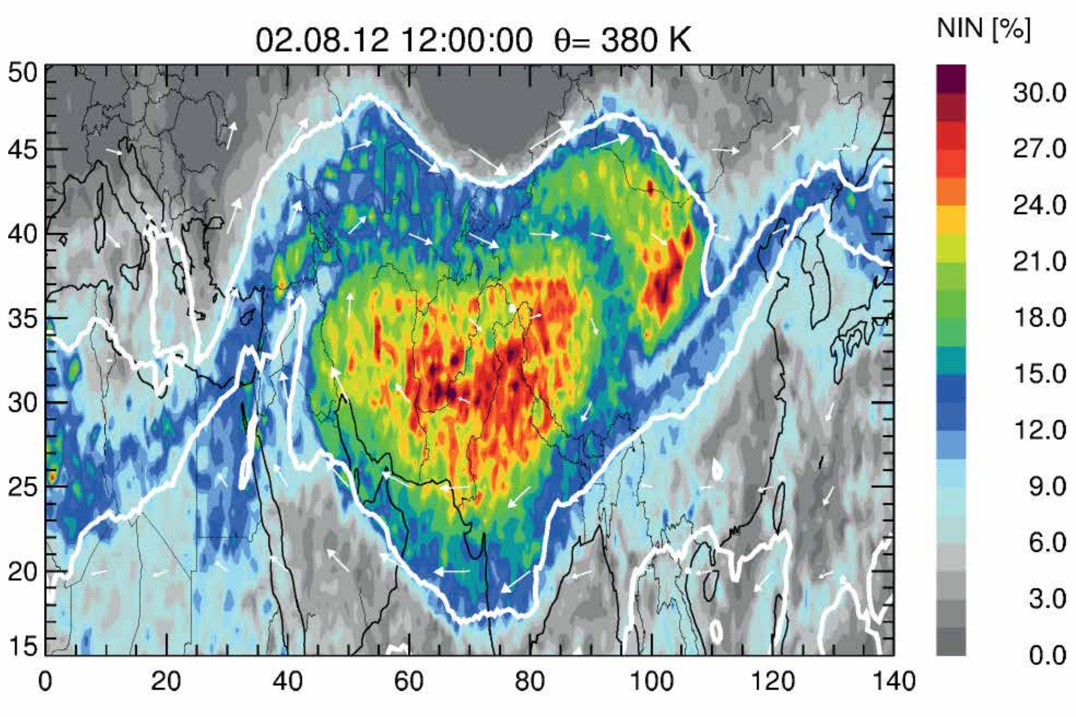

Figure 8: Distribution of the fraction of air originating from Northern India at the 380K potential temperature level on 2 August 2012 from a CLaMS model simulation with emission tracers. The 4.5PVU surface roughly marks the edge of the anticyclone and is shown with a white line (details discussed in Vogel *et al*., 2015, doi:10.5194/acp-15-13699-2015).

precipitation and convection, and Rossby wave dynamics. El Niño/Southern Oscillation (ENSO) influences interannual variability, although interactions are complex. Further work aims at evaluating STE and behaviour of the tropopause linked to monsoon dynamics (**Yimin Liu**, **Chiara Cagnazzo**, **Mathias Nuetzel**, **Rongcai Ren**, **Yutian Wu**, **Pengfei Zhang**).

Transport

Transport associated with the ASM anticyclone was the most discussed topic during the workshop. Using different approaches and tools, the participants addressed and explored several issues and questions.

Anticyclone transport boundaries and pathways from the boundary layer

To quantify transport and confinement within the anticyclone, it is important to identify its boundaries. Discussions included the use of geopotential height, stream function, jet structure, and isentropic potential vorticity (PV) gradient to identify the edge of the anticyclone. Analyses of the thermal tropopause and cold point show that the ASM tropopause is higher than the equatorial tropopause during this season. Quantifying preferred transport pathways from the boundary layer to the UTLS anticyclone is important for understanding driving processes and identifying dominant source regions. Various approaches show that the southern flank of the Tibetan Plateau is a key region for boundary layer air to enter the anticyclone. The pathways and time scales for air in the anticyclone to enter the stratosphere are topics of active research.

Influence of convection on the UTLS

Calculations estimating the influence of deep convection on the UTLS can be made using backward or forward trajectories coupled with (diurnally-resolved) brightness temperatures from geostationary satellites (as a proxy for deep convection). Preferred source regions for the monsoon are the chronic deep convective regions over the South China Sea and Bay of Bengal. Global calculations of 'convective influence' demonstrate that most of the tropical upper troposphere has intersected convection within the previous ~2-5 days.

