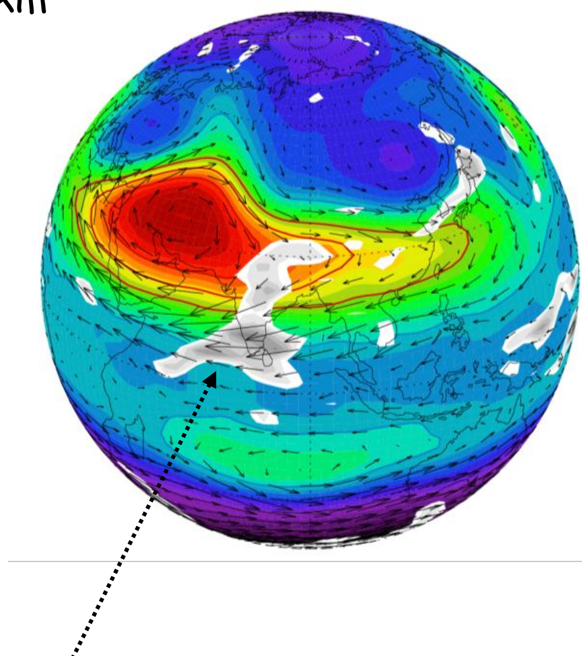
UTLS Asian monsoon anticyclone

- 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?

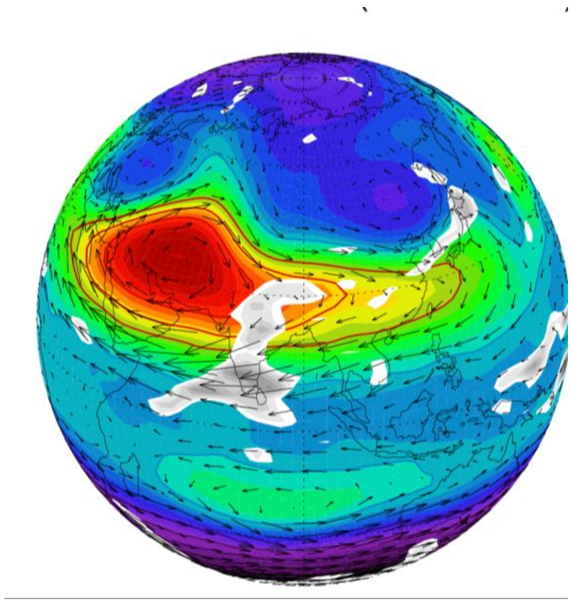
monsoon circulation near 16 km



deep convection

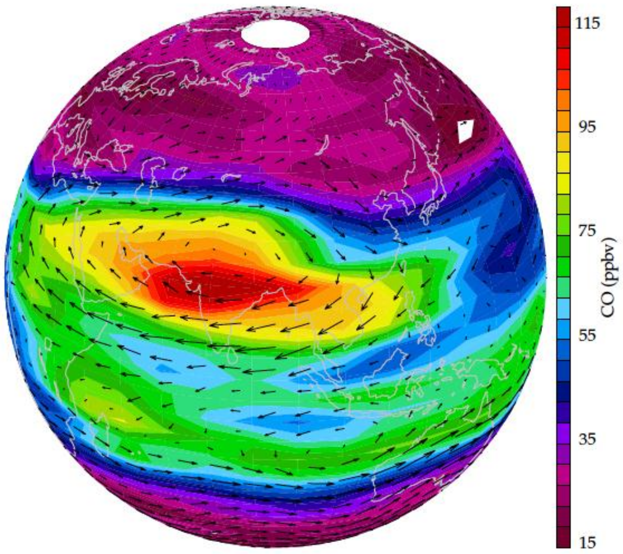
- dominant circulation feature of NH summer UTLS
- forced by deep convection over India and Bay of Bengal
- associated with local maxima in trace constituents (water vapor, ozone, pollutants)
- active region for stratosphere-troposphere coupling

monsoon
circulation
near 16 km



carbon monoxide
(pollution tracer)
near 16 km

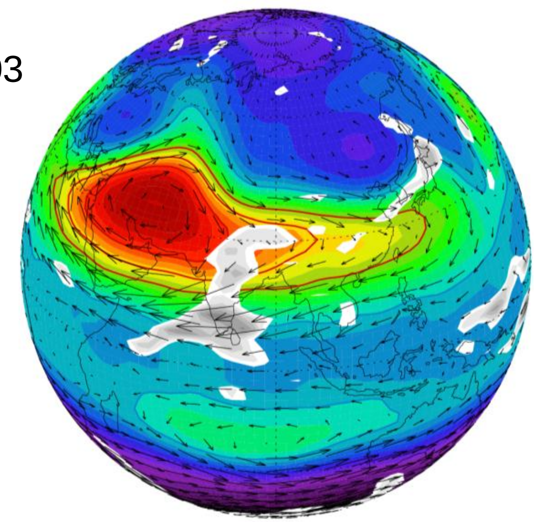
MLS satellite

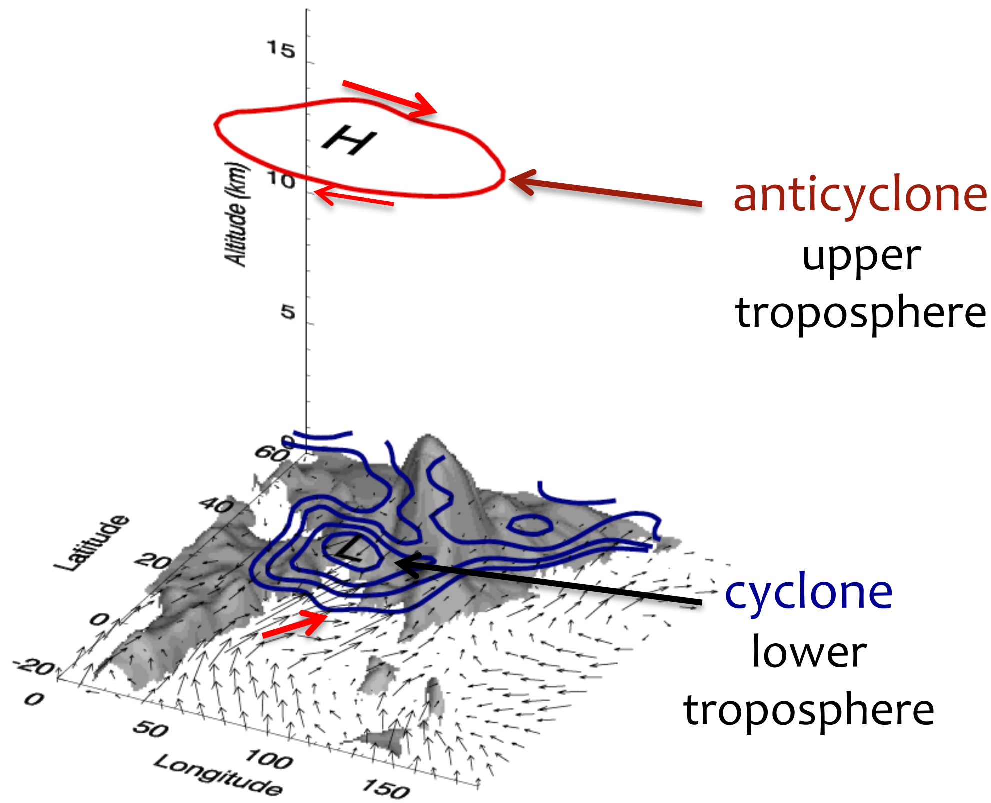


Dynamical Background

Cyclone at the surface, anticyclone in the upper troposphere

one-day
‘snapshot’
July 10, 2003



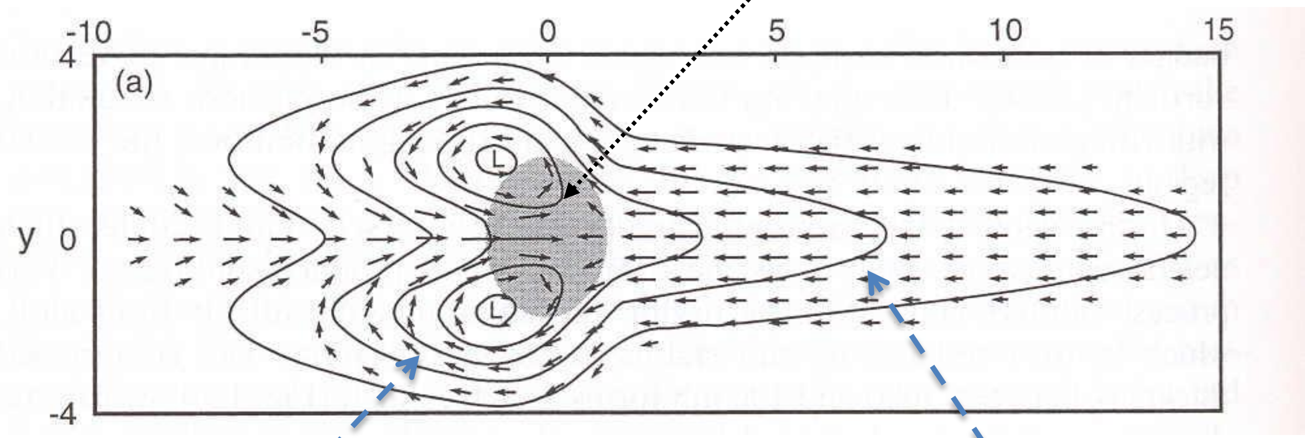


Hoskins and Rodwell, 1995
Highwood and Hoskins, 1998

atmosphere response to steady tropical heating (Gill, 1980)

near surface

imposed heating



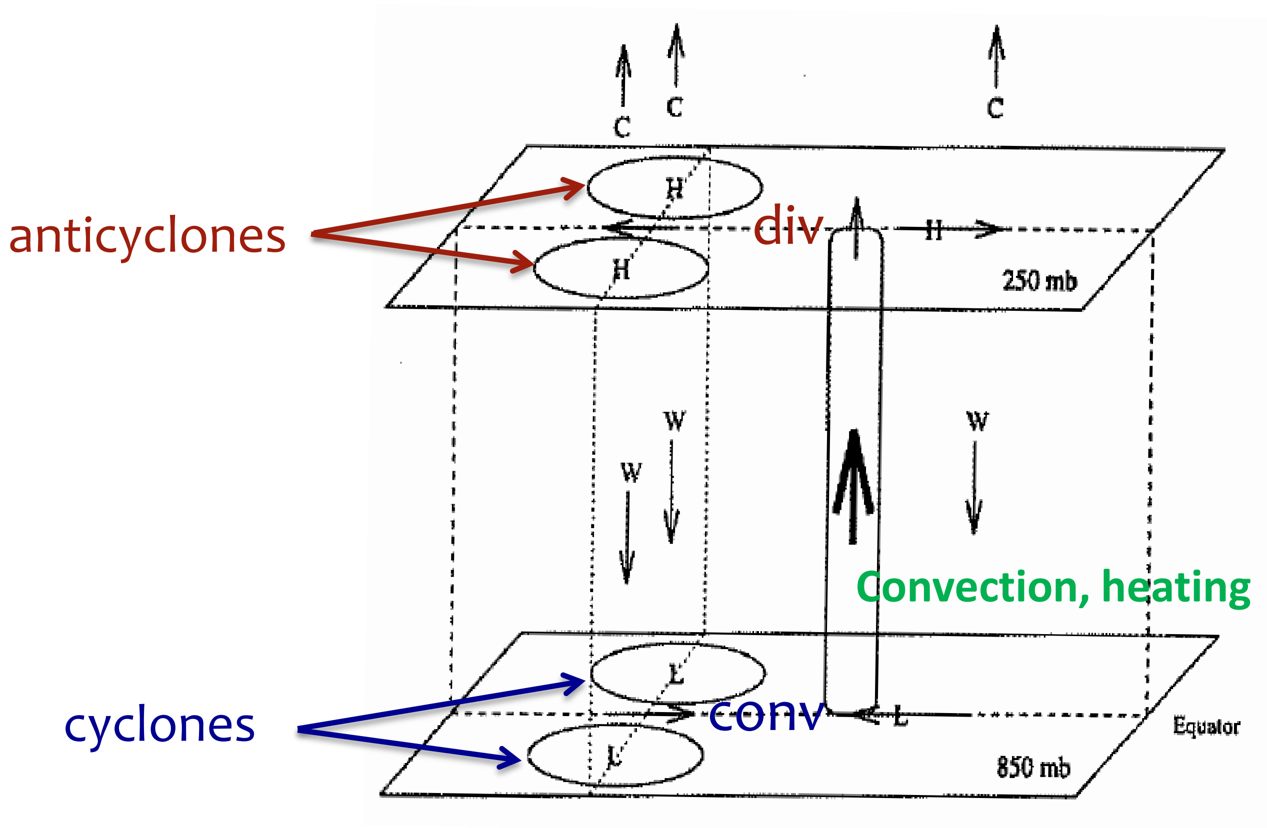
latitude

longitude

symmetric
Rossby gyres
west of heating

Kelvin wave
east of heating

idealized vertical structure



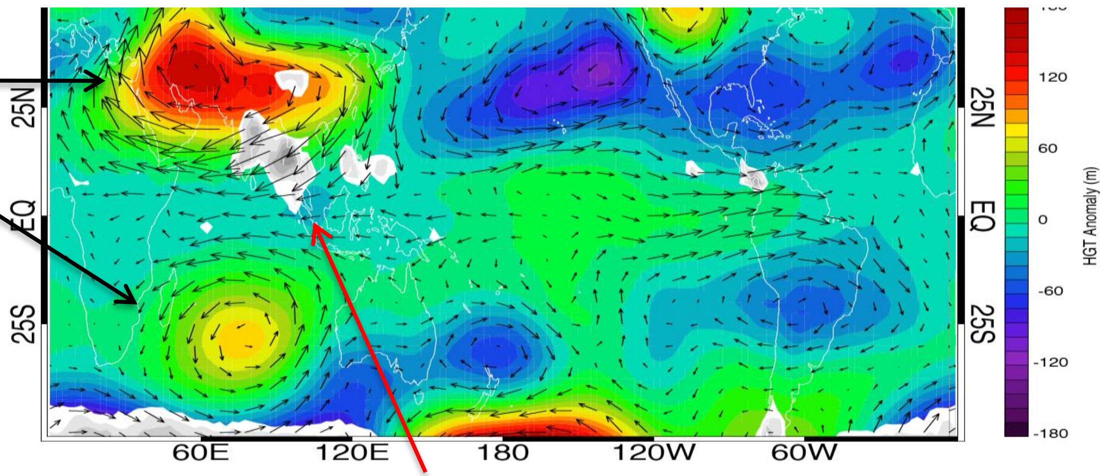
Highwood and Hoskins (1998)

Anticyclones in the Upper Troposphere

geopotential height and winds 100 hPa

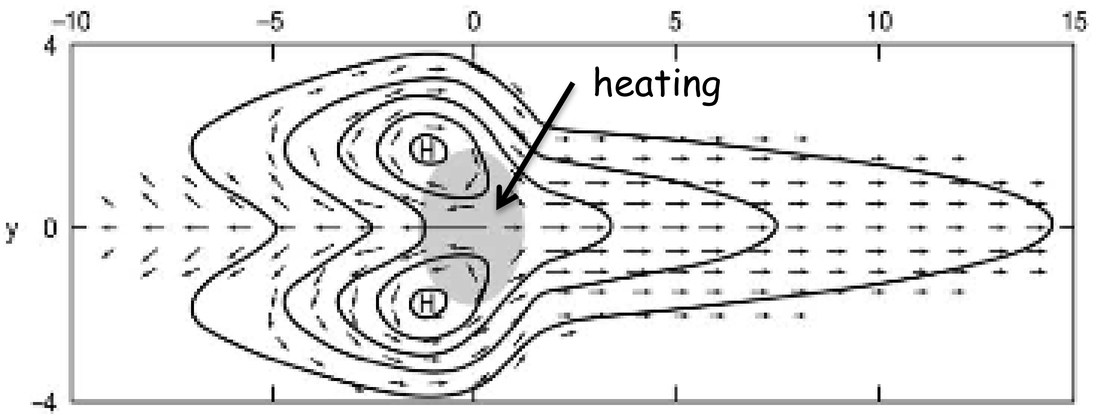
observations, zonal average removed

anticyclones



Convection (heating)

