Impact of the Asian monsoon on the chemical composition of the tropical tropopause layer (TTL)

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Asian monsoon - an effective pathway into the stratosphere?
Asian monsoon anticyclone

(a) MLS CO (Jul-Aug) 100 hPa

Park et al., JGR, 2007
Asian monsoon anticyclone

HCN at 13.5 km, JJA
Randel et al., Science, 2010
...the monsoon circulation provides an effective pathway for pollution from Asia, India, and Indonesia to enter the global stratosphere...

averaged between 0 and 100 E
Objectives

Impact of the Asian monsoon on the distribution of $O_3$, CO and $H_2O$ in the Tropical Tropopause Layer (TTL), i.e. at the “gateway” into the stratosphere

In particular:
Is the observed annual cycles of $O_3$ a pure tropical issue, i.e. how important is the isentropic transport from the extratropics (from the northern summer hemisphere) into the TTL (in-mixing) ?
(e.g. Chen et al., 1995, Dunkerton et al., 1995, Hayens and Shuckburgh, 2005, JGR)
Tropical tape-recorder – a signature of transport into the stratosphere (across the TTL)
$H_2O$ tape-recorder

$\pm 10^\circ N$ $H_2O$ tape recorder (Mote et al., JGR, 1996), here from the HALOE climatology (1991-2002), Grooß and Russell, ACP, 2005.
...driven by the annual cycle in tropical temperature here from Randel et al, 2007, JAS

$H_2O$ and the Asian monsoon

Gettelman et al., JGR, 2007

...the Asian monsoon circulation may contribute 75% of the total net upward water vapor flux in the tropics at tropopause levels from July to September.
CO tape-recorder

Schoeberl et al., GRL, 2006
...driven by the annual cycle in tropical upwelling here from Randel et al, 2007, JAS

Schoeberl et al., GRL, 2006
...driven by the annual cycle in tropical upwelling here from Randel et al, 2007, JAS

HCN tape recorder
~two-year cycle of the HCN anomaly (Pumphrey et al., 2008, GRL)
anomaly correlated with fires in Indonesia (Pommrich et al., 2010, GRL)

Schoeberl et al., GRL, 2006
Annual cycle in $O_3$

Randel et al. JAS, 2007 (also Folkins et al., GRL, 2006) from SHADOZ and HALOE observations

..."the annual variation of O3 at the tropical tropopause occurs primarily due to annual cycle in the tropical upwelling (that is in phase with annual variation of temperature)", Randel et al., JAS, 2007

...summer ozone maximum due to weaker upwelling in summer, ...more time for ozone production

Fig. 2. Seasonal cycle fit of ozone mixing ratio (ppmv) at each of the SHADOZ stations at 15, 17.5, and 20 km. Each line represents the harmonic fit of the data at the individual stations. The heavy dashed line at 17.5 km is the corresponding result from HALOE data over 10°N–S.
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Which picture is correct? isolated tropics or significant in-mixing? contribution of the Asian monsoon?

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Modeling with CLaMS
CLaMS - Lagrangian Chemistry Transport Model with $\approx 10^6$ air parcels

air parcel = “pivotal point with mixing ratios $\mu_i$, of $m$ species with $i = 1, \ldots, m$”

Potential temperature/pressure as vertical coordinate in the stratosphere/troposphere

Horizontal meteor. winds (ECMWF, NCEP, WACCM)

Vertical velocity: diabatic approach ($\dot{\theta}$ from radiation, latent heat rather than $\dot{p}$)

Lagrangian mixing

Full stratospheric and simplified tropospheric chemistry

Lagrangian particle sedimentation scheme

parallelized code (JUMP)

McKenna et al., JGR, 2002, Konopka et al., JGR, 2004, Grooß et al., 2005, ACP, Konopka et al., 2007, 2010, ACP

Greenland from space shuttle (NASA)
Troposphere+Stratosphere, hybrid coordinate, Mahowald et al., JGR, 2002
Diabatic vertical velocity $\dot{\theta}$ above 100/300 hPa for ECMWF-analysis/ERA-Interim
Annually averaged mass conservation, Rosenlof, JGR, 1995