Transport and mixing tied to monsoon circulations

The global behaviour of UTLS mixing during boreal summer was discussed based on various mixing diagnostics. The ASM anticyclonic flow plays a key role for mixing of higher latitude lower stratospheric air into the low latitude tropical tropopause layer (TTL), influencing the seasonal cycle, and may also contribute to cross-equatorial transport. Transport through the anticyclone may be evaluated using tracers and diagnostics based on meteorological analyses (such as identifying manifolds or Lagrangian Coherent Structures). **Figure 8** provides an example of a diagnostic of the impact of Northern India source regions on UTLS composition, based on the Lagrangian CLaMS model. The large fraction of Northern India emission at the 380K level is consistent with the effective pathway of uplifting near the southern flank of the Tibetan Plateau.

The analyses presented involve Lagrangian models (**Ken Bowman**, **Bernard Legras**, **John Bergman**, **Paul Konopka**, **Rolf Müller**, **Baerbel Vogel**), chemical transport and chemistry-climate models (**Suvarna Fadnavis**, **Laura Pan**), diagnostics from dynamical fields and idealized tracers (**Marta Abalos**, **Clara Orbe**) and studies combining trajectory model calculations and observations (**Brice Barret**, **Klaus Gottschaldt**, **Mike Fromm**, **Nathaniel Livesey**).

Composition and Chemistry

Large-scale behaviour of chemical composition from satellite observations

The ASM impact on UTLS composition has been documented by satellite measurements, especially from the decade-long records from limb-sounding the MLS, MIPAS, and ACE-FTS instruments. These datasets reveal strong signatures of enhanced boundary layer tracers within the anticyclone. The observations also show synoptic-scale variability in numerous species with stratospheric or tropospheric origins and the combination of species provides a fingerprint of source regions for the UTLS. Observations of pollution tracers (such as CO from MLS or PAN from MIPAS) demonstrate transport and eddy shedding events tied to dynamical circulations (**Michelle Santee**, **Gabi Stiller**, **Mijeong Park**, **Federico Fierli**, **Suvarna Fadnavis**, **Jiali Luo**).

In situ observations from aircraft and balloons

Limited *in situ* measurements from in-service aircraft have provided detailed composition measurements, including short-lived hydrocarbon species that demonstrate rapid transport (a few days) from the boundary layer to the upper troposphere (10-12km). However, the lack of such measurements above ~12km limits the understanding of transport to higher altitudes. There are limited measurements of reactive nitrogen in the monsoon UTLS, and poor understanding of the contributions of near-surface emissions versus lightning generation. Campaign-based balloon measurements of water vapour, ozone, aerosol, and cirrus information (from COBALD backscatter measurements) have been made in the monsoon region over China since 2009,