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



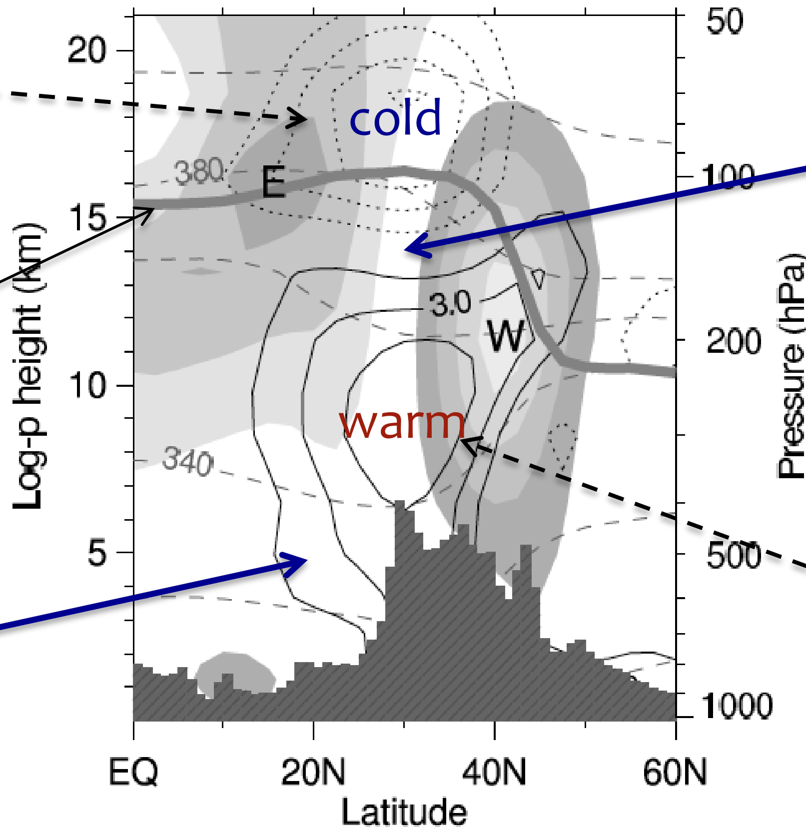
Matsuno-Gill Solution

Anticyclonic circulation extends into lower stratosphere

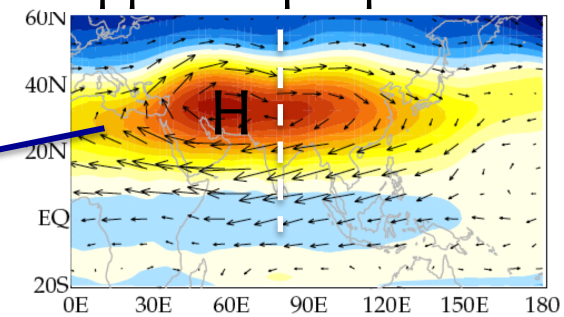
balanced dynamical structure

cold tropopause and lower stratosphere

tropopause

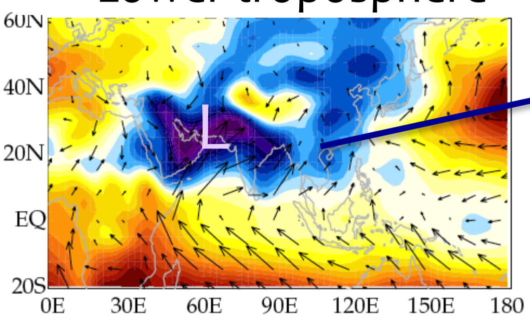


Upper troposphere



warm troposphere

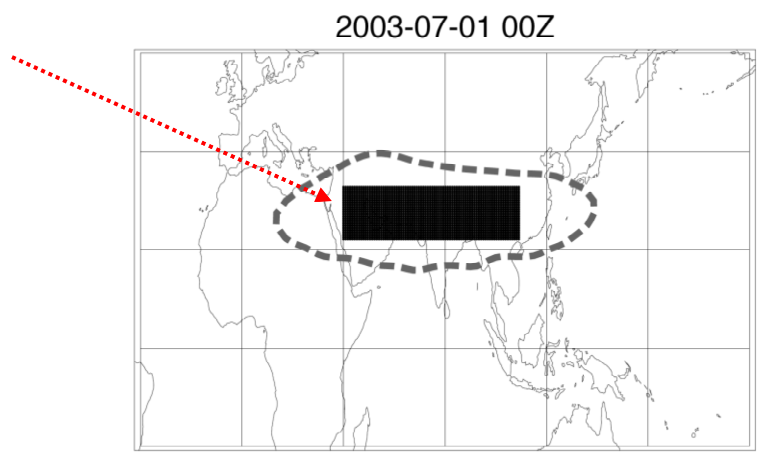
Lower troposphere



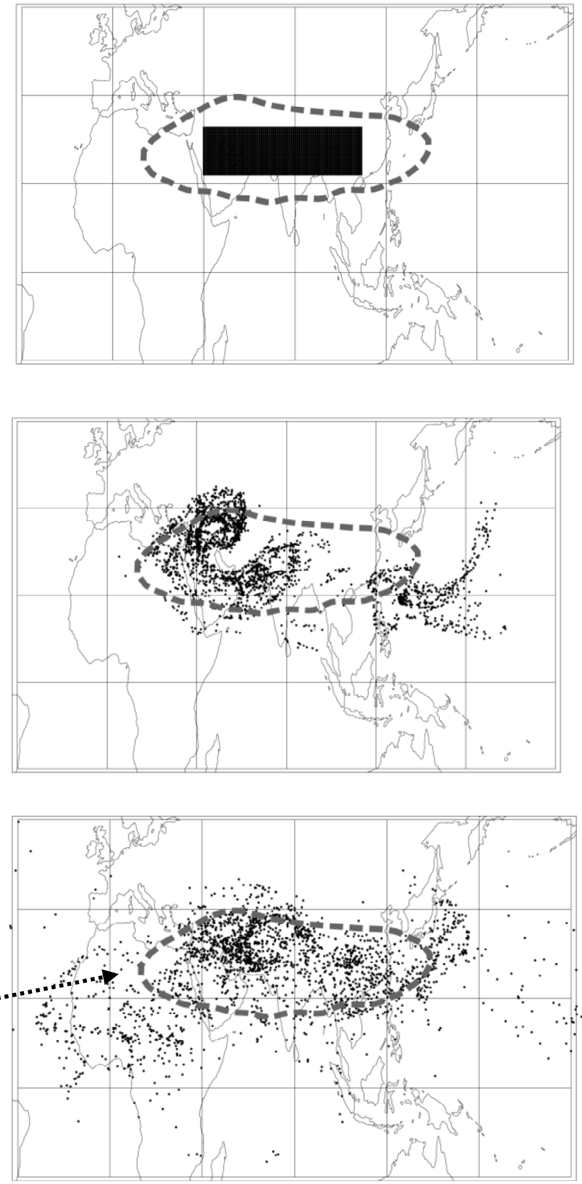
Randel and Park, JGR, 2006

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



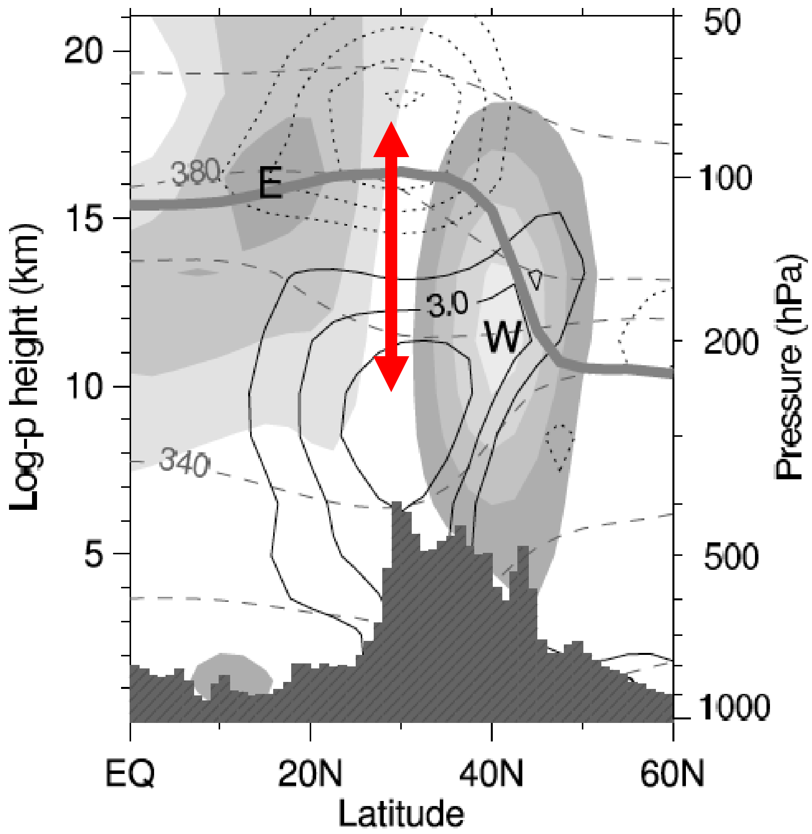
day 0

day 10

day 20

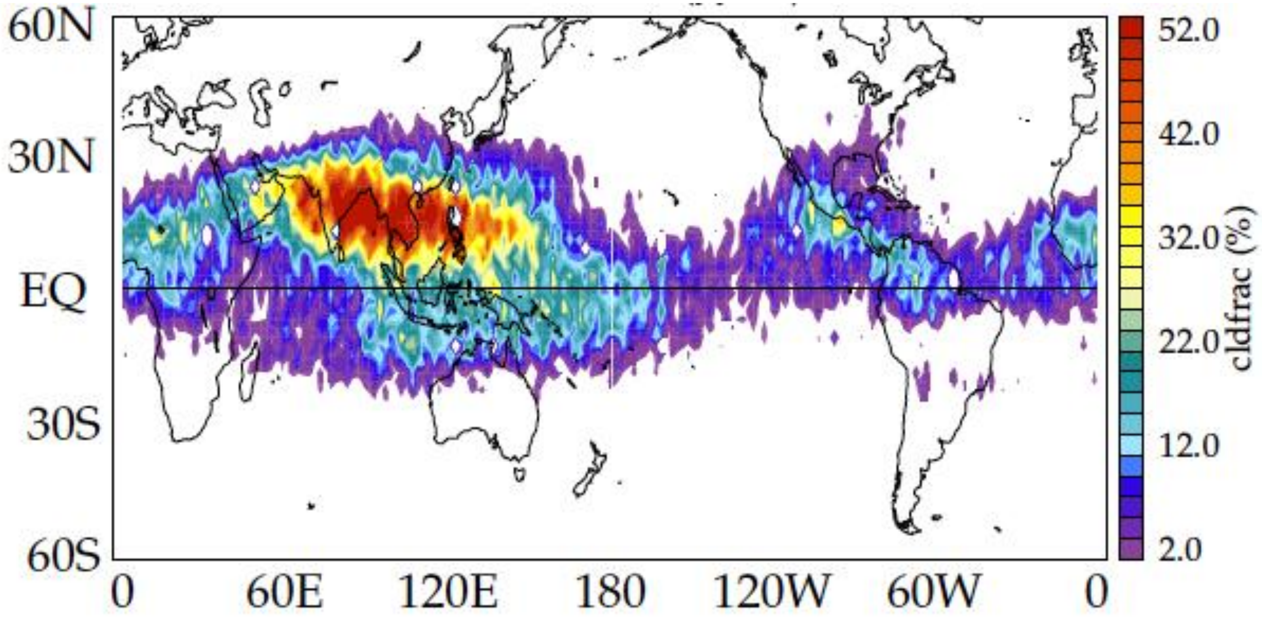
large fraction remain inside anticyclone tests at different pressure levels show that confinement mainly occurs over altitudes with strongest winds

~ 10-18 km

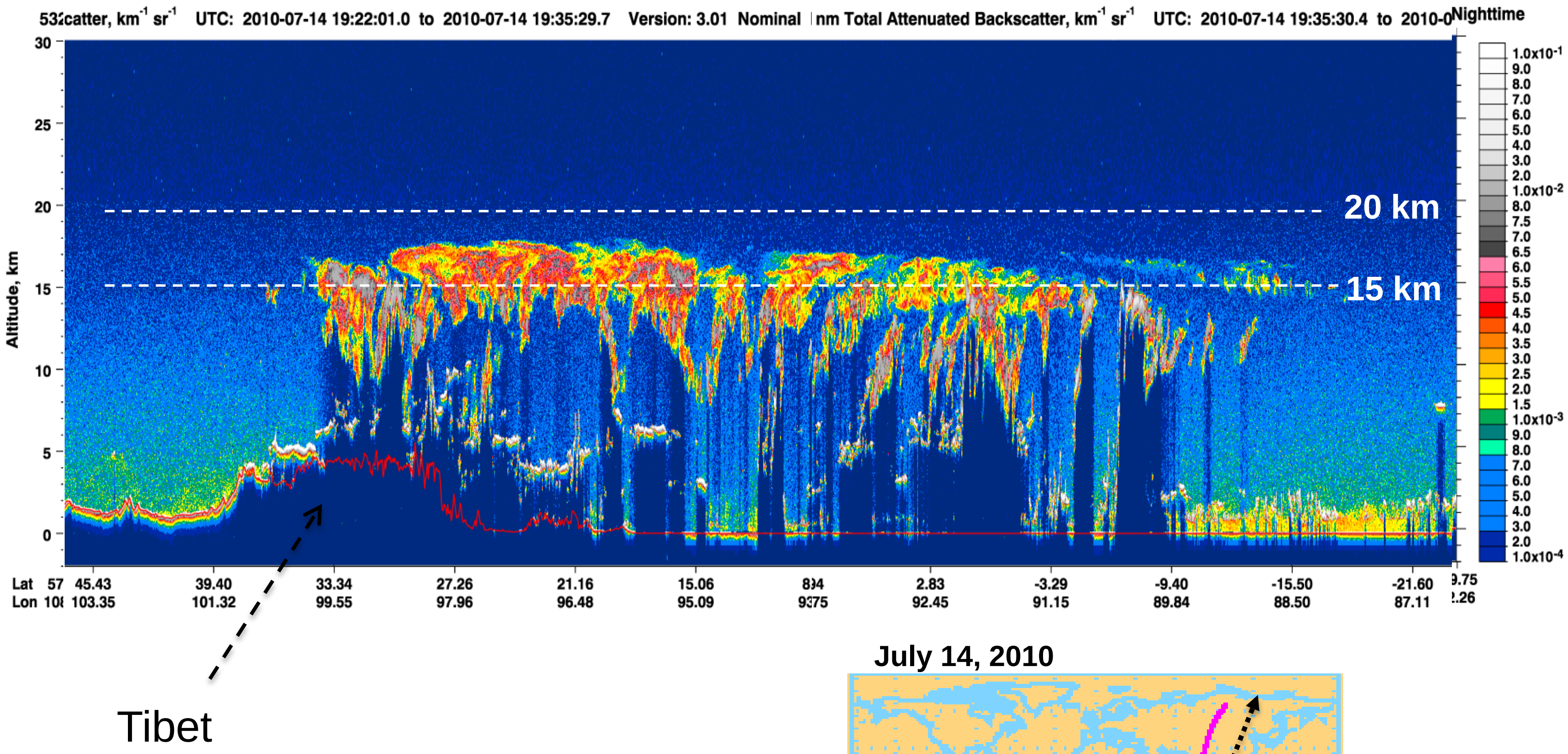


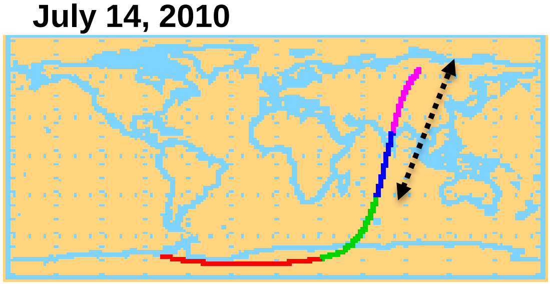
Frequent tropopause-level cirrus clouds in monsoon region

CALIPSO cloud fraction near 16 km

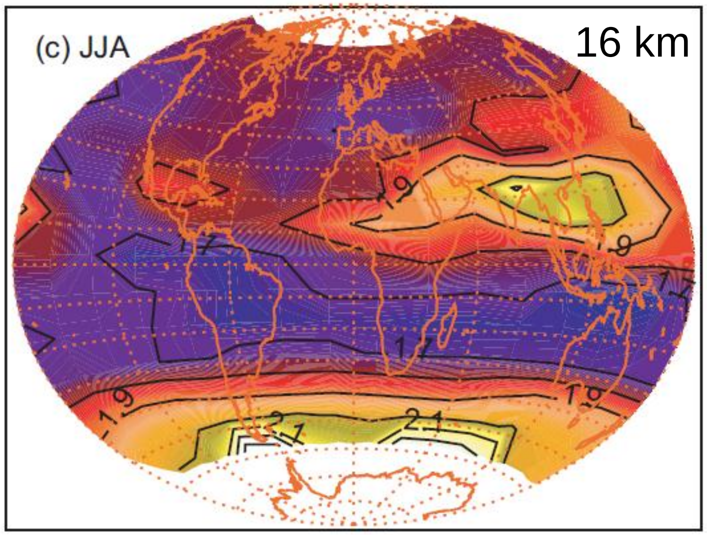


CALIPSO satellite lidar cloud observations

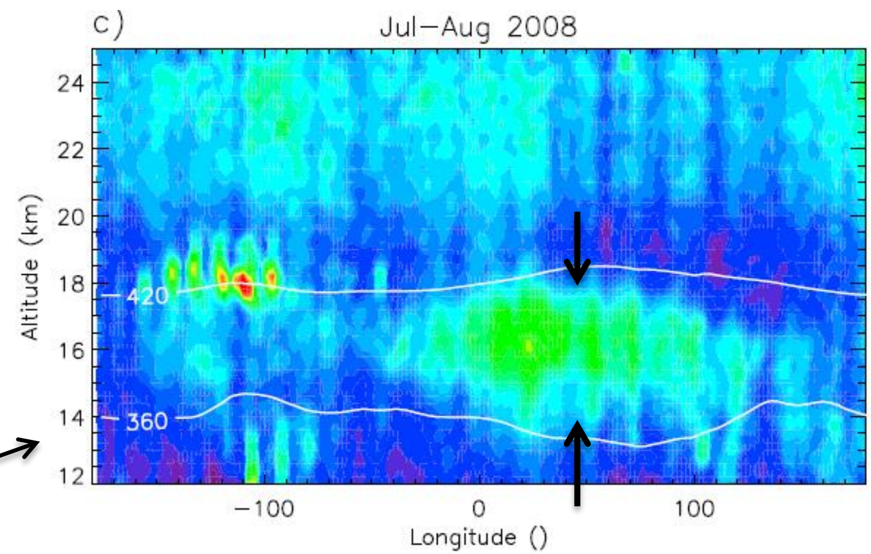




Asian monsoon aerosol layer near 16 km



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

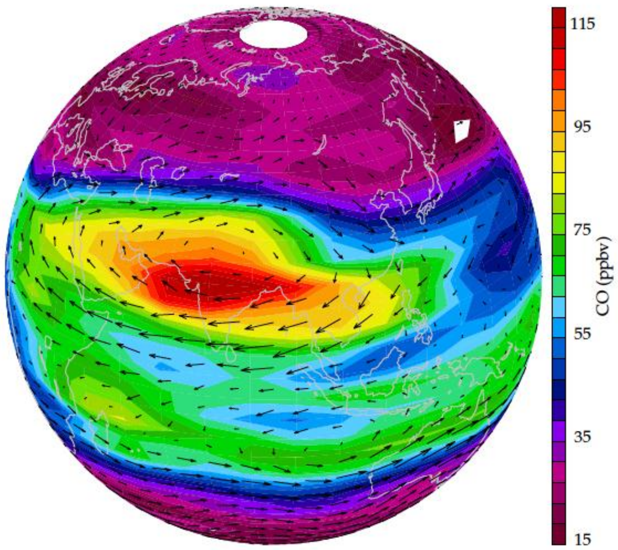


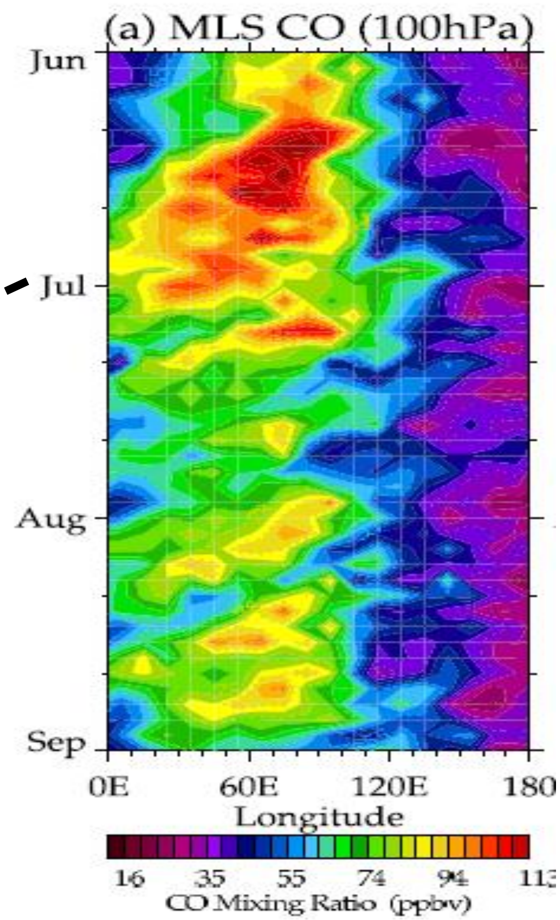
CALIPSO measurements
Vernier et al , GRL, 2011

