Lecture 5: Monsoon circulations in the UTLS

• Dynamics and transport in the Asian monsoon anticyclone

• Chemical variability linked to the monsoon

• Instability and eddy shedding

• Transport to stratosphere

• Eruption of Mt. Nabro in June 2011

• Water isotopes in the UTLS
Summer Broad-Scale Circulations

- persistent anticyclone
- deep convective transport
- anomalous chemistry clouds/aerosols
- transport to stratosphere
- Hadley cell
- Walker cell
Dynamical Background

Cyclone at the surface, anticyclone in the upper troposphere

one-day ‘snapshot’
July 10, 2003


Hoskins and Rodwell, 1995
Highwood and Hoskins, 1998

anticyclone
upper troposphere

cyclone
lower troposphere

Park et al., 2009, J. Geophys. Res.
Anticyclones in the Upper Troposphere

Note that the anticyclone does not lie on top of the deep convection

Matsuno-Gill Solution

Park et al., 2007, J. Geophys. Res.
Anticyclonic circulation extends into lower stratosphere

Randel and Park, JGR, 2006

Lower troposphere

Upper troposphere

balanced dynamical structure

cold tropopause and lower stratosphere

tropopause

Lower troposphere

warm troposphere

Randel and Park, JGR, 2006
Confinement within the anticyclone: idealized transport experiments

- initialize 2400 particles inside anticyclone
- advect with observed winds for 20 days
- test different pressure levels

transport simulation at 150 hPa

large fraction remain inside anticyclone

tests at different pressure levels show that confinement mainly occurs over altitudes with strongest winds

Frequent tropopause-level cirrus clouds in monsoon region
CALIPSO satellite lidar cloud observations

Tibet

Jul 14, 2010
Monsoon aerosol layer near 16 km

SAGE II measurements 1999-2005
Thomason and Vernier, ACP, 2013

CALIPSO measurements
Vernier et al, GRL, 2011

Narrow layer near tropopause
strong chemical influence on summer UTLS

MLS 100 hPa
carbon monoxide (CO)


variability linked to monsoon convection
ACE Fourier Transform Spectrometer

ACE occultations, 2004-2006

Low latitudes: 4 samples / year
Randel et al., 2012, J. Geophys. Res.

All observations for June-August
ACE-FTS (04-06/JJA) 1233
ACE measurements  JJA 2004-2006

High CO and HCN are associated with the Asian monsoon anticyclone

Park et al., 2007, J. Geophys. Res.

Park et al., 2008, Atmos. Chem. Phys.
ACE-FTS CO Profiles

all profiles 10° - 40° N

inside vs. outside

Inside anticyclone

outside
other tropospheric tracers

Enhancement inside the anticyclone up to ~20 km

\[ \tau = 2 \]
\[ \tau = 5 \]
\[ \tau = 1.5 \]
\[ \tau = 0.5 \]
$C_2H_2$ measurements from ACE-FTS satellite

photochemical lifetime ~ 2 weeks

evidence of relatively rapid transport to the UTLS
$\text{C}_2\text{H}_2/\text{CO}$ ratio ~ measure of photochemical age

relatively young air inside the anticyclone, up to $\sim$17 km
Greenhouse gas relationships in the Indian summer monsoon plume measured by the CARIBIC passenger aircraft

T. J. Schuck¹, C. A. M. Brenninkmeijer¹, A. K. Baker¹, F. Slemr¹, P. F. J. von Velthoven², and A. Zahn³

Enhanced CH$_4$ within anticyclone
Characterization of non-methane hydrocarbons in Asian summer monsoon outflow observed by the CARIBIC aircraft

A. K. Baker¹, T. J. Schuck¹, F. Slemr¹, P. van Velthoven², A. Zahn³, and C. A. M. Brenninkmeijer¹

ACP, 2011
Age of air estimated from short-lived hydrocarbons

Result: air is relatively young: ~5-12 days

Baker et al, ACP, 2011
chemical transport models can simulate observed large-scale behavior

**MLS observations**

(a) MLS CO 100 hPa

**MOZART simulation**

(b) MOZART-4 CO 100 hPa

Park et al, JGR, 2009
simulation for one day

MLS observations

MOZART simulation

Park et al, JGR, 2009
Questions:

• How sharp is the ‘chemical edge’?
• When and where does air ‘escape’ the anticyclone?
Transport pathways derived from observations and models

- Convective transport (main outflow near 200 hPa)
- Confinement by anticyclone + transport to stratosphere
- Transport above 200 hPa by convection / circulation
- Convective transport (main outflow near 200 hPa)
- Surface emission (India and Southeast Asia)

Key points:

• Asian monsoon anticyclone is dynamical response to monsoon convection (heating)

• Climatological feature every year ~June-September

• Cold tropopause, frequent clouds, aerosol layer

• Strong chemical anomalies inside anticyclone, due to:
  ✓ Rapid transport from surface (evidenced by short-lived chemical species)
  ✓ Circulation traps air inside anticyclone
What happens to the outflow from deep convection?