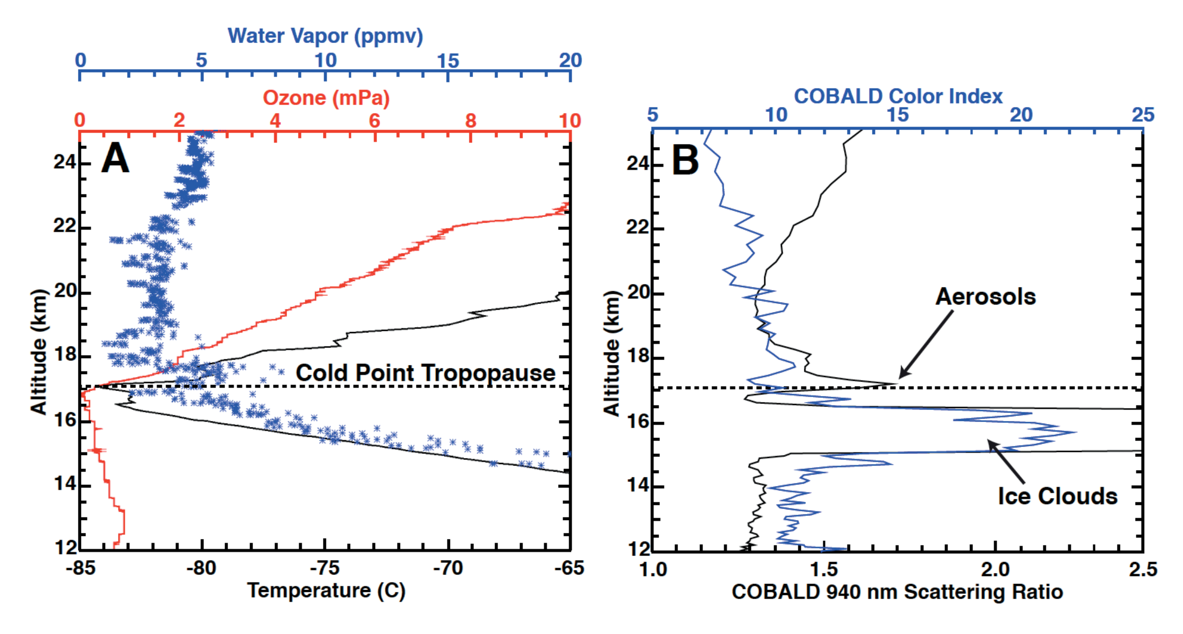

Figure 9: An example of balloon measurements from Hyderabad, India, from 13 August 2015, showing the complexity of ASM UTLS reflected in (a) temperature, ozone, and water vapour, and (b) cirrus and the aerosol layer. The data shown are from an integrated payload of ozonesonde, Cryogenic Frost-point Hygrometer (CFH), optical particle counters (OPC, data not shown), and Compact Optical Backscatter and AerosoL Detector (COBALD). This flight was coordinated by TiFR, NASA Langley, the University of Wyoming, and Indian National Atmospheric Research Laboratory. Figure courtesy Jean Paul Vernier and colleagues.

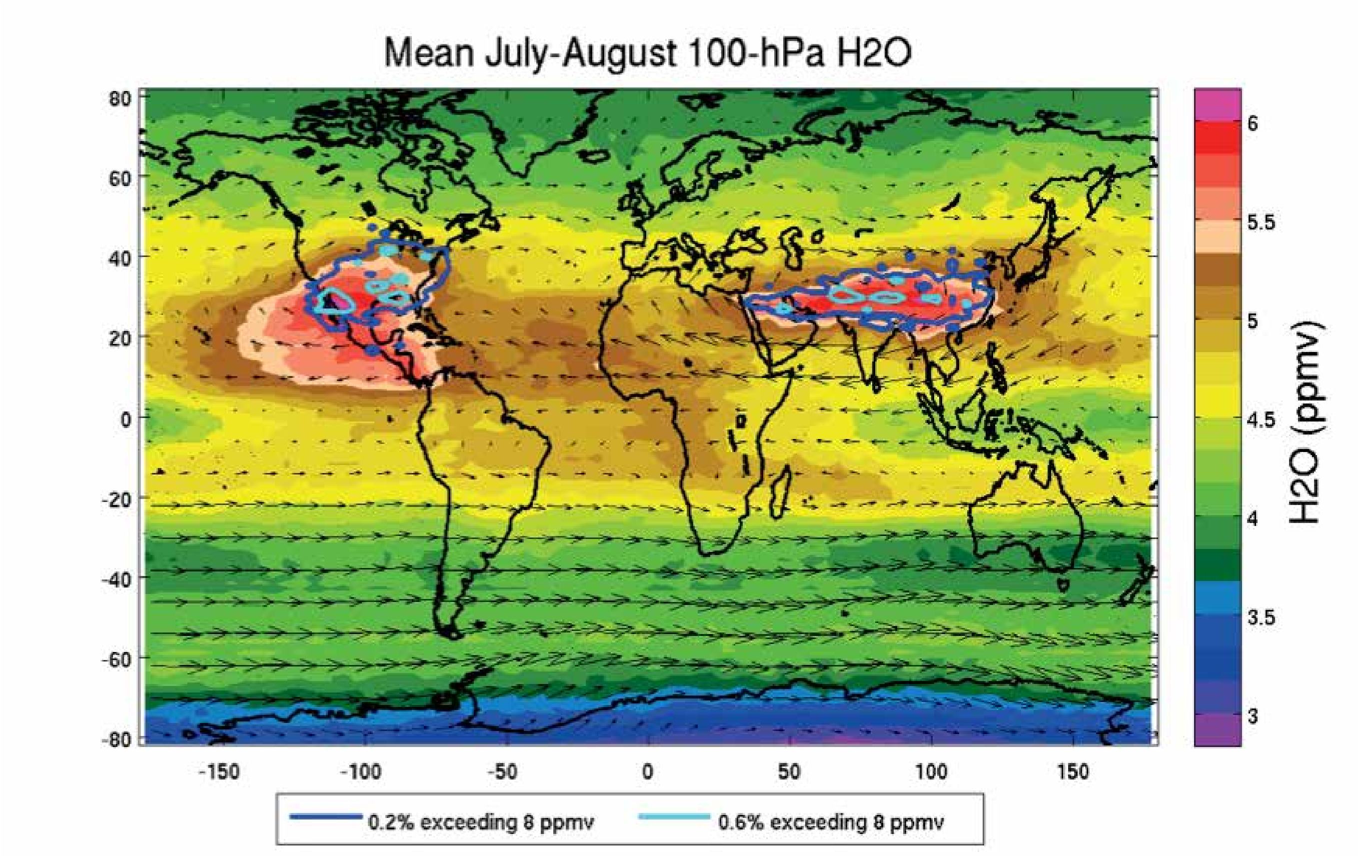

Figure 10: Colours show climatological average July-August water vapour at 100hPa, highlighting maxima over the Asian and North American monsoon regions. Colour contours indicate incidences of extreme outliers (individual measurements above 8ppmv at 100hPa). Results are derived from MLS observations during 2004-2012. Arrows indicate corresponding average circulation at 100hPa.

more recently including particle counter measurements. A similar measurement campaign was conducted from five launch sites in India last year, and **Figure 9** shows an example of balloon data from Hyderabad, India. While limited in sampling, these provide a novel ground-truth evaluation of satellite measurements, quantitative estimates of supersaturation and cloud microphysical processes, and aerosol behaviour (**Angela Baker**, **Jianchun Bian**, **Jean Paul Vernier**, **Shradda Dhungel**).