Narrow layer near tropopause

strong chemical influence on summer UTLS

MLS 100 hPa
carbon monoxide (CO)



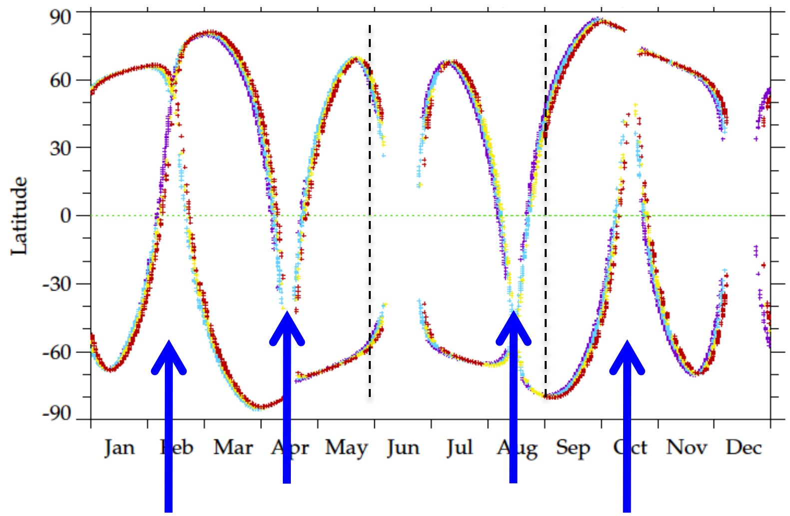


variability linked to monsoon convection

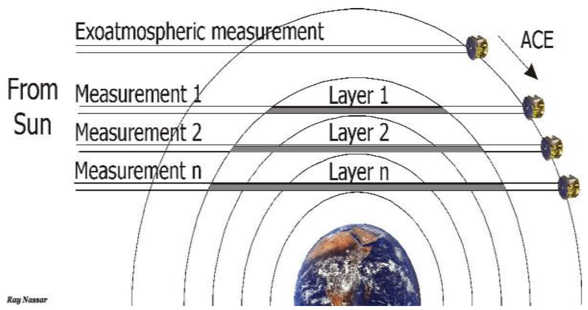
Park et al, JGR, 2008, 2009

ACE Fourier Transform Spectrometer

ACE occultations, 2004-2006

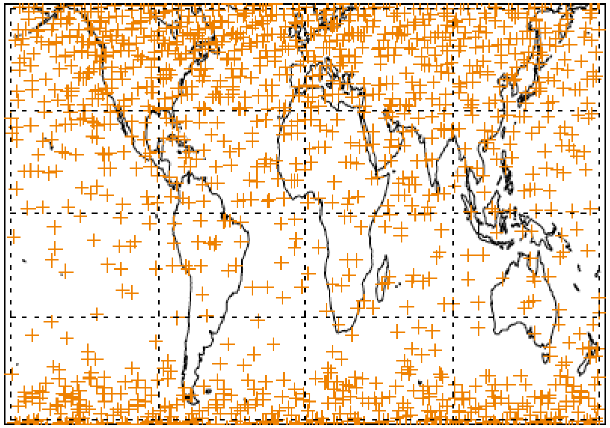


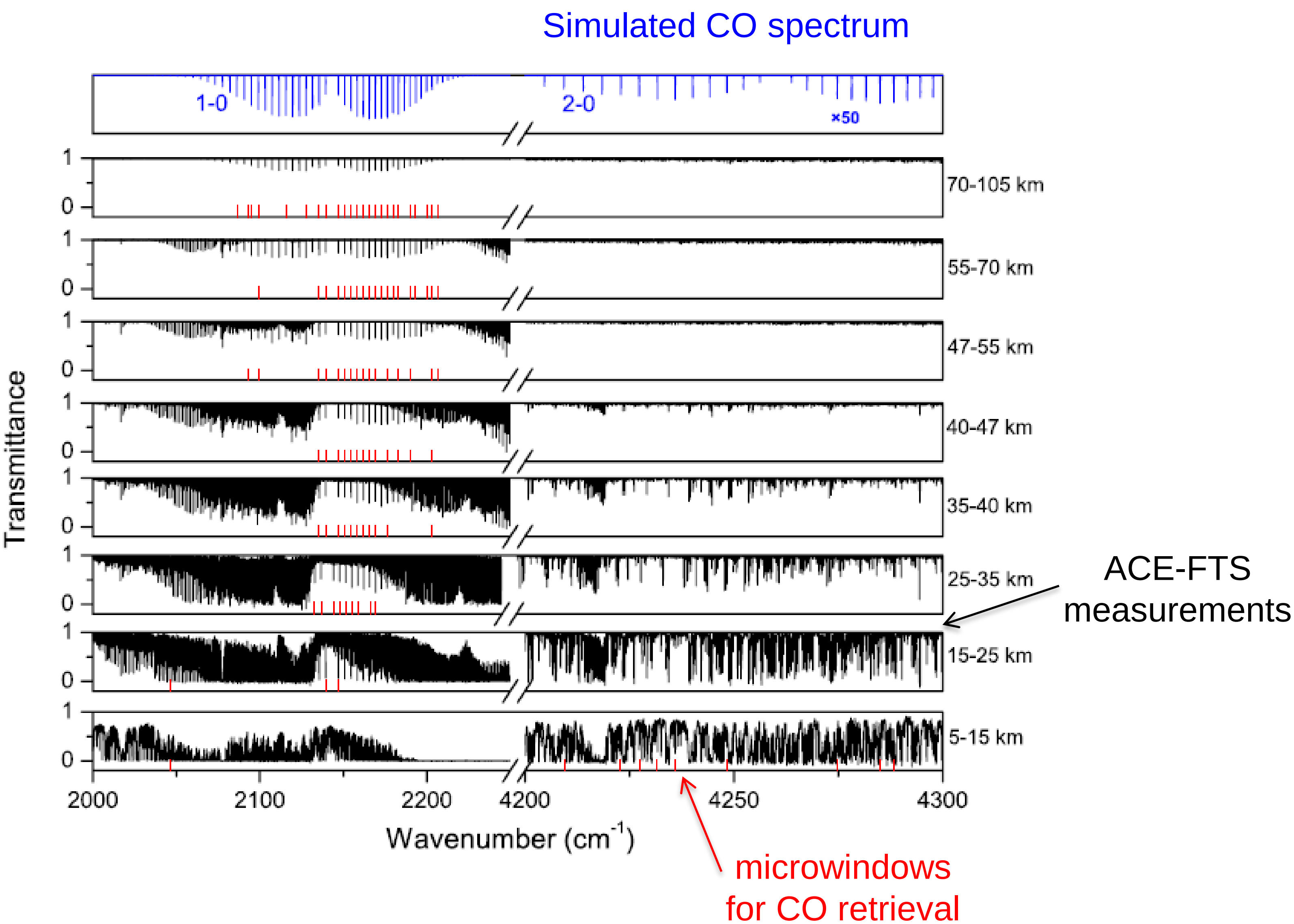
Low latitudes: 4 samples / year



All observations for June-August

ACE-FTS (04-06/JJA) 1233

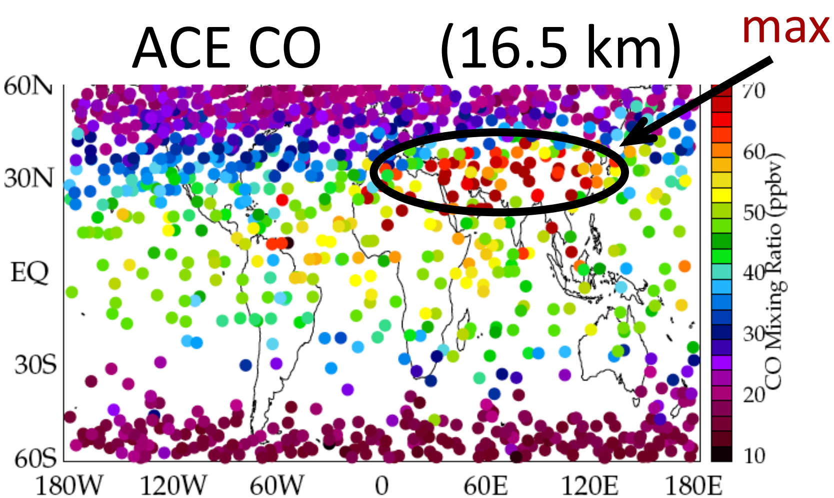




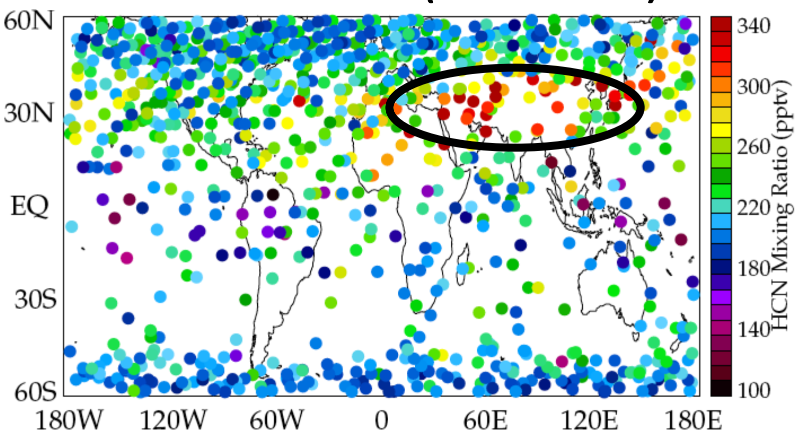
Clerbaux et al, ACP, 2008

ACE measurements JJA 2004-2006

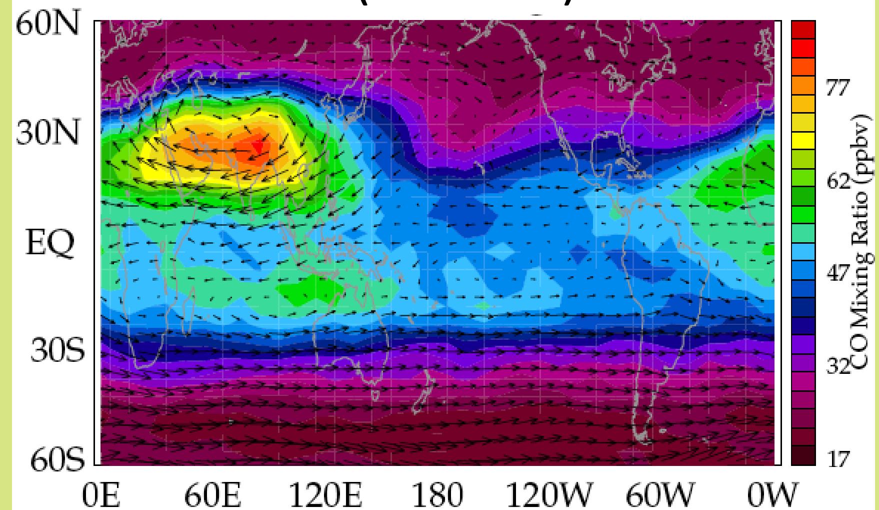
ACE CO (16.5 km)



ACE HCN (16.5 km)

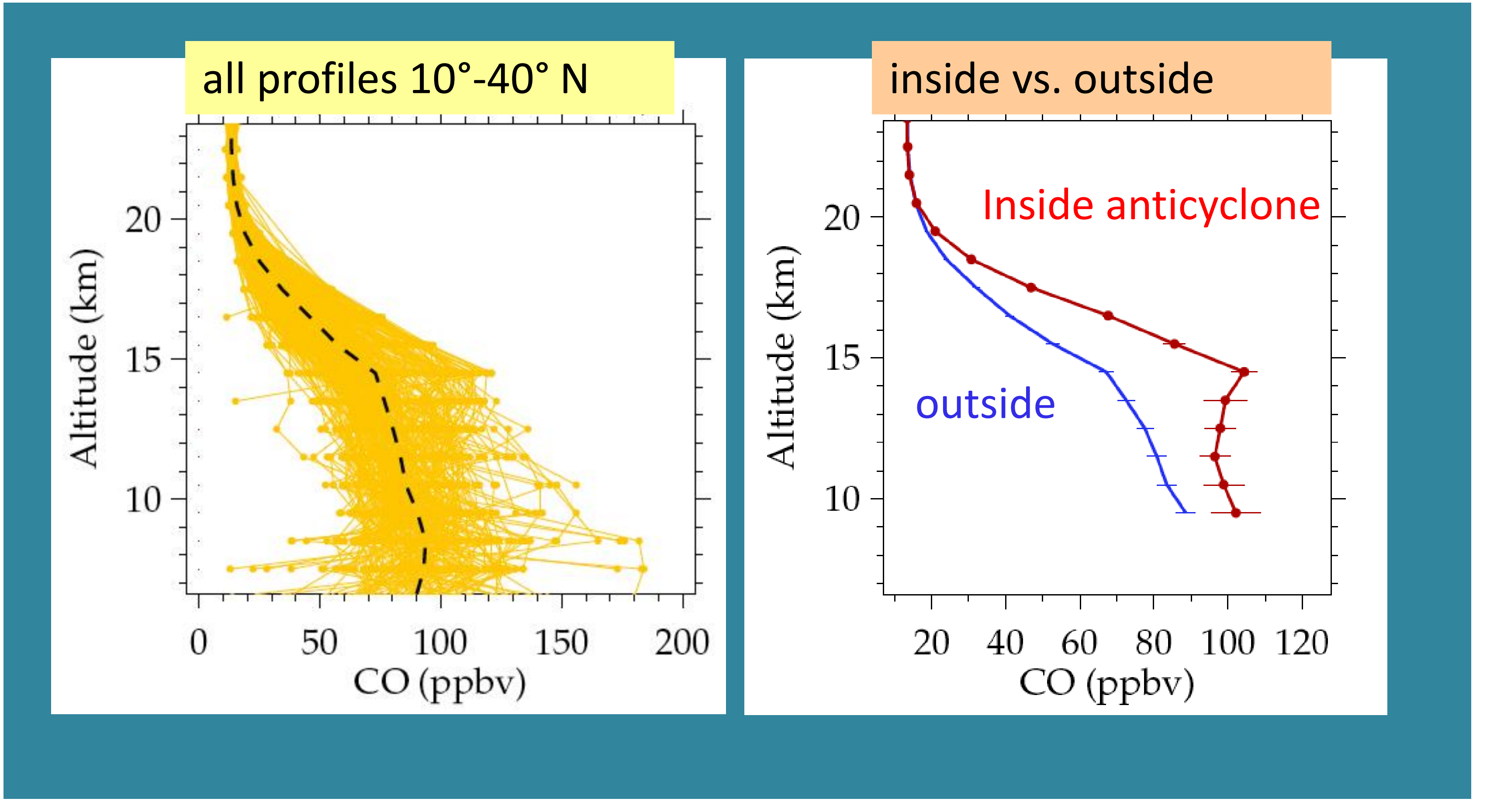


MLS CO (100 hPa)