3D trajectories initialized at 200 hPa in regions of deep convection OLR < 160 K

+ 10 days

+ 20 days

confinement within anticyclone

from Hella Garney
Comparison of trajectory calculations with MLS CO climatology

Colors: MLS CO climatology

Black contours: trajectory calculations
Three-dimensional diabatic trajectories

Note: this is work in progress, and not well understood yet
Monsoon circulation is inherently unstable

Hsu and Plumb 2000 JAS

‘eddy shedding’ from monsoon circulation
Anticyclone viewed in potential vorticity

Dynamic variability of the Asian monsoon anticyclone observed in potential vorticity and correlations with tracer distributions

H. Garny and W. J. Randel

JGR 2013
PV in monsoon region at 360 K  

May 1 - September 30, 2006

Day 1 = May 1
   32  June 1
   62  July 1
   93  Aug 1
  123  Sept 1

Dynamical variability echoed in tracers

PV at 360 K

CO from Aura MLS

Garney and Randel, 2013, JGR
Transport to the stratosphere via the monsoon anticyclone

**HCN - biomass burning tracer**
- Minimum in tropics (ocean sink)
- Long lived in free atmosphere

**ACE HCN (JJA, 16.5 km)**
- Monsoon maximum
- Minimum for air with recent ocean contact
- Transport to stratosphere via monsoon
WACCM simulation of HCN

- climatological emission sources
- parameterized ocean sink
Seasonal cycle of HCN from ACE-FTS

Africa and S. America biomass burning

maxima persist in stratosphere because of long HCN lifetime
HCN 'tape recorder' from ACE-FTS measurements

boreal summer maxima from Asian monsoon circulation
Key points:

• Trajectory studies valuable for understanding fate of convective outflow
• Fundamental instability of anticyclone: eddy shedding
• HCN provides evidence for monsoon transport to stratosphere
Nabro eruption
June 14, 2011

Red Sea
SO$_2$ plume from Nabro

SO2 vertical column [DU]
GOME-2 – DLR/BIRA-IASB/EUMETSAT

13 June 2011
SO$_2$ plume from Nabro
SO$_2$ plume from Nabro

16 June 2011
SO$_2$ plume from Nabro

17 June 2011
Primary eruption was to middle / upper troposphere (~10-16 km) (and small amount to stratosphere, above 18 km)

trajectories for June 13-16

trajectories overlaid with GOME SO$_2$

Bourassa et al, 2012
Stratospheric aerosols from OSIRIS satellite

Bourassa et al, 2012

June 21

July 1

Nabro eruption June 13-14

July 6

July 11
Bourassa et al, 2012
OSIRIS aerosol extinction

eruption June 13
Interpretation:

• Nabro SO₂ plume in upper troposphere, transported around monsoon circulation to eastern side.

• Transport to stratosphere through monsoon circulation (and convection?)

• Confined to anticyclone, converted to stratospheric sulfate aerosol ~ 1 month

• Further evidence of transport to lower stratosphere via monsoon (Nabro in right place at right time)

Bourassa et al., 2012, Science
July 17
34 days after eruption

Nabro aerosols

Bourassa et al., 2012, Science
Ongoing research:

• What are the contributions of different chemical source regions to the upper troposphere? Is reactive chemistry important? How much reactive nitrogen is in the anticyclone?

• When and where does air escape the anticyclone? Are there sharp gradients across edges?

• What is the role of deep convection vs. large-scale upward circulation to the stratosphere? How important are diurnal variations in convection?

• What is the nature of the tropopause aerosol layer? Does it influence UTLS clouds?
Extra slides
200 hPa streamfunction JJA

observations

linear model with heating

reasonable agreement

diabatic heating from reanalyses

Result: heating from convection mainly forces monsoon anticyclone
July 1: 18 days after eruption
Also enhanced water vapor in monsoon regions

Asian monsoon

North American monsoon

white contours: deep convection
Anticyclone viewed in potential vorticity

PV in monsoon region at 360 K  May 1 – September 30, 2006

Day 1 = May 1
32  June 1
62  July 1
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123  Sept 1

Global variations of Water Vapor Isotopes from ACE-FTS satellite data
Water vapor isotopes: $\text{H}_2\text{O}^{16}$, HDO, $\text{H}_2\text{O}^{18}$, $\text{H}_2\text{O}^{17}$

Key point: heavier isotopes are preferentially depleted as water changes phase

Values often expressed in delta notation:

$$\delta D = 1000 \times \left[ \frac{([\text{HDO}]/[\text{H}_2\text{O}])_{\text{measurement}}}{([\text{HDO}]/[\text{H}_2\text{O}])_{\text{VSMOW}}} - 1 \right]$$

'per mil'
What do we expect to see for water isotopes in the stratosphere?