Impacts on stratospheric water vapour

The Asian and North American monsoon regions are characterised by enhanced water vapour in the lower stratosphere (**Figure 10**) and frequent occurrence of cirrus near the tropopause. Observational and modelling studies are aimed at understanding the contribution of large-scale circulation versus extreme deep convection in maintaining these patterns. Trajectory studies based on meteorological reanalyses, incorporating convective influence, are able to capture the broad-scale water vapour and cirrus behaviour. Temporal variations in lower stratospheric water vapour are closely tied to temperatures and dehydration on the equatorward (cold) side of the anticyclone. However, extremely moist air in the lower stratosphere is observed (infrequently) in satellite measurements (and field campaigns), demonstrating the direct influence of extreme convection. The relative influence of large- versus small-scale processes on UTLS water vapour and clouds is an outstanding research topic (**Michael Schwartz**, **Rei Ueyama**, **Wuke Wang**, **Bill Randel**).

Aerosols and Clouds in ASM region

The Asian Tropopause Aerosol Layer (ATAL) was discovered based on satellite lidar measurements. It is an annually occurring feature that may be strengthening over time as a result of growing Asian pollution. Several balloon-based measurement campaigns have made direct measurements of the ATAL, with results showing reasonable agreement with satellite-derived observations. Recent measurements, including aerosol backscatter and particle size distribution measurements, suggest that the ATAL may be primarily composed of sulphate aerosols. Global aerosol modelling studies (incorporating climatological surface precursor emissions) show reasonable agreement with satellite and *in situ* measured aerosol behaviour, and suggest a modest radiative impact for the ATAL (**Jean Paul Vernier**, **Terry Deshler**, **Jianchun Bian**, **Simone Brunamonti**, **Teresa Jorge**, **Ru-Shan Gao**, **Pengfei Yu**, **Mian Chin**).

Outstanding questions

The last half day of the workshop was aimed at discussions on outstanding questions and strategies for future measurement and modelling activities. Some of the key questions include:

1. How will the monsoons (including the UTLS circulation) evolve in a changing climate? What are the impacts of increasing pollution over south east Asia?
2. What controls the strong upward circulations in the monsoon? What are the specific influences of aerosols?
3. Is the monsoon anticyclone bimodal in location or intensity? If so, what are the links to convection, 3D circulation, and transport?
4. What is the altitude profile of convective outflow in the monsoon regions? How can we best characterize the full spectrum of convection?
5. What are the relative roles of deep convection and large-scale circulation in pumping boundary layer air to the tropopause level? What is the time scale for air within the ASM anticyclone to enter the stratosphere?
6. What is the relationship and coupling between ASM 3D circulation and the monsoon Hadley cell, and with the stratospheric Brewer-Dobson circulation? What are the relationships between vertical and horizontal transport?
7. What reactive chemistry and aerosol growth processes occur in the UTLS? Is there an anthropogenic signal in the ATAL? Is the monsoon a pathway for transport of sulfur to the stratosphere?

The workshop discussions provided an updated picture of the state of the science regarding ASM UTLS research. The discussions also provided useful input for the StratoClim project, which is making an active effort to target some of these questions in an upcoming airborne field campaign (campaign plan overviewed by **Markus Rex**).

Report on the Workshop on Atmospheric Blocking

6-8 April 2016, University of Reading, UK

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Atmospheric blocking plays a crucial role in modulating the variability of the mid-latitude circulation, particularly from sub-seasonal to annual and interannual timescales. Blocking also heavily affects weather conditions at the surface, being associated with largescale cold spells during winter and persistent heatwave episodes during summer.

During the Workshop on Atmospheric Blocking, over 100 experts from 22 countries (**Figure 11**) gathered to discuss recent advances in our understanding of blocking, its impacts and its representation in numerical models. Topics spanned from weather to climate timescales, and from theoretical developments to the latest operational capabilities.

Each of the three days of the workshop addressed a key topic: blocking identification and diagnostic tools, past trends and impacts of blocking, and the representation of blocking in numerical models and future projections.

Brian Hoskins opened the first day with a historical review onftheories of blocking, starting with the