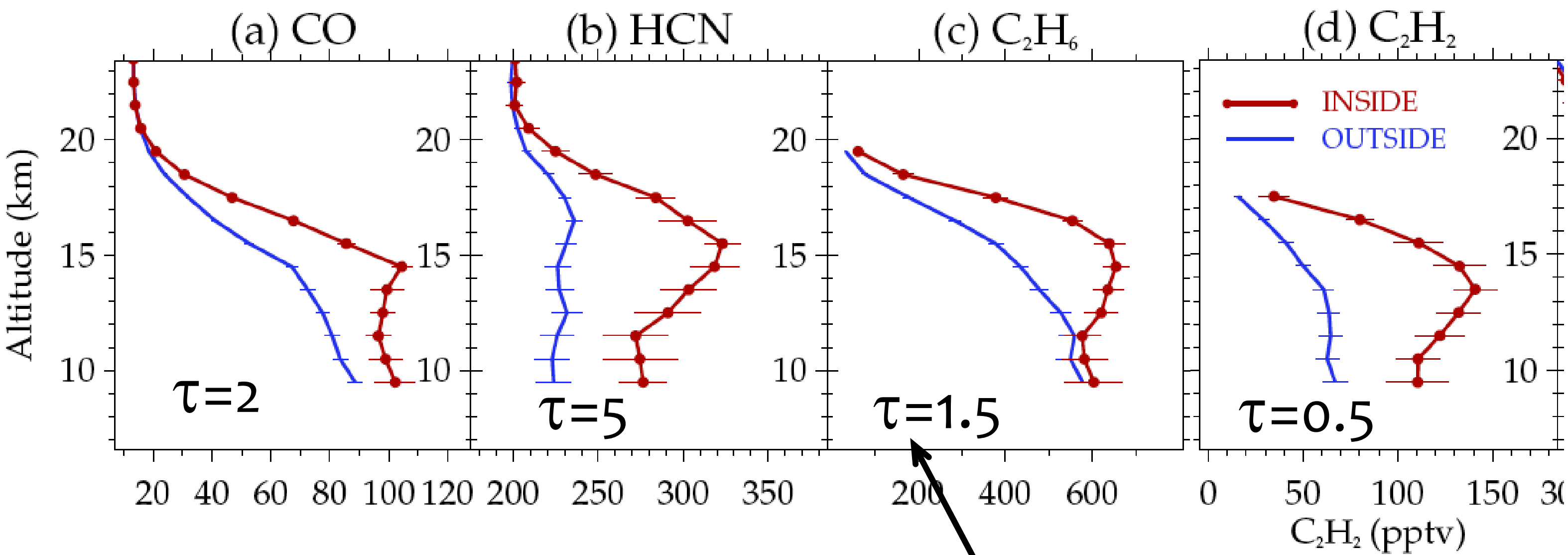
High CO and HCN are associated with the Asian monsoon anticyclone

ACE-FTS CO Profiles



other tropospheric (pollution) tracers

enhancement inside the anticyclone up to ~20 km



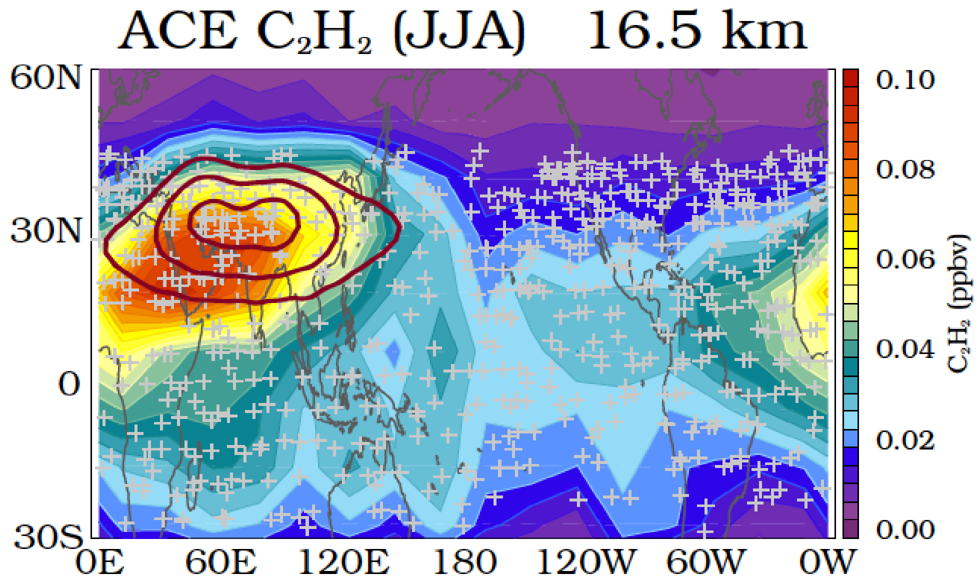
photochemical lifetime in months

Park et al JGR 2008

C_2H_2 measurements from ACE-FTS satellite

photochemical lifetime ~ 2 weeks

evidence of relatively rapid transport to the UTLS



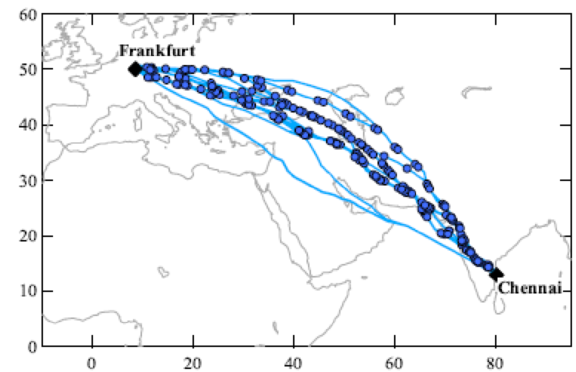
Atmos. Chem. Phys., 10, 3965–3984, 2010
www.atmos-chem-phys.net/10/3965/2010/

Atmospheric Chemistry and Physics

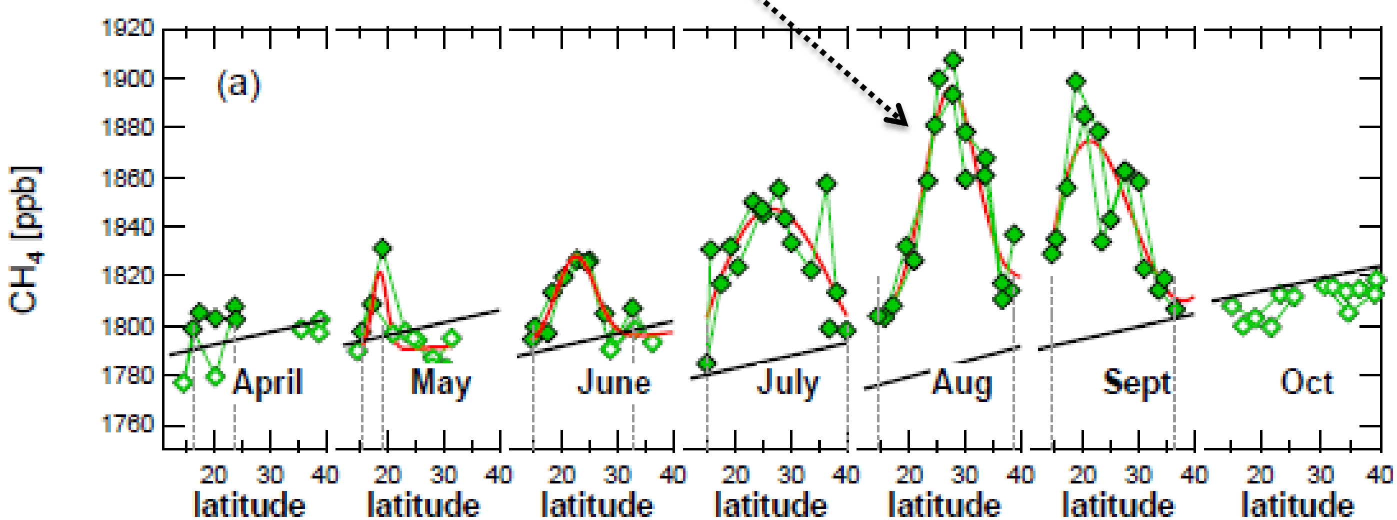
Aircraft measurements

Greenhouse gas relationships in the Indian summer monsoon plume measured by the CARIBIC passenger aircraft

T. J. Schuck[1], C. A. M. Brenninkmeijer[1], A. K. Baker[1], F. Slemr[1], P. F. J. von Velthoven[2], and A. Zahn[3]



Enhanced CH_4 within anticyclone

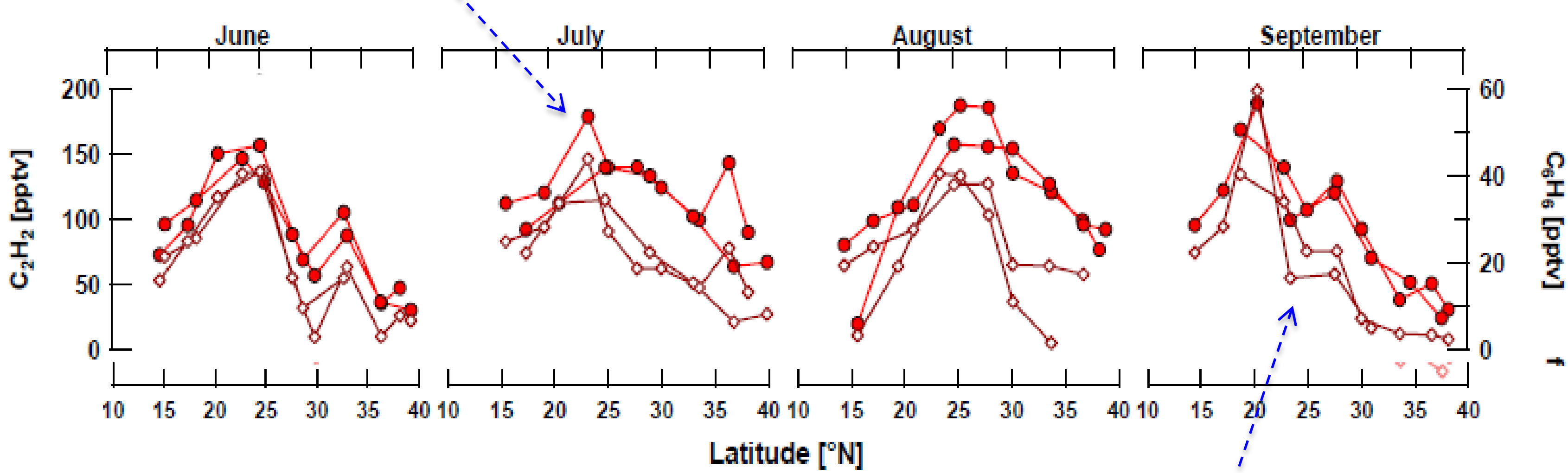


Characterization of non-methane hydrocarbons in Asian summer monsoon outflow observed by the CARIBIC aircraft