Brewer, 1949

Answer: preferential depletion of heavier isotopes, as air is slowly dehydrated on passing the cold point tropopause

Very small HDO/H₂O
But observations show a different story: 
**persistent increase in TTL region, heavy stratosphere**

\[ \delta D = 1000 \times \left[ \frac{([HDO]/[H_2O])_{\text{measurement}}}{([HDO]/[H_2O])_{\text{FSMOW}}} - 1 \right] \]

Moyer et al 1997  
Hanisco et al 2007  
Fueglistaler et al, 2009
But observations show a different story: 

**persistent increase in TTL region, heavy stratosphere**

Moyer et al 1997
Hanisco et al 2007
Fueglistaler et al, 2009

transport of ice in overshooting deep convection ?

\[ \delta D = 1000 \times \left[ \frac{([HDO]/[H_2O])_{\text{measurement}}}{([HDO]/[H_2O])_{\text{FSMOW}}} - 1 \right] \]
ACE-FTS water isotopologues

FTS measurements: 2.2 – 13.3 μm
5+ years of data (Feb. 2004 – present)
  ~ 3,500 occultations /year
All major isotopologues of water and methane

Resolution: ~300 km horizontal, 3 km vertical

ACE occultations, 2004-2009

Data presented here:
~20,000 occultations
  (entire V2.2 dataset 2004-2009)
3-month seasonal averages DJF, ...
  (~ global coverage)

Low latitudes: 4 samples / year

Randel et al 2012
ACE-FTS δD profiles show similarities to previous measurements:

*persistent increase in TTL region, heavy stratosphere*

Nassar et al, JGR 2008
Climatologies for March-May

Global behavior derived from ACE-FTS

H$_2$O

HDO

δD

Note HDO ~ 10,000 times smaller than H$_2$O

very difficult measurement!

δD = 1000 × \left[ \frac{([HDO]/[H$_2$O])_{measurement}}{([HDO]/[H$_2$O])_{VSMOW}} - 1 \right]
Seasonal variation of δD

TTL minimum below tropopause

Minimum in winter hemisphere
PDF of ACE-FTS in the tropics

Rayleigh curves

vertical coordinate is H$_2$O; similar behavior for altitude coordinate
Tropical seasonal structure (15° N-S)

- Minimum below tropopause
- Strongest depletion in February

Randel et al., 2012, J. Geophys. Sci.
Tape recorder and seasonal cycle in H$_2$O, HDO

Randel et al., 2012, J. Geophys. Sci.

Note: only 4 months of data per year
seasonal minimum below tropopause
(convection, not temperature)
Randel et al., 2012, J. Geophys. Sci.

little evidence of tape recorder in $\delta$D
Tropical dehydration processes constrained by the seasonality of stratospheric deuterated water

MIPAS satellite observations

Note these results are very different from Payne et al 2007 analysis of MIPAS data.
Conservation of H:

\[(H_2 + H_2O + 2*CH_4) = \text{const.}\]

Observations + models:

\[\Delta H_2O \sim -2.0 \times (CH_4 - CH_{4\text{entry}})\]

Conservation of D:

\[(HD + HDO + CH_3D) = \text{const.}\]

\[\Delta HDO = - \Delta HD - \Delta CH_3D = -4.5 \times 10^{-4} (CH_4 - CH_{4\text{entry}})\]
δD – corrected for methane effects using ACE CH₄
Seasonal cycle of methane-corrected $\delta$D

Monsoon signal
Longitudinal structure and ACE-FTS sampling

14.5 km

DJF

JJA

c. deltaD  JJA  14.5 km

climatological deep convection
$\delta D$ at 16.5 km

isotopically depleted air close to deep convection
Distinct behavior of Asian, NA summer monsoon regions

Very different $\delta D$

Similar $H_2O$ patterns over Asian, NA monsoons
Relevant physics: depth of overshooting convection, into unsaturated stratosphere (e.g. Dessler and Sherwood, 2004)
Clouds and thermodynamic profiles over monsoons

Asia monsoon

higher saturation over Asian monsoon

N. America monsoon

Caveat: CALIPSO misses late afternoon deep convection

Cloud Fraction

Cloud fraction

RHI (%)
Asian monsoon signal in $\delta D$

(comes mainly from N America)

[Diagram of ACE $\delta D$ JJA]

[Map showing isotope maximum mainly from N. America]


Asian monsoon signal in HCN

[Map showing HCN maximum from Asian monsoon]
Key points:

• Isotopic increase of water vapor above TTL is supported in ACE data
  - convective overshooting and/or mixing from extratropics?

• Significant spatial structure to global seasonal cycle of δD
  - spatial variability tied to convection
  - convection has different effects in different places
    (tied to background thermodynamic structure)

• Strong enhancement associated with N America summer convection.
  - persistent signal, leads to NH-SH asymmetry in stratosphere

• Curious lack of tape recorder signal in δD
Things we don’t understand:

• What causes the seasonal variation in tropical δD? (max. depletion during NH winter)

• Why is there a shift in max. TTL depletion towards winter hemisphere? (is this related to ACE-FTS sampling?)

• How does tropical variability couple with monsoon signal, so that there is little vertical propagation in the tropics (lack of ‘tape recorder’)?
Mechanisms for the increase of $\delta D$ above tropopause:

1) Convective ice lofting

2) Mixing from extratropics

Simulation by Max Bolot, LMD
Reference1


Reference 4