<table>
<thead>
<tr>
<th>species</th>
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<th>upper boundary</th>
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<tbody>
<tr>
<td>CH$_4$</td>
<td>CMDL</td>
<td>HALOE</td>
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<td>Mean Age</td>
<td>linear source</td>
<td>MIPAS (SF6)</td>
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<tr>
<td>CO$_2$</td>
<td>CMDL</td>
<td>Mean Age</td>
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<tr>
<td>CO</td>
<td>CMDL + MOPITT</td>
<td>Mainz-2D</td>
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<td>O$_3$</td>
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<td>HALOE, $\theta \geq 500$ K</td>
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<td>HCl</td>
<td>0</td>
<td>HALOE, $\theta \geq 500$ K</td>
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<tr>
<td>H$_2$O</td>
<td>ECMWF, $\theta \leq 380$ K</td>
<td>HALOE</td>
</tr>
<tr>
<td>N$_2$O, F11</td>
<td>CMDL (CATS)</td>
<td>0</td>
</tr>
<tr>
<td>HCN</td>
<td>MODIS</td>
<td>0</td>
</tr>
</tbody>
</table>

Simplified chemistry

- HALOE - Climatology:
  - Grooss and Russell, ACP, 2005
  - CO$_2$/CH$_4$/CO since 1979/84/91
  - P. Tans, K. Masarie, P. Novelli
  - CMDL: CATS (4 stations)
  - N$_2$O, F11, J. Elkins
- MIPAS, SF6-Age
  - Stiller et al., ACP, 2008
  - MOPITT (V3, V4)
  - Pommrich at al., PhD, 2008
- HCN
  - Pommrich at al., GRL, 2010

Multi-annual CLaMS simulations (2001-10)
Mixing in CLaMS

Hurricane Ivan from space shuttle (NASA)

Subtropical jet over Himalayas
Mixing in CLaMS

Subtropical jet over Himalayas

Strong deformations ...

Hurricane Ivan from space shuttle (NASA)
Mixing in CLaMS

Hurricane Ivan from space shuttle (NASA)

Subtropical jet over Himalayas

... and mixing!
Konopka et al., 2004, JGR
Pan et al., 2006, JGR

Hurricane Ivan from space shuttle (NASA)
Mean age at $\theta = 380$ K

3 July 2008 /$\theta = 380 \pm 5$ K

Age (months)

- Snapshot: 75 km hor. resolution

- Asian monsoon anticyclone

- Mass transport $\sim (u, v, w)$
- Tracer transport $\sim (u, v, w) + \nabla \mu$
- E.g. in zonal mean
two-way tracer transport versus one-way mass transport
Vertical cross section (S-N at 90°E, 09.08.2003)

CO - tropospheric signatures in the stratosphere (up to θ = 450 K)
Vertical cross section (S-N at 90°E, 09.08.2003)

O$_3$ - stratospheric signatures in the troposphere (down to the boundary layer)
Asian monsoon and seasonality of $O_3$

CLaMS climatology (2002-05)
$\theta = 380$ K

$O_3$ at $\theta = 500$ K - HALOE clim
$O_3$ at Earth surface = 0
only phot. $O_3$ production and $HO_x$-induced loss

DJF
Asian monsoon and seasonality of $O_3$

CLaMS with aver. kernel

Aura-MLS climatology (2005-08) at $\theta = 380$ K
Anticyclones drive in-mixing

PV climatology at $\theta = 370$ K

ECMWF, 2002-05, $\theta = 370$ K

JJA

DJF
Asian monsoon anticyclone

Asian monsoon anticyclone

Inside: effective upward transport of young tropospheric air (with enhanced HCN, CO) into the stratosphere at the northern edge of the TTL, Park et al., JGR, 1997, Randel et al., Science, 2010.

