UTLS Asian monsoon anticyclone

- Dynamics and transport in the monsoon anticyclone
- Chemical variability linked to the monsoon
- Instability and eddy shedding; PV diagnostics
- Transport to stratosphere
- Eruption of Mt. Nabro in June 2011
What is the monsoon anticyclone, and why is it interesting?

- dominant circulation feature of NH summer UTLS
- forced by deep convection over India and Bay of Bengal
- associated with local maxima in trace constituents (water vapor, ozone, pollutants)
- active region for stratosphere-troposphere coupling
monsoon circulation near 16 km

carbon monoxide (pollution tracer) near 16 km

MLS satellite
Dynamical Background

Cyclone at the surface, anticyclone in the upper troposphere

Hoskins and Rodwell, 1995
Highwood and Hoskins, 1998

one-day ‘snapshot’
July 10, 2003

anticyclone
upper troposphere

cyclone
lower troposphere
atmosphere response to steady tropical heating (Gill, 1980)

near surface

imposed heating

latitude

d longitude

symmetric
Rossby gyres
west of heating

Kelvin wave
east of heating
idealized vertical structure

Highwood and Hoskins (1998)
Anticyclones in the Upper Troposphere

Geopotential height and winds 100 hPa

Convection (heating)

Matsuno-Gill Solution

Note that the anticyclone does not lie on top of the deep convection
Anticyclonic circulation extends into lower stratosphere

balanced dynamical structure

Lower troposphere
cold tropopause and lower stratosphere
tropopause

Lower troposphere
warm troposphere

Upper 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

day 0

day 10

day 20
tests at different pressure levels show that confinement mainly occurs over altitudes with strongest winds ~ 10-18 km
Frequent tropopause-level cirrus clouds in monsoon region

CALIPSO cloud fraction near 16 km
CALIPSO satellite lidar cloud observations

Tibet

July 14, 2010
Asian 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)

Park et al, JGR, 2008, 2009

variability linked to monsoon convection
ACE Fourier Transform Spectrometer

ACE occultations, 2004-2006

Low latitudes: 4 samples / year

All observations for June-August

ACE-FTS (04-06/JJA) 1233
Simulated CO spectrum

Transmittance

Wavenumber (cm\(^{-1}\))

ACE-FTS measurements

microwindows for CO retrieval

Clerbaux et al, ACP, 2008
High CO and HCN are associated with the Asian monsoon anticyclone.
ACE-FTS CO Profiles

all profiles 10°-40° N

inside vs. outside

Inside anticyclone

outside
other tropospheric (pollution) tracers

\[ \tau = 2, \tau = 5, \tau = 1.5, \tau = 0.5 \]

enhancement inside the anticyclone up to \(~20\) km

Park et al. JGR 2008
$C_2H_2$ measurements from ACE-FTS satellite

photochemical lifetime $\sim 2$ weeks

evidence of relatively rapid transport to the UTLS
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. Zahn¹

Enhanced CH₄ 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

acetylene $\text{C}_2\text{H}_2$

benzene $\text{C}_6\text{H}_6$
Age of air estimated from short-lived hydrocarbons

Result: air is relatively young: ~ 4-12 days

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

Park et al, JGR, 2009
simulation for one day

100 hPa

MLS observations  MOZART simulation

Park et al, JGR, 2009
Vertical structure of CO from model simulation

Questions:
- How sharp is the 'chemical edge'?
- When and where does air 'escape' the anticyclone?
monsoon influences are also evident in lower stratosphere water vapor
Transport pathways derived from observations and models

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

Park et al, JGR, 2008, 2009
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

Garney and Randel 2015
Comparison of trajectory calculations with MLS CO climatology

Colors: MLS CO climatology

Black contours: trajectory calculations
Transport up and down!

Three-dimensional diabatic trajectories

Tropopause

360 K
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. Garny¹ and W. J. Randel²

following Popovic and Plumb, 2001

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

animation of daily PV maps for one summer
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

maxima persist in stratosphere because of long HCN lifetime

Africa and S. America biomass burning
HCN 'tape recorder' from ACE-FTS measurements

boreal summer maxima from Asian monsoon circulation
Key points:

- Trajectory studies show fate of convective outflow (up and down)
- Fundamental instability of anticyclone: eddy shedding
- HCN provides evidence for monsoon transport to stratosphere
Eruption of Mt. Nabro         June 13, 2011             Eritrea, Africa
Nabro eruption
June 14, 2011
Red Sea
SO₂ plume from Nabro

13 June 2011
SO₂ plume from Nabro

SO₂ vertical column [DU]

GOME-2 – DLR/BIRA-IASB/EUMETSAT

15 June 2011
SO$_2$ plume from Nabro

16 June 2011
SO$_2$ plume from Nabro
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

July 6

July 11

Nabro eruption June 13-14
OSIRIS aerosol extinction

eruption June 13
Interpretation:

- Nabro SO$_2$ 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)

June 17  

[Map showing SO$_2$ plume]  

July 6  

[Global map showing stratospheric aerosol]
July 1: 18 days after eruption
July 17
34 days
after eruption

Nabro aerosols

532 nm Total Attenuated Backscatter, km\(^{-1}\) sr\(^{-1}\)

Version: 3.01 Nominal Nighttime

- 20 km
- 15 km
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 over Tibet?

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

observations

A Model of the Asian Summer Monsoon. Part I: The Global Scale
BRIAN J. HOSKINS AND MARK J. RODWELL
JAS 1995

diabatic heating from reanalyses

reasonable agreement

linear model with heating

Result: heating from convection mainly forces monsoon anticyclone