A. K. Baker[1], T. J. Schuck[1], F. Slemr[1], P. van Velthoven[2], A. Zahn[3], and C. A. M. Brenninkmeijer[1]

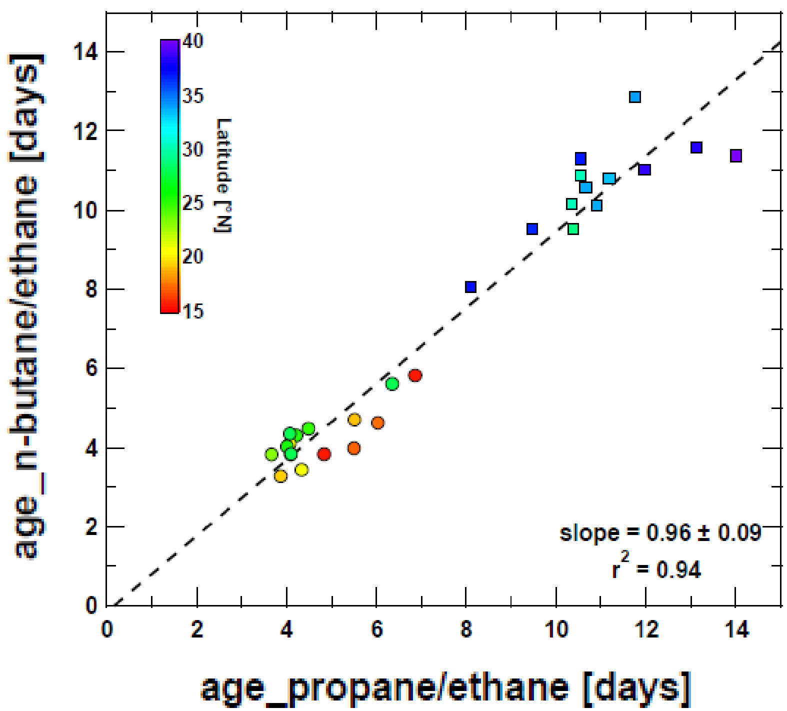
ACP, 2011

acetylene C_2H_2



benzene C_6H_6

Age of air estimated from short-lived hydrocarbons

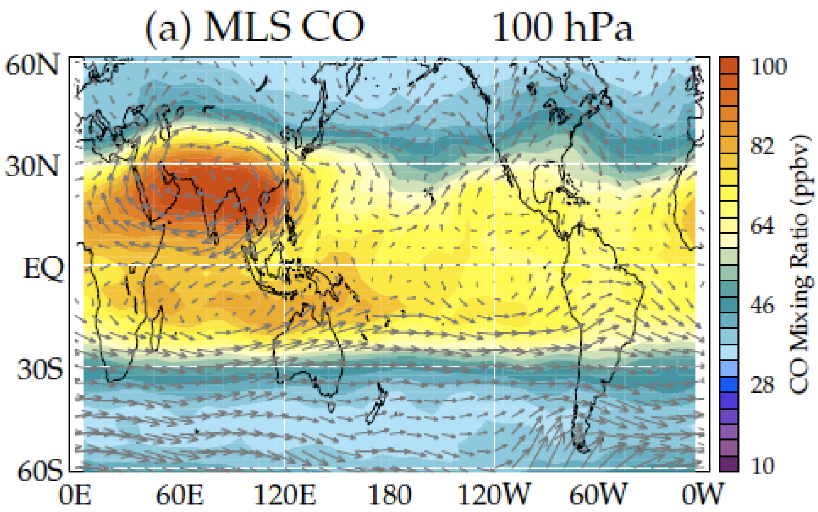


Result: air is relatively young: ~ 4-12 days

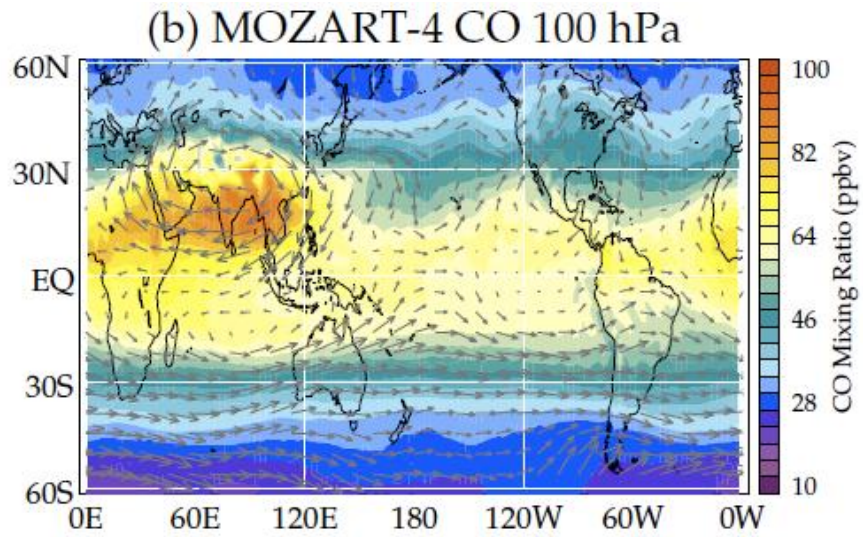
Baker et al, ACP, 2011

chemical transport models can simulate observed large-scale behavior

MLS observations



MOZART simulation

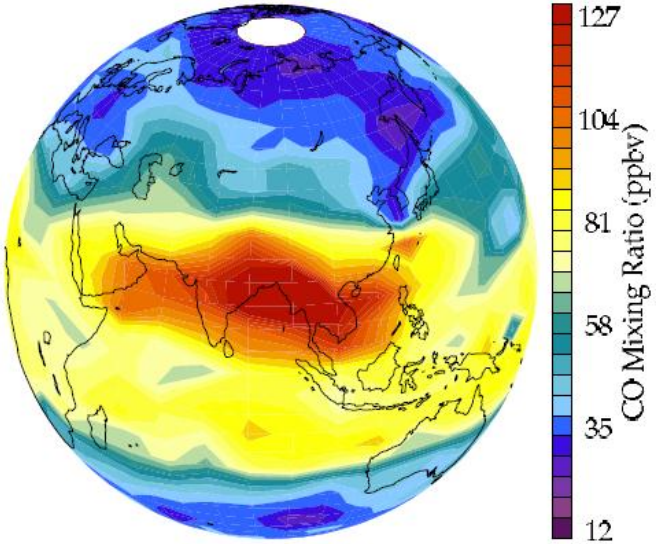


Park et al, JGR, 2009

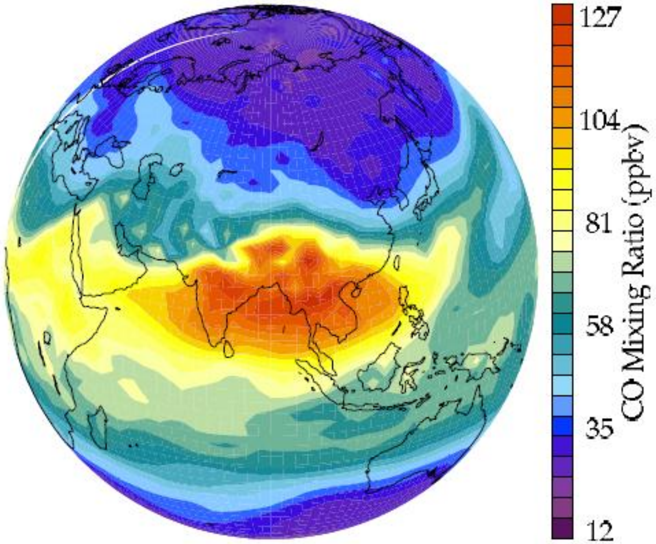
simulation for one day

100 hPa

MLS observations

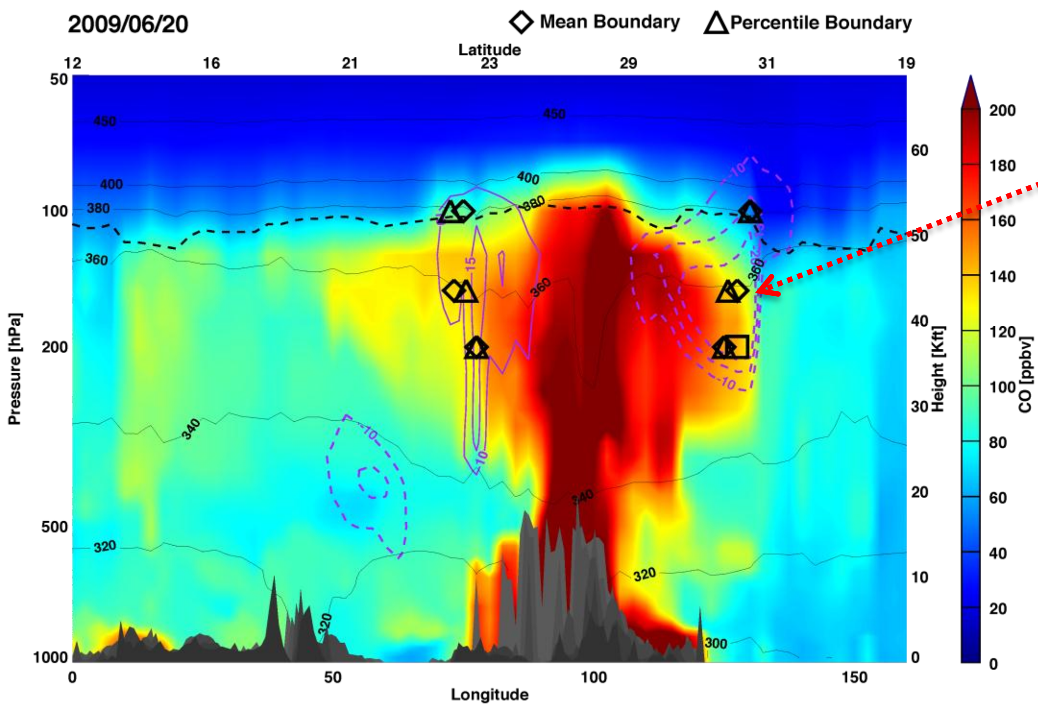


MOZART simulation



Park et al, JGR, 2009

Vertical structure of CO from model simulation



dynamical 'edge' of anticyclone

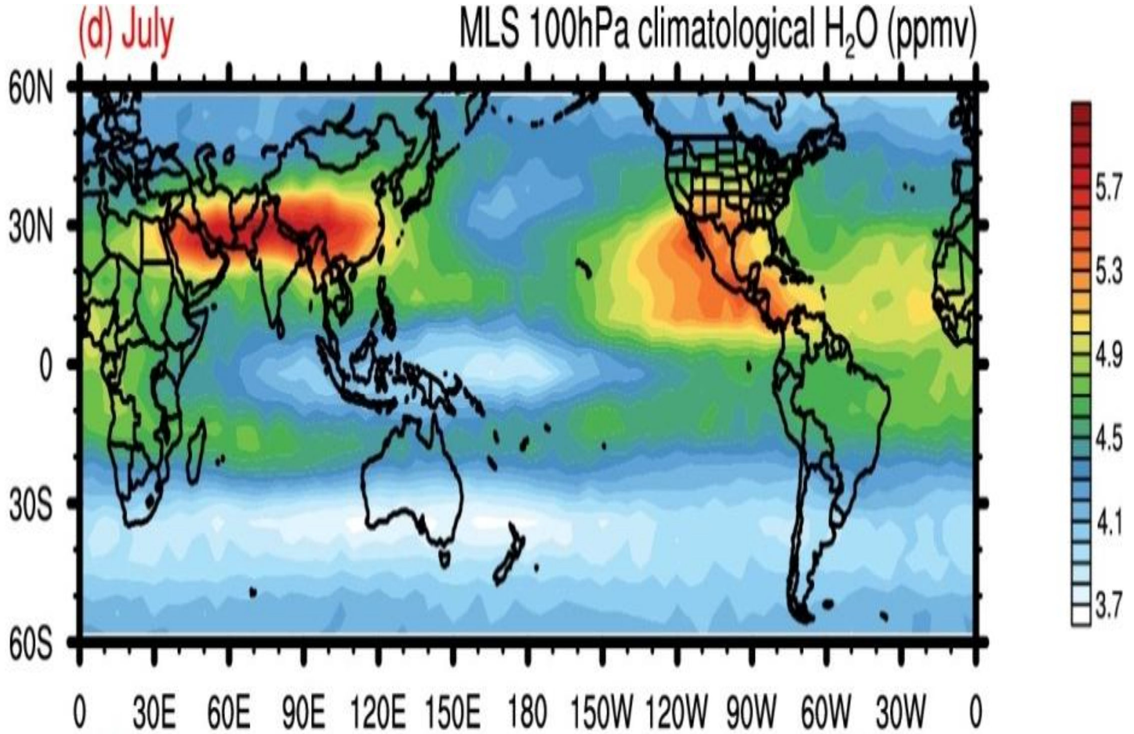
from Laura Pan

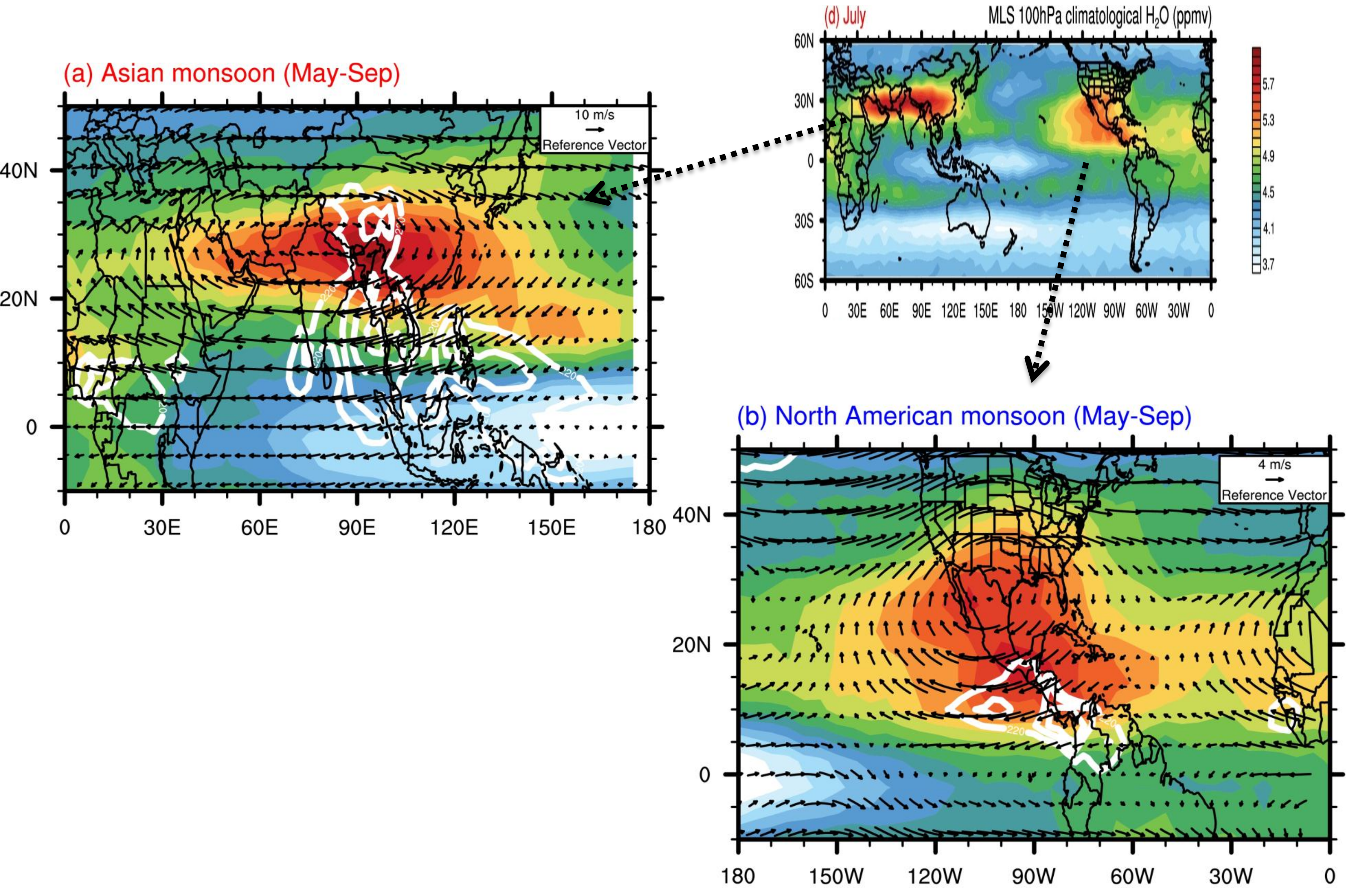
<u>Questions:</u>

- How sharp is the 'chemical edge'?
- When and where does air 'escape' the anticyclone?

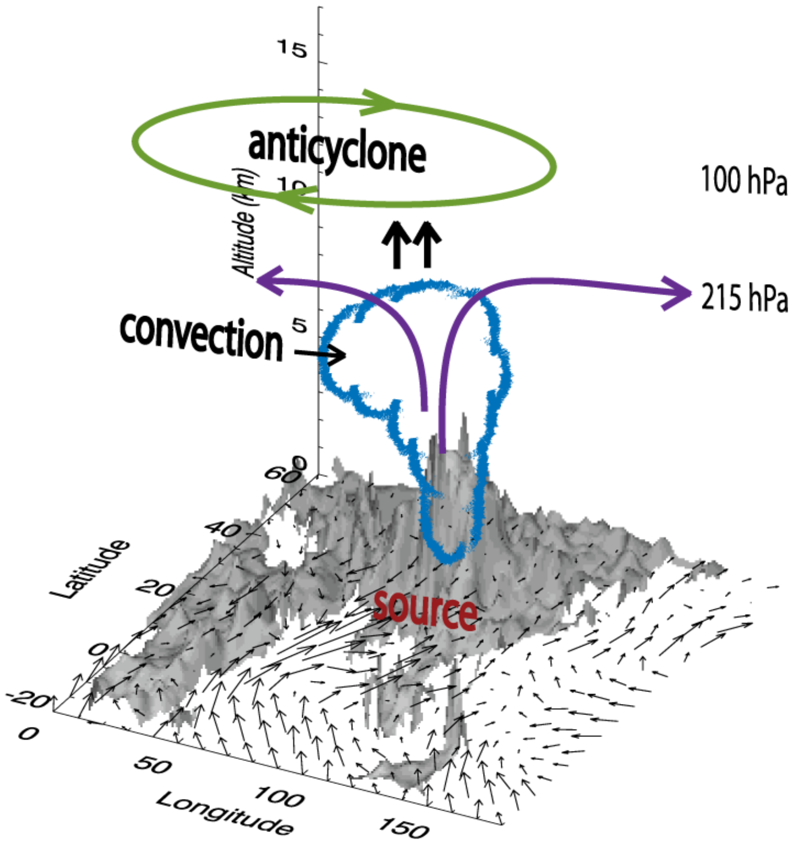
monsoon influences are also evident in lower stratosphere water vapor

Aura
MLS H_2O




(a) Asian monsoon (May-Sep)
10 m/s
Reference Vector
40N
20N
0
30E
60E
90E
120E
150E
180
(d) July
MLS 100hPa climatological H2O (ppmv)
60N
30N
30S
60S
5.7
5.3
4.9
4.5
4.1
3.7
(b) North American monsoon (May-Sep)
4 m/s
Reference Vector
150W
120W
90W
60W
30W

Transport pathways derived from observations and models



Park et al, JGR, 2008, 2009

confinement by anticyclone
+ transport to stratosphere

Transport above 200 hPa
by convection / circulation

convective transport
(main outflow near 200 hPa)

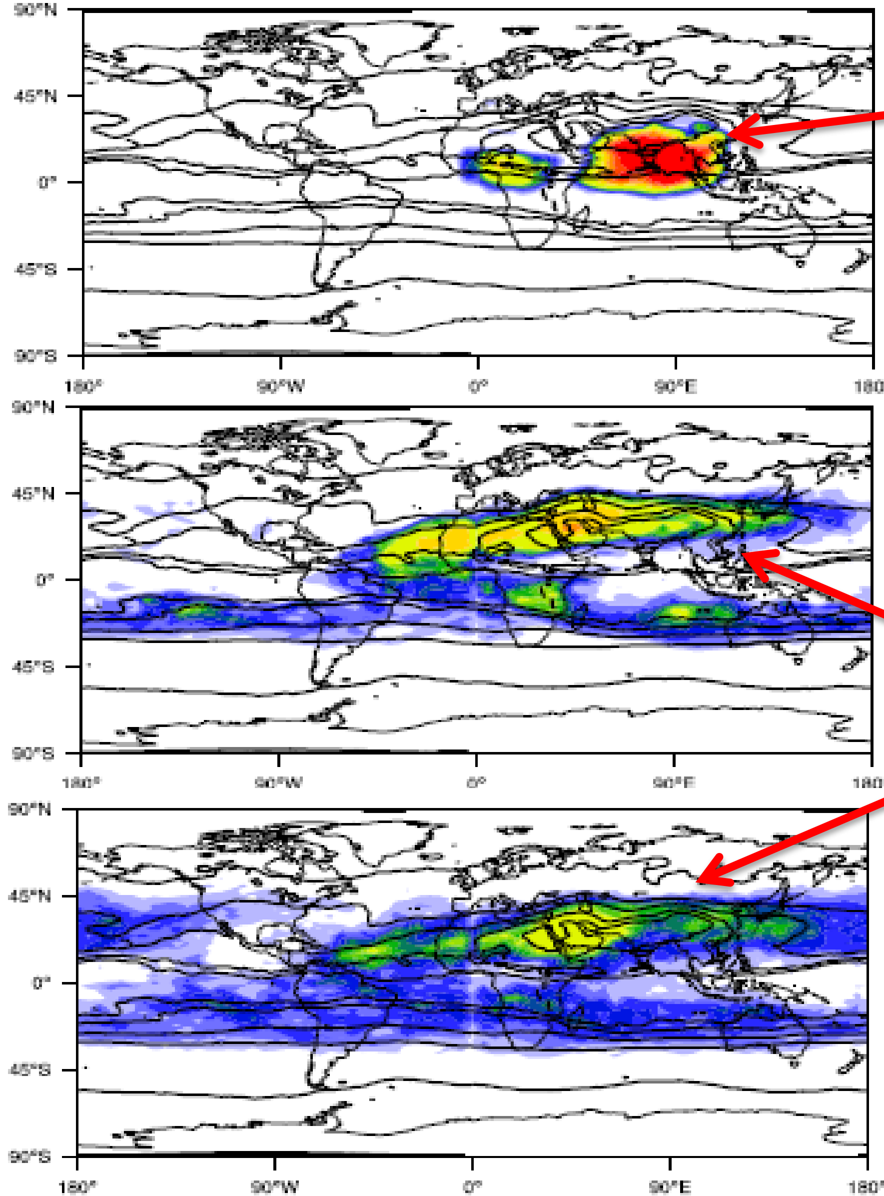
surface emission
(India and Southeast Asia)

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?

black lines = PV



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

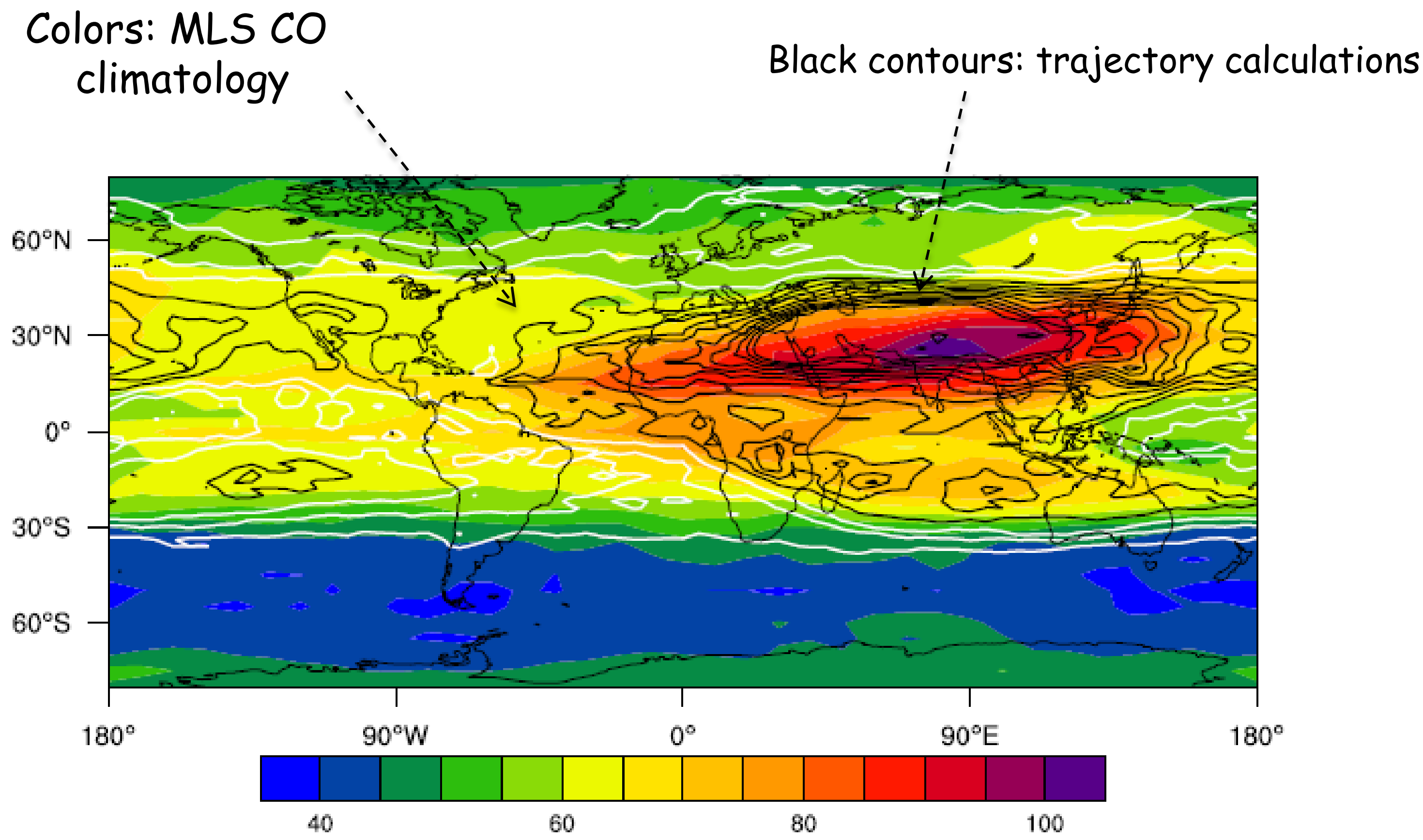
+ 10 days

+ 20 days

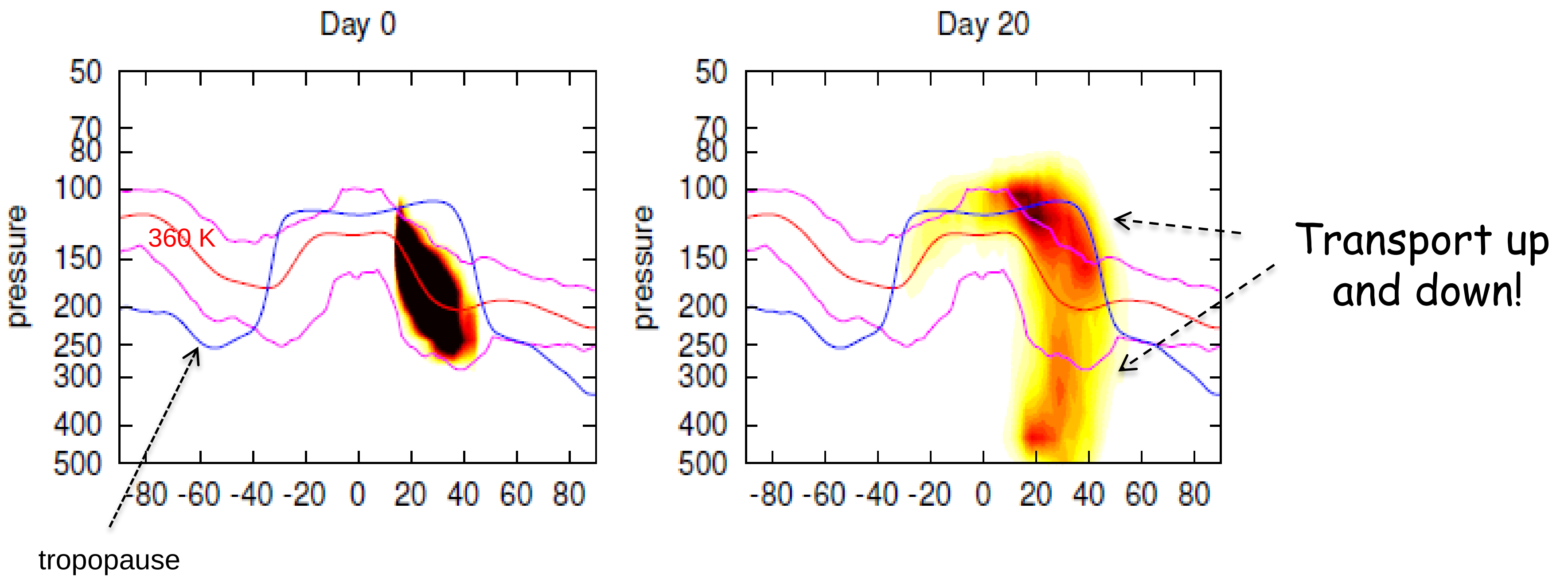
confinement within anticyclone

Garney and Randel 2015

Comparison of trajectory calculations with MLS CO climatology



Three-dimensional diabatic trajectories

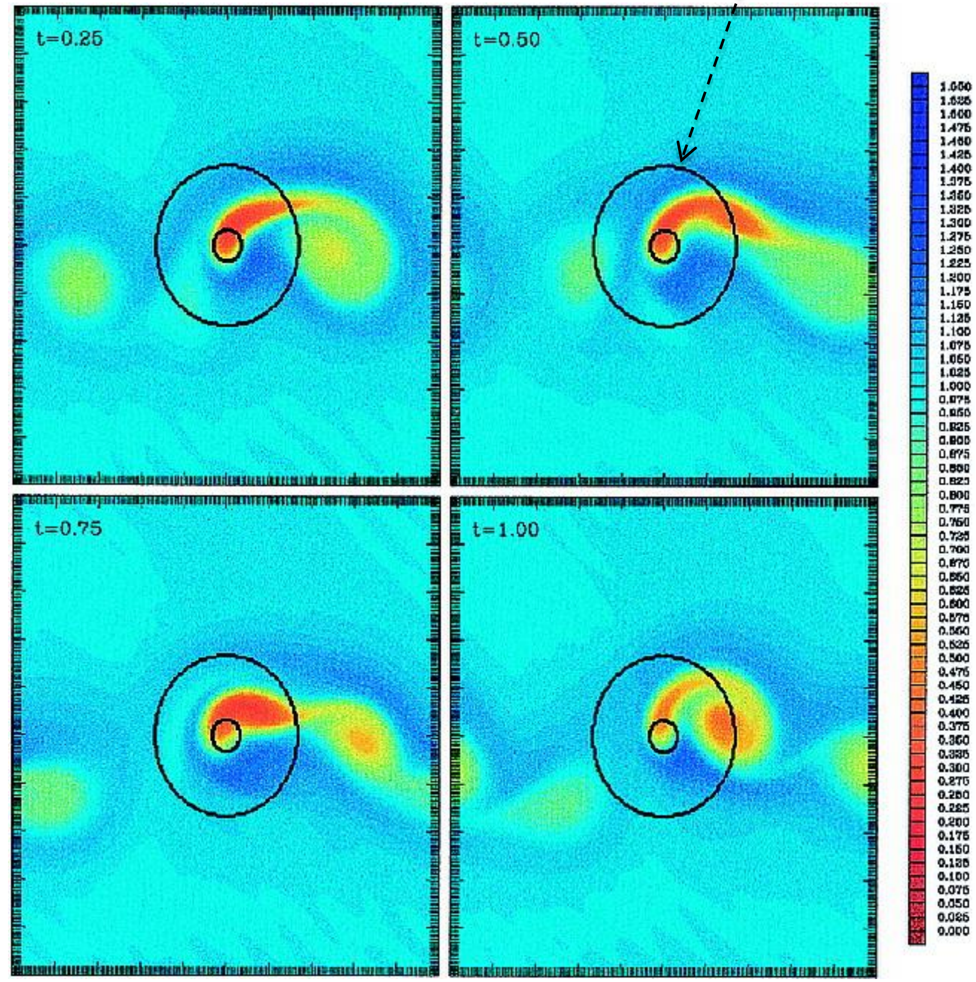


Monsoon circulation is inherently unstable

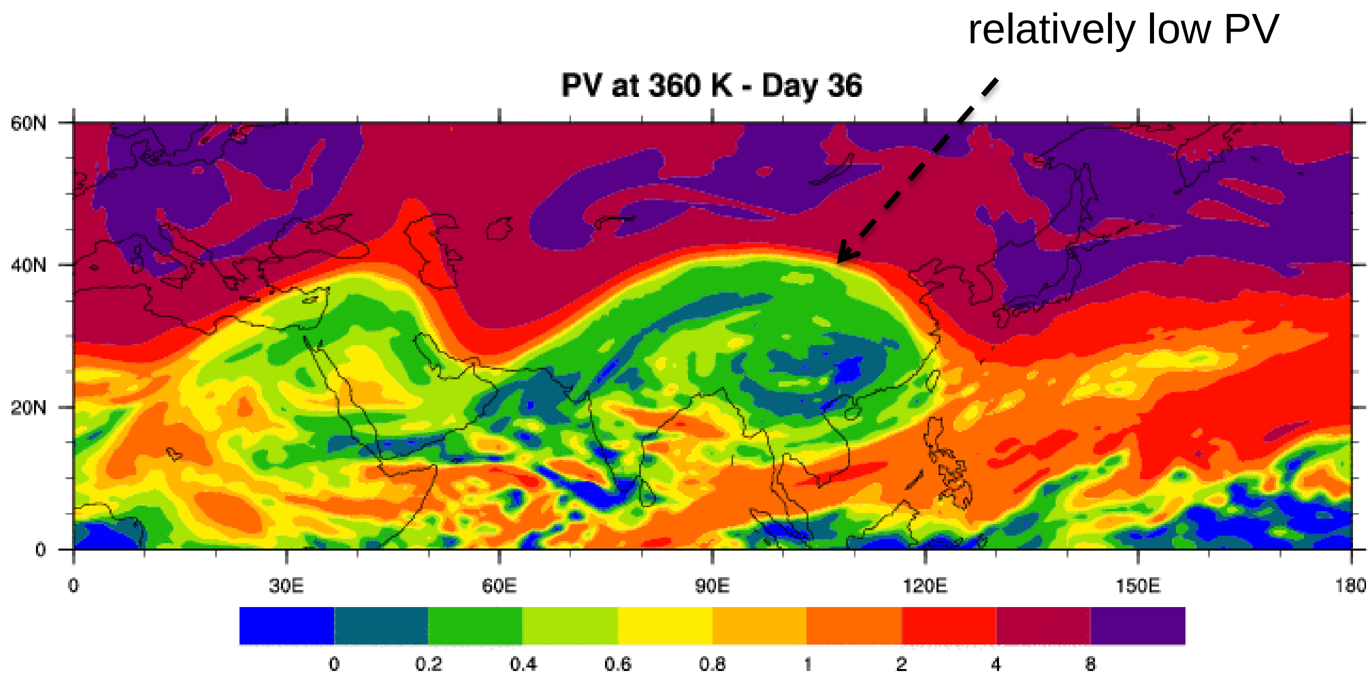
Hsu and Plumb 2000 JAS

'eddy shedding' from monsoon circulation

time-independent divergence forcing



Anticyclone viewed in potential vorticity



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

H. Garny[1] and W. J. Randel[2]

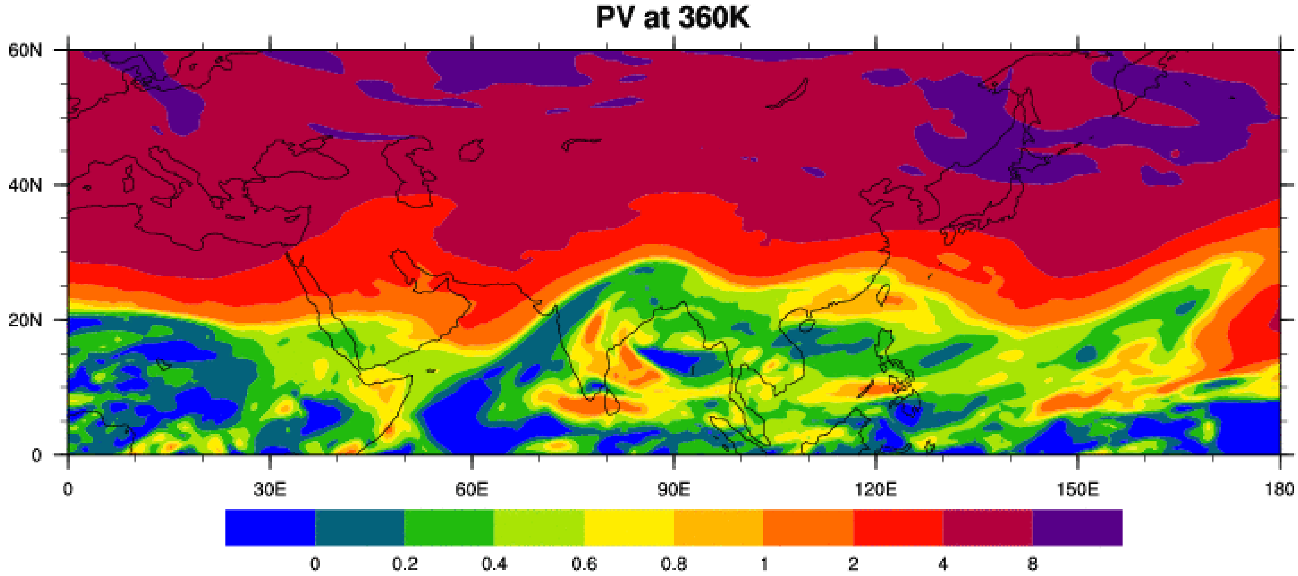
JGR 2013

following Popovic and Plumb, 2001

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

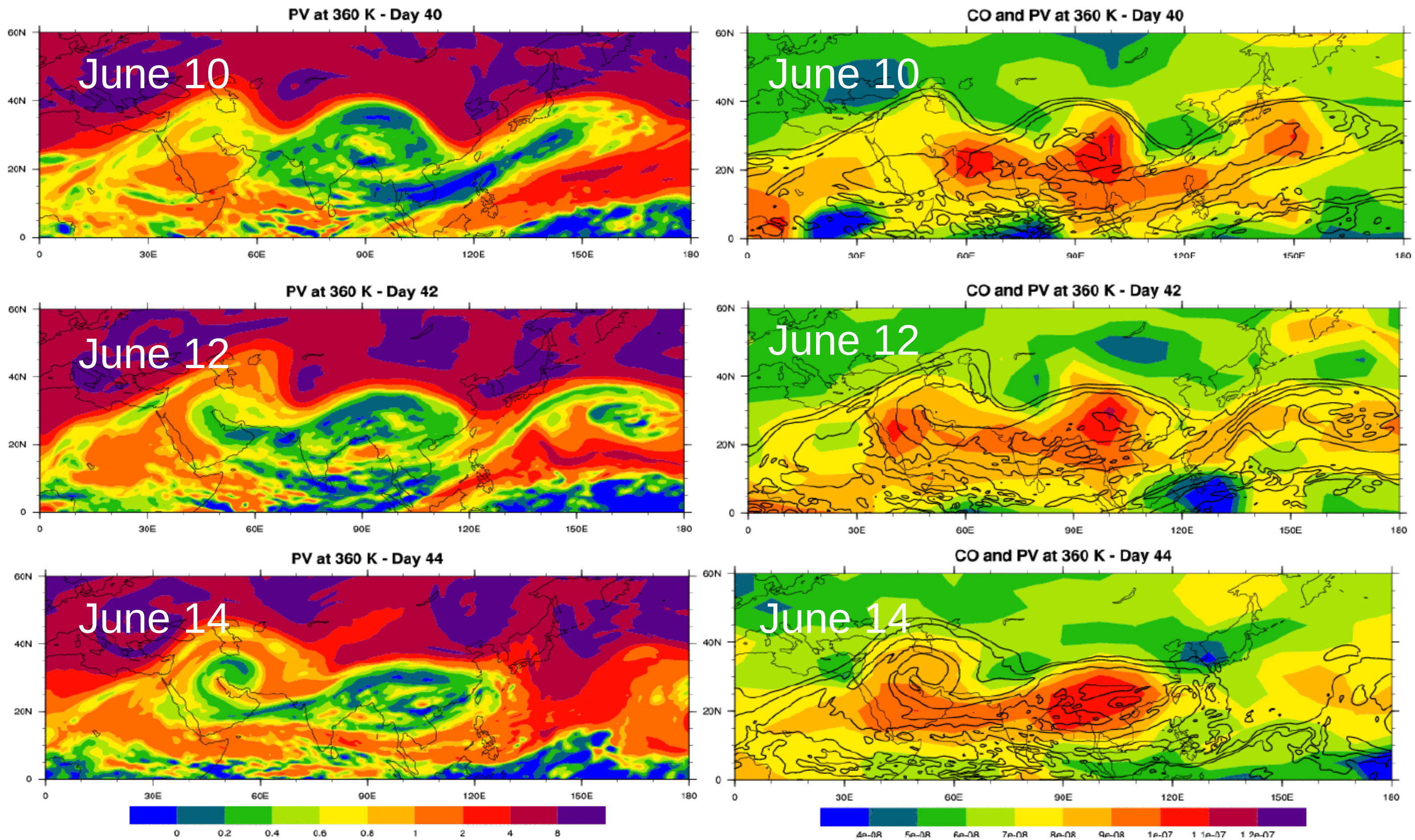
Day 1 =	May 1
32	June 1
62	July 1
93	Aug 1
123	Sept 1

animation of daily PV maps for one summer



Dynamical variability echoed in tracers

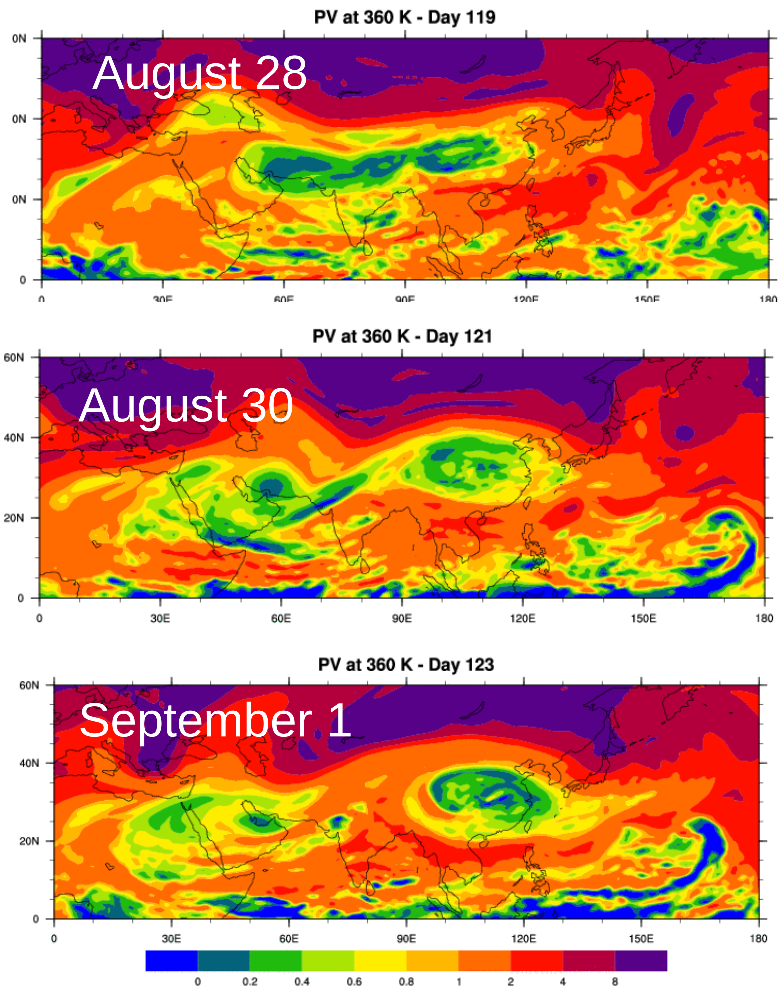
PV at 360 K | CO from Aura MLS



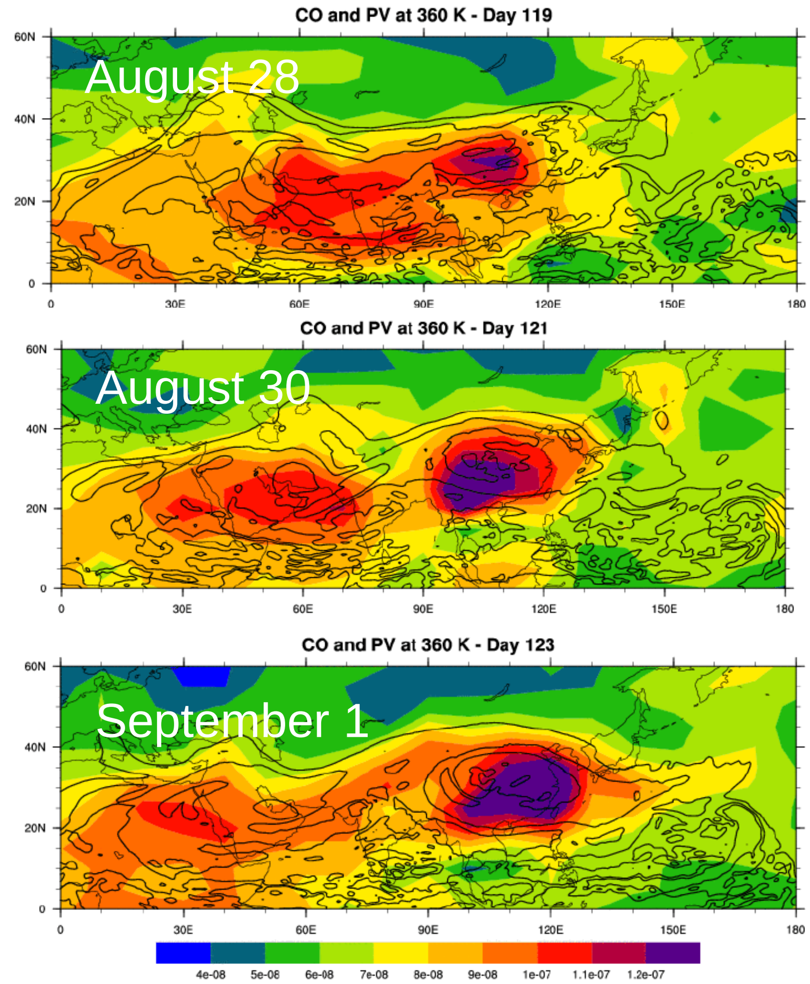
Garney and Randel, 2013, JGR

Another example

PV at 360 K



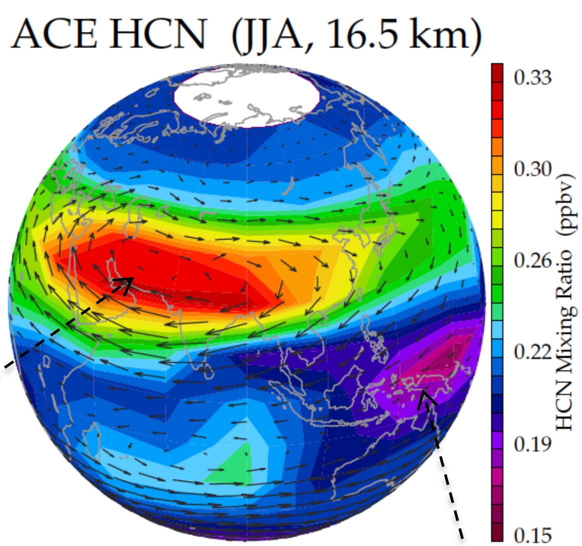
CO from Aura MLS



Transport to the stratosphere via the monsoon anticyclone

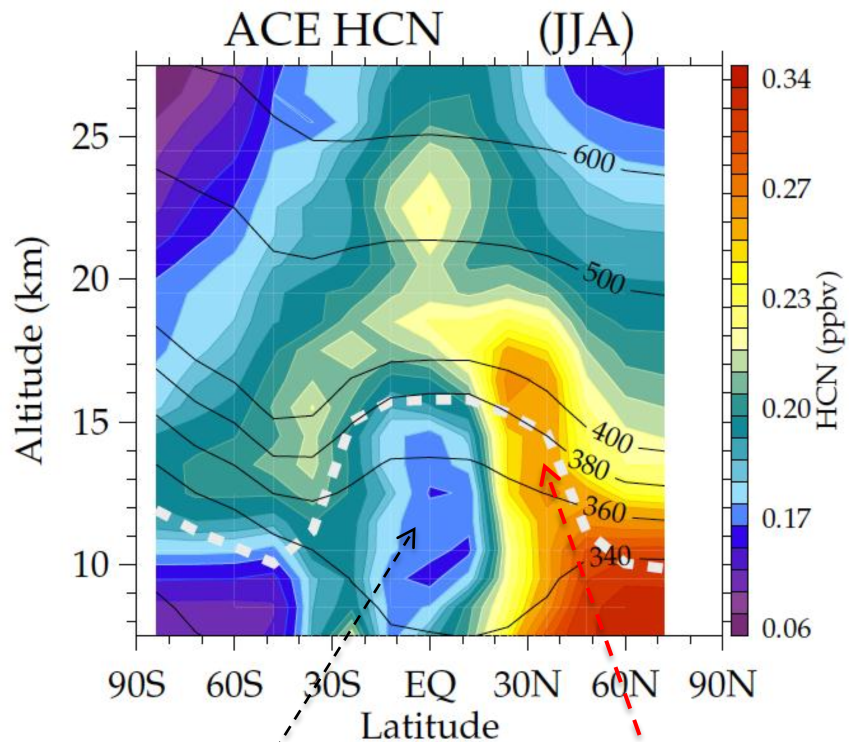
HCN – biomass burning tracer

- Minimum in tropics (ocean sink)
- Long lived in free atmosphere



monsoon maximum

minimum for air with recent ocean contact



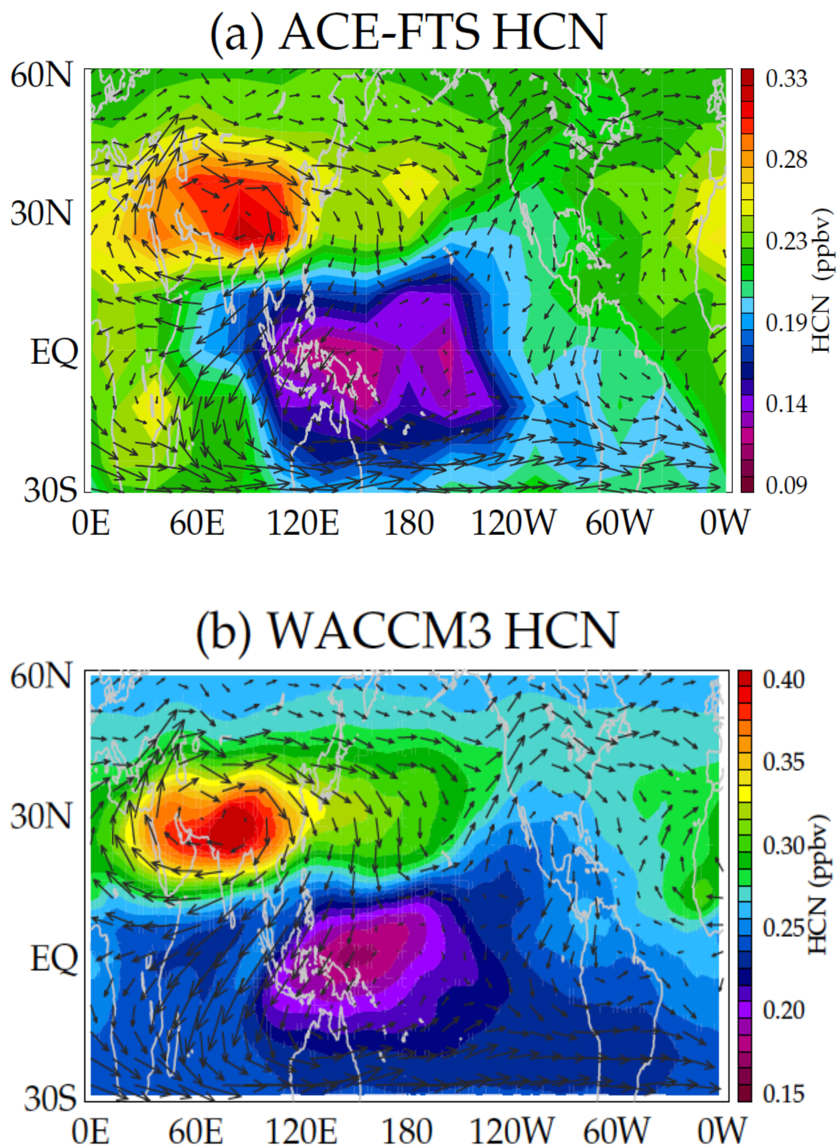
tropical minimum

transport to stratosphere via monsoon

JJA

WACCM simulation of HCN

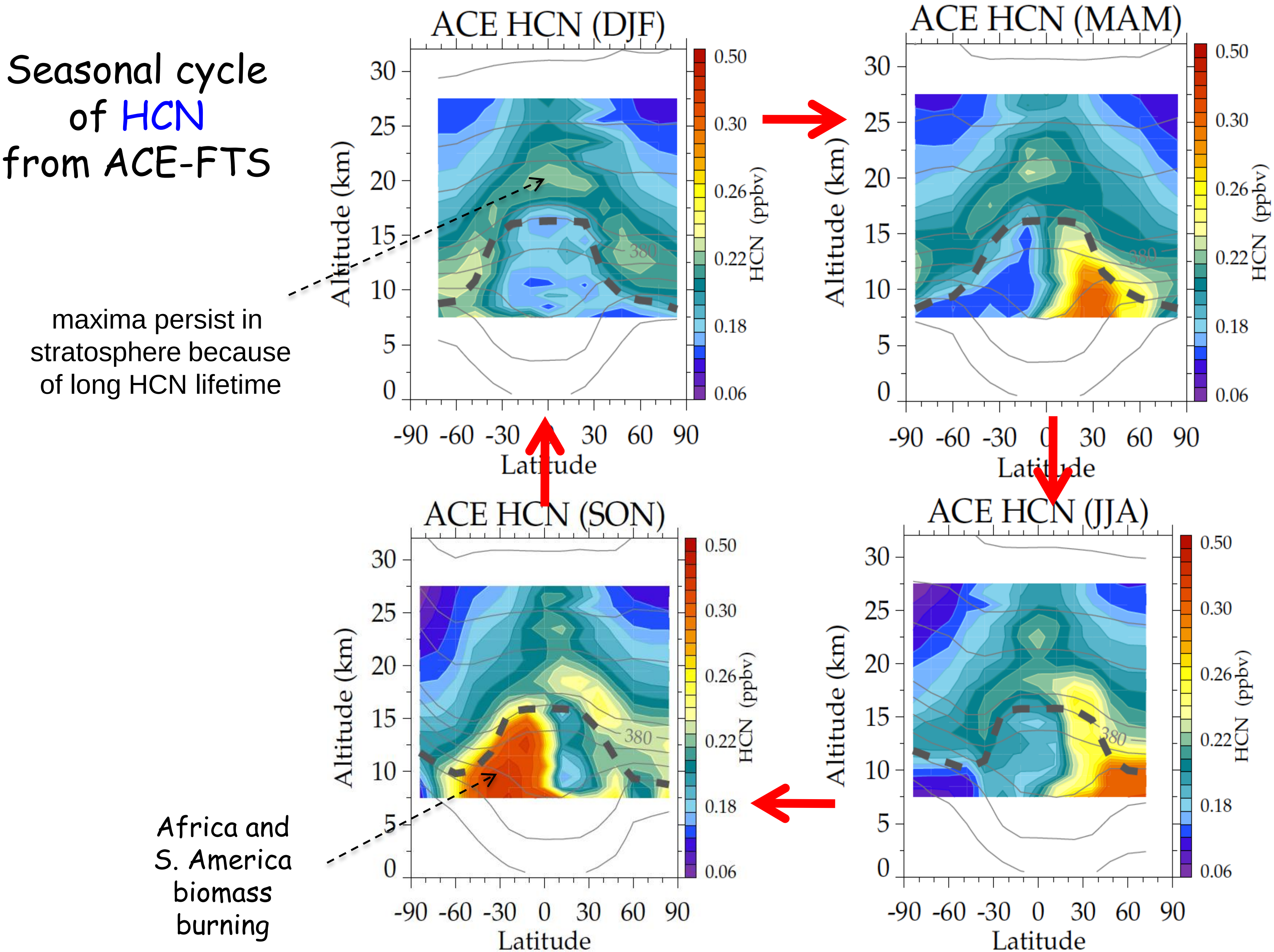
- climatological emission sources
- parameterized ocean sink



ACE

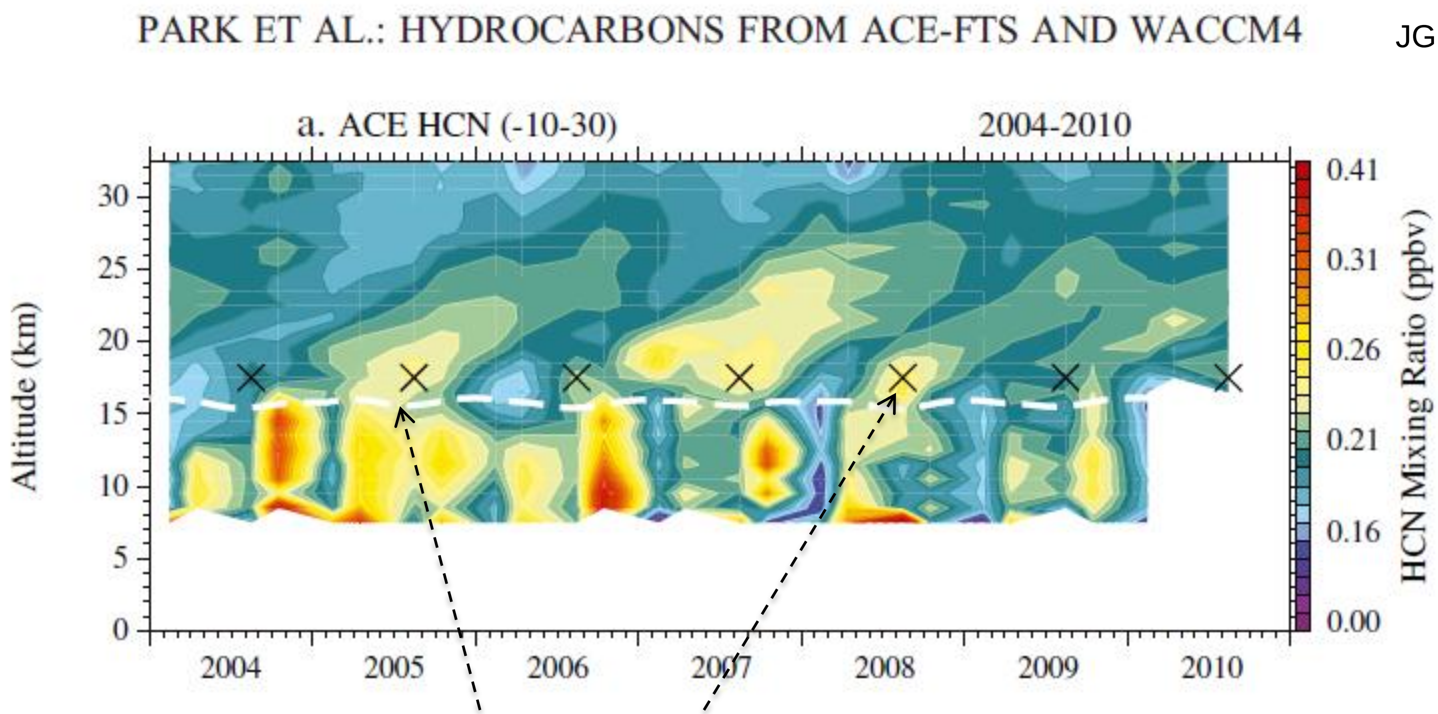
WACCM

Seasonal cycle of HCN from ACE-FTS



HCN 'tape recorder' from ACE-FTS measurements

JGR, 2013

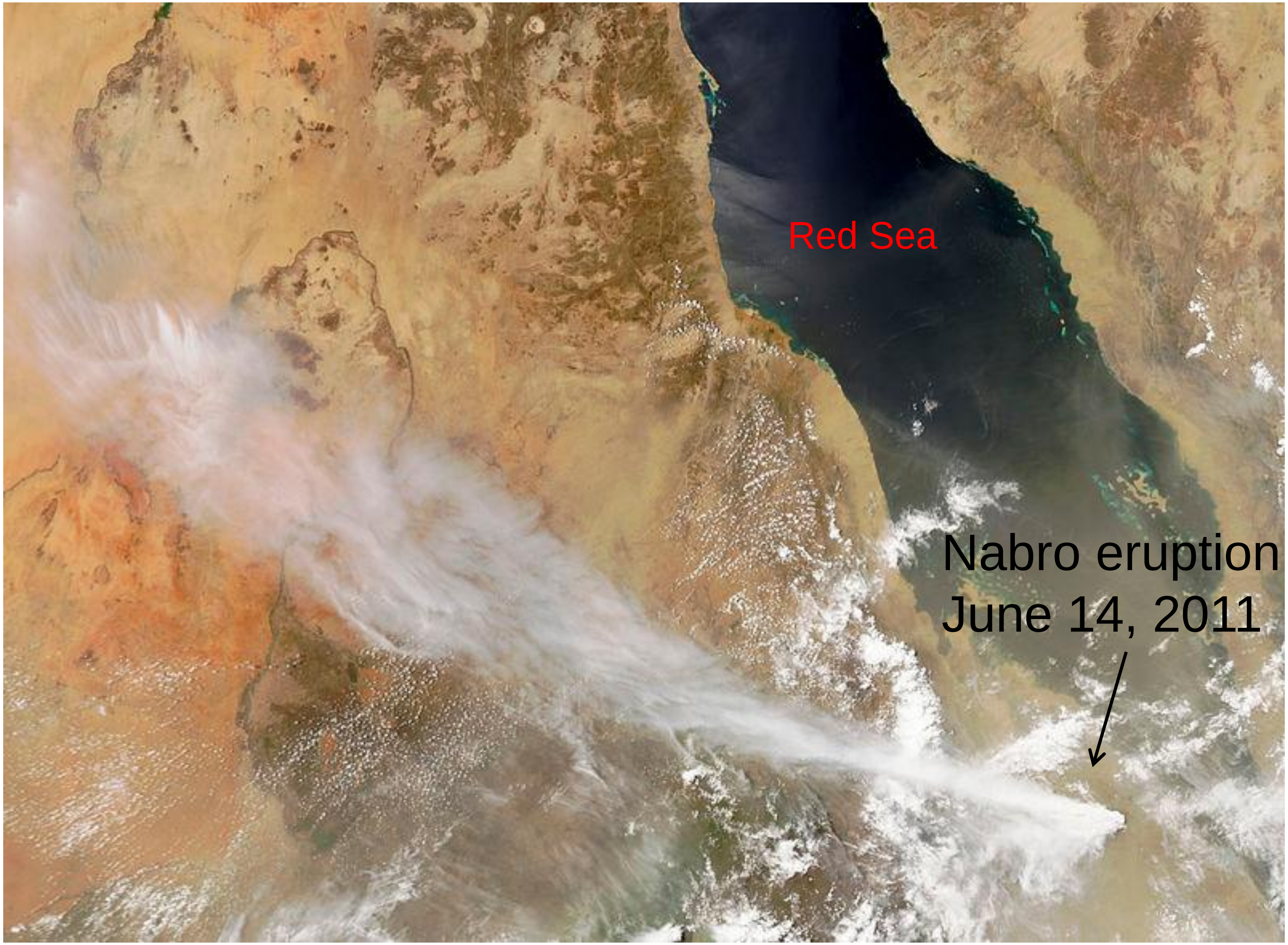


boreal summer maxima from
Asian monsoon circulation

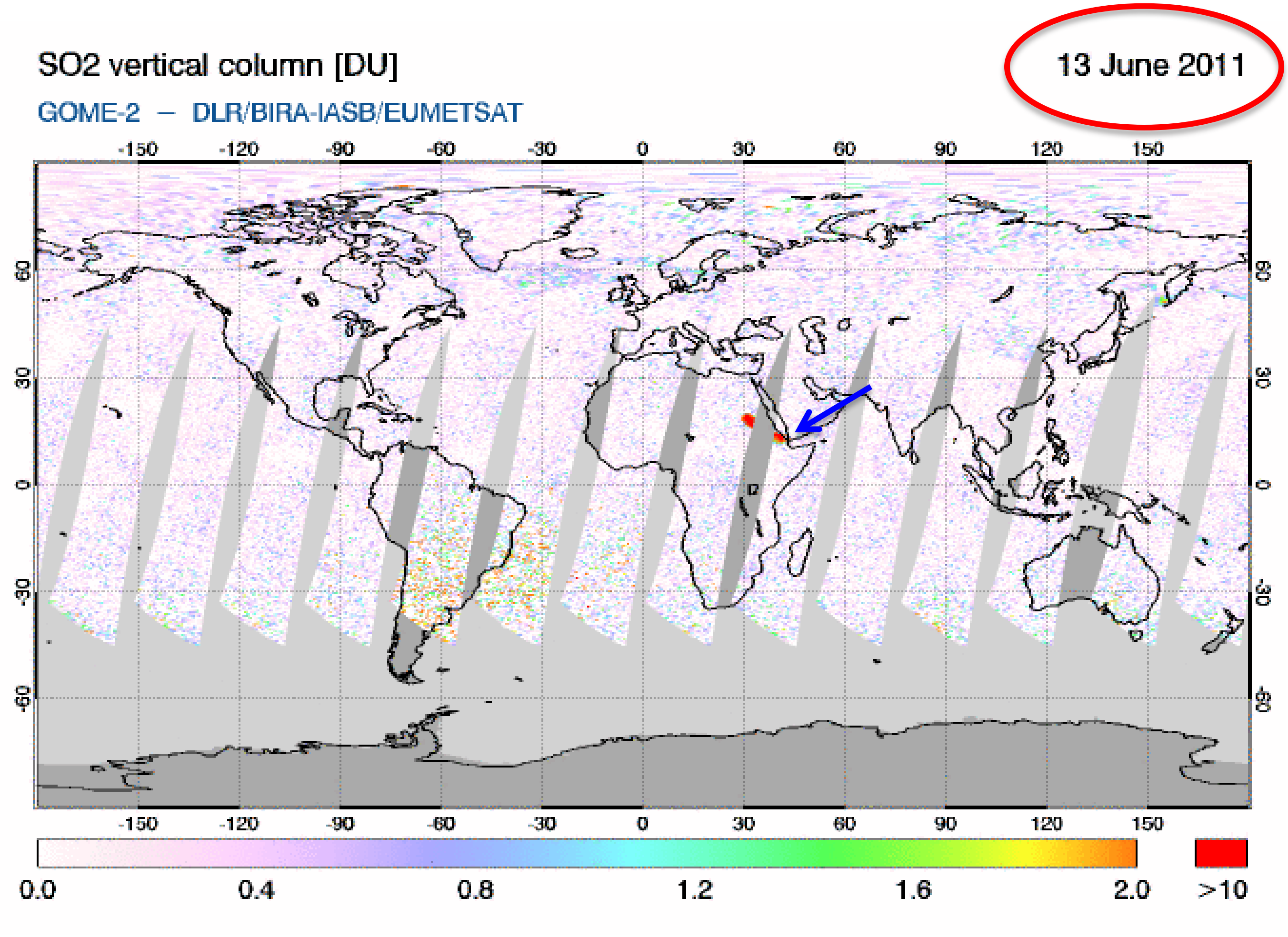
Key points:

- Trajectory studies show fate of convective outflow (up and down)
- Fundamental instability of anticyclone: eddy shedding
- HCN provides evidence for monsoon transport to stratosphere

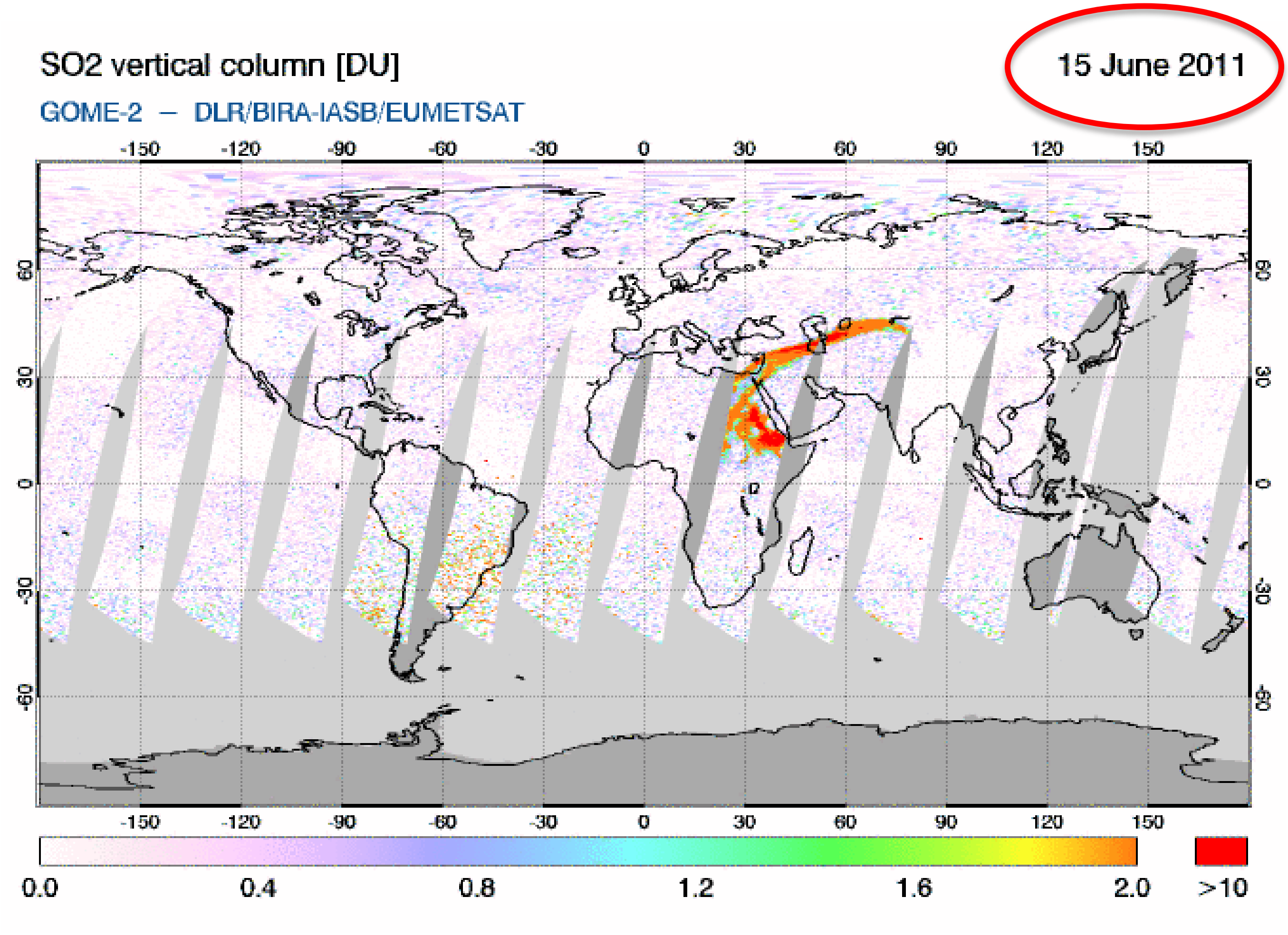
Eruption of Mt. Nabro June 13, 2011 Eritria, Africa


Red Sea
Nabro eruption
June 14, 2011

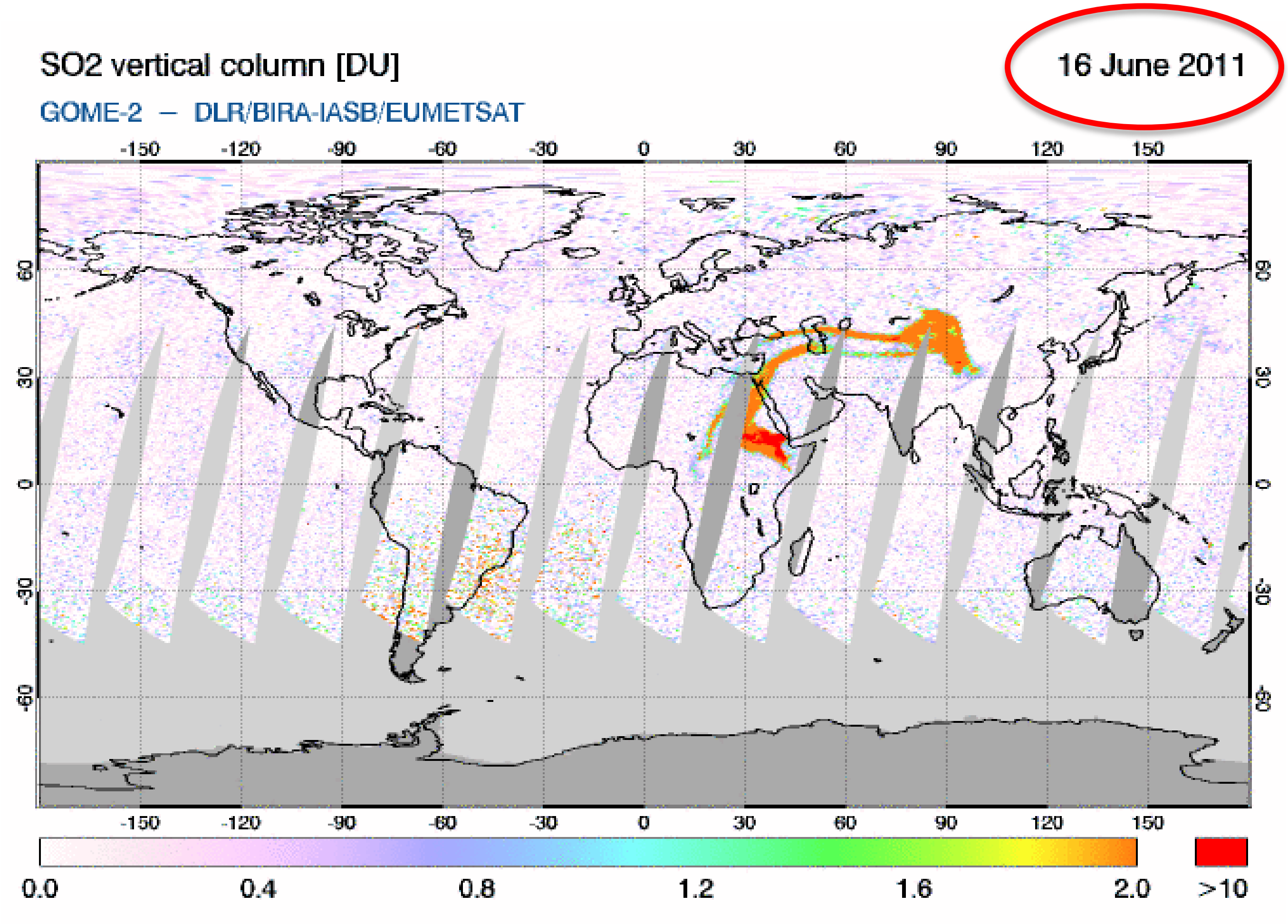
SO_2 plume from Nabro



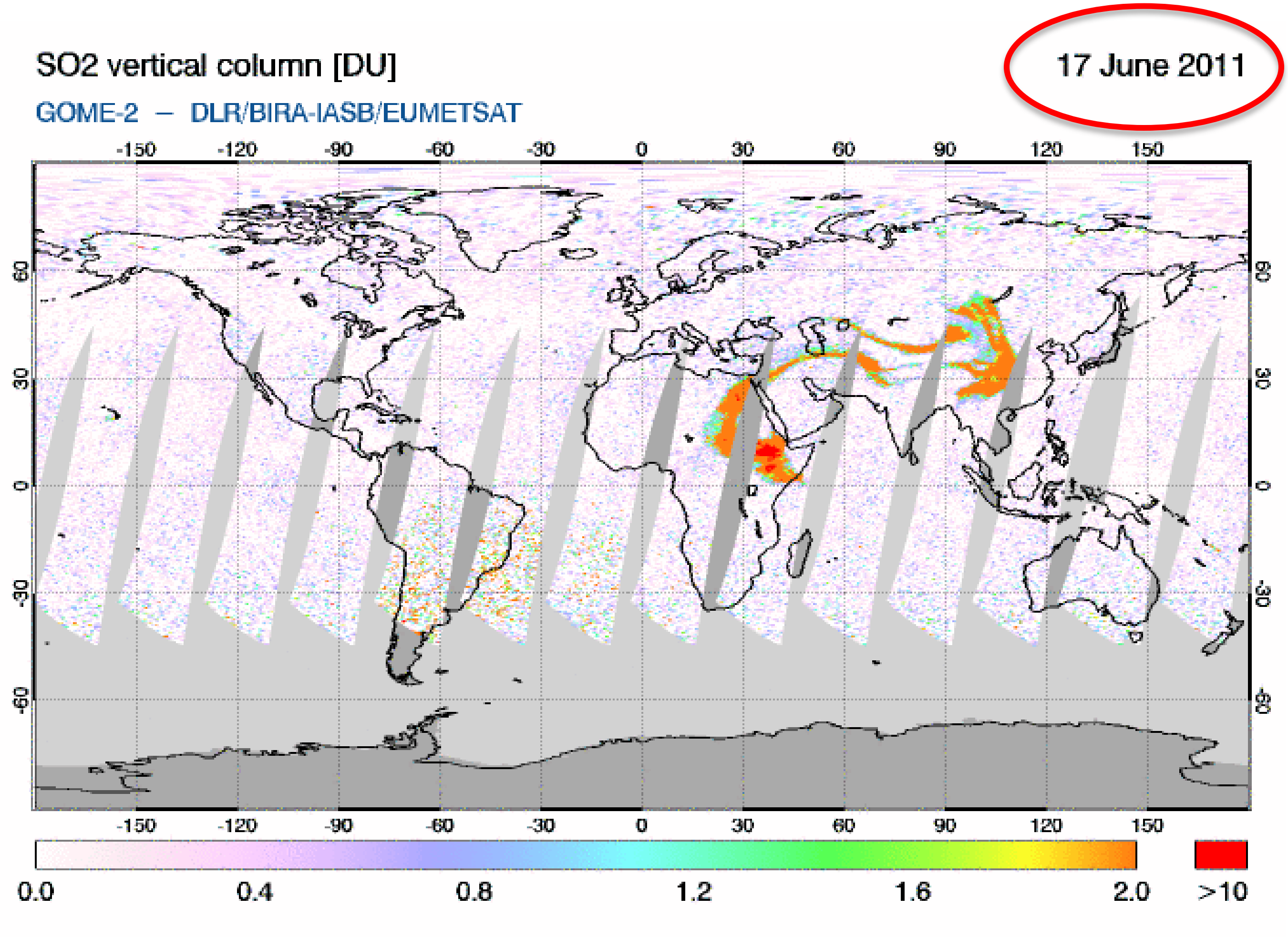
SO_2 plume from Nabro



SO_2 plume from Nabro