Outside: effective isentropic in-mixing of old stratosphere air (enhanced O₃, reduced CO) into the TTL, Konopka et al., JGR, 2009, ACP, 2010.

JJA

θ = 380 K
Asian monsoon and seasonality of CO

CLaMS, $\theta = 380$ K

CO (BL) - Globalview between BL and 500 hPa - MOPPIT
simplified CO chemistry (OH) lifetime $\approx$ 3 month

JJA

DJF
Asian monsoon and seasonality of CO

CO anomaly
CLaMS, $\theta = 420$ K

Aura-MLS climatology
(2005-08) at $\theta = 420$ K
Seasonality of in-mixing

Up to 50% of ozone in summer due to in-mixing (CLaMS)!
(Konopka et al., ACP, 2010)
Annual cycle in ozone
a simplified view (trajectories)
Ozone reconstruction along back-trajectories

Backward-trajectories starting at $\theta = 400$ K ($\pm 20$ N)
- ERA-Interim winds
- full diabatic approach
- $O_3$-production + $HO_x$-induced ozone loss
- Initialization: ECMWF
Origin of air from back-trajectories

- 90 days backward trajectories
- PDFs of the endpoints

- ≈ 20000 trajectories
- PDFs of their end positions, gridded within 250 km bin width

JJA

DJF
Annual cycle of ozone

\[ \Delta O_3/O_3 [%] \]

- MLS
- HALOE
- SHADOZ

Observed fractional annual cycle of \( O_3 \) at \( \theta = 400 \) K (±30° eq. lat.)
Annual cycle of ozone

$\Delta O_3/O_3 [%]$

- MLS
- HALOE
- SHADOZ
- only upwelling (tropical, TST trajectories)
Annual cycle of ozone

![Graph showing the annual cycle of ozone with data points for MLS, HALOE, and SHADOZ. The graph includes labels for different data sets such as trop and ext, indicating extra-tropical and STT trajectories. The data spans from 2005 to 2006 and highlights the in-mixing aspect of the ozone cycle.](image-url)
Annual cycle of ozone

In-mixing = essential contribution!

Full reconstruction versus observation
...but what about scenarios without in-mixing?

...but a very strong seasonal cycle of upwelling

Vert. velocity

Ozone

only tropical trajectories (TST)
...but what about scenarios without in-mixing?

(too) strong seasonal cycle of upwelling makes annual cycle of $O_3$ possible!

...but slower upwelling in summer makes in-mixing more likely!

Vert. velocity

only tropical trajectories (TST)

...but a very strong seasonal cycle of upwelling
Conclusions

The seasonality of the composition of the TTL results from interaction of the annual cycle of upwelling (maximum in winter, vertical transport from the tropics into the TTL) and of the annual cycle of the horizontal in-mixing (maximum in summer, isentropic transport from the extratropics into the TTL).

The in-mixed air in summer contains both young tropospheric air from the core of the Asian monsoon anticyclone (high CO) and old stratospheric air (high $O_3$).

We find that between 380 and 420 K during the boreal summer more than 50% of ozone is due to this effect (CLaMS).

This pattern is a robust feature of our simulations although the absolute values of in-mixing are sensitive to the used scenario of the vertical winds and of the mixing intensity (use diabatic instead of kinematic vertical velocities from ERA-Interim).

Some related publications:
- Konopka et al., JGR, 2009, ACP, 2010
- Pommrich et al., GRL, 2010
- Ploeger et al., JGR, 2010, ACP, 2011
Key points and outstanding issues

- Quantification of in-mixing (Asian monsoon) on the composition of air in the TTL
- In particular transport of $H_2O, SO_2, ..., HCN$ (two-year cycle of the anomaly versus annual cycle of the Asian monsoon)
- Only very few aircraft/balloon measurements available (Kunming, China, 2009)
- Satellite observations (MLS - vertical resolution, ACE - coverage, PREMIER - 201?)
- Planned campaigns:
  - SEAC$^4$RS (Southeast Asia Composition, Cloud, Climate Coupling Regional Study) - NASA airborne field campaign, anticipated deployment period: August-September 2012
  - ATTREX (Airborne Tropical TRopopause EXperiment) - NASA Global Hawk, 2011-14
Transport across the TTL

Tropical Tropopause Layer (TTL) – region coupling the convectively-dominated free troposphere (Hadley/Walker circulation) with the radiation-dominated stratosphere (Brewer-Dobson circulation), see e.g. Fueglistaler et al., 2009, Rev. Geophys.
Smog over China, early October 2010

Smog and fog from MODIS on NASA’s Aqua satellite
Smog over China, early October 2010

Smog and fog from MODIS on NASA’s Aqua satellite

Aerosol index and SO$_2$ from OMI on NASA’s Aura
Asian monsoon anticyclone

Randel and Park, JGR, 2006: GPH and MPV at 150 hPa
AIRS H₂O and O₃ at 360 K

... high pressure system in the upper troposphere that extends well into the lower stratosphere up to about 20 km (or \( \theta = 420 \) K)

≈ nearly stationary disturbance of the subtropical jet during summer
Asian monsoon in the troposphere

...the strongest influence of the Earth orography on the composition of the atmosphere

...the most populated and polluted area on Earth, more than half the world’s population
Asian monsoon in the troposphere dominated by orographic insulation of the Himalaya (Boos and Kuang, Nature, 2010)

...the strongest influence of the Earth orography on the composition of the atmosphere

...the most populated and polluted area on Earth, more than half the world’s population
Figure 1 | Observational estimates of June–August thermodynamic structure, precipitation and wind. **a**, Satellite-based (AIRS) estimate of mass-weighted vertical mean temperature for 175–450 hPa. **b**, ERA40 equivalent potential temperature on a terrain-following model level about 20 hPa above the surface. **c**, TRMM precipitation rate (colour shading) and ERA40 850 hPa winds (vectors). In all panels, grey lines denote coasts and thick black contours surround surface pressures lower than 900 hPa and 700 hPa. The contour interval is 1 K in **a**, 2 K in **b** and 2 mm d$^{-1}$ in **c**.
Asian monsoon in the troposphere

NCAR - Community Atmosphere Model (CAM 3.0)
standard topography

no topography

topography north of Himalaya set to 0 (no Tibetan plateau)

from Boos and Kuang, Nature, 2010
Asian monsoon in the troposphere

...sensible heat over Tibetan plateau is a second order effect to drive the Asian monsoon.

from Boos and Kuang, Nature, 2010
Asian monsoon in the stratosphere

Figure 1. (a) Horizontal structures of July–August 2005 average National Centers for Environmental Prediction (NCEP) geopotential height anomalies (deviations from the zonal mean, unit: meter) and horizontal winds (m s\(^{-1}\)) at 100 hPa. Horizontal wind fields are shown as vectors, and shaded regions indicate deep convection (outgoing longwave radiation (OLR) \(\leq 205\, \text{W m}^{-2}\)). (b) Revised “Gill-type” solution at the upper level of the atmosphere [adapted from Gill, 1980, Figure 1b]. Shaded regions indicate the imposed heat source. Copyright Royal Meteorological Society. Reproduced with permission. Permission is granted by John Wiley and Sons Ltd on behalf of RMETS.

Idealized Gill solution for \(p\) and \((u, v)\) anomalies

Shallow-water eq. in steady state “heat source” + “Coriolis force”


from Park et al., JGR, 2007
Mass versus tracer transport

Mass transport is driven only by the velocity fields \((u, v, w)\)

Tracer transport is driven by the velocity fields AND by their spatial (mainly isentropic) gradients - two-way transport
**Kinematic versus diabatic vertical velocities**

Reconstruction of O_3 along the backward trajectories sensitive to the used vertical velocity ⇒ too much noise in the kinematic vertical velocities!

Kunming campaign (August 2009, 25°N, 102.6°E) first in situ observations of water vapor and ozone during the Asian summer monsoon.
Seasonality of in-mixing

Mean age at $\theta = 380$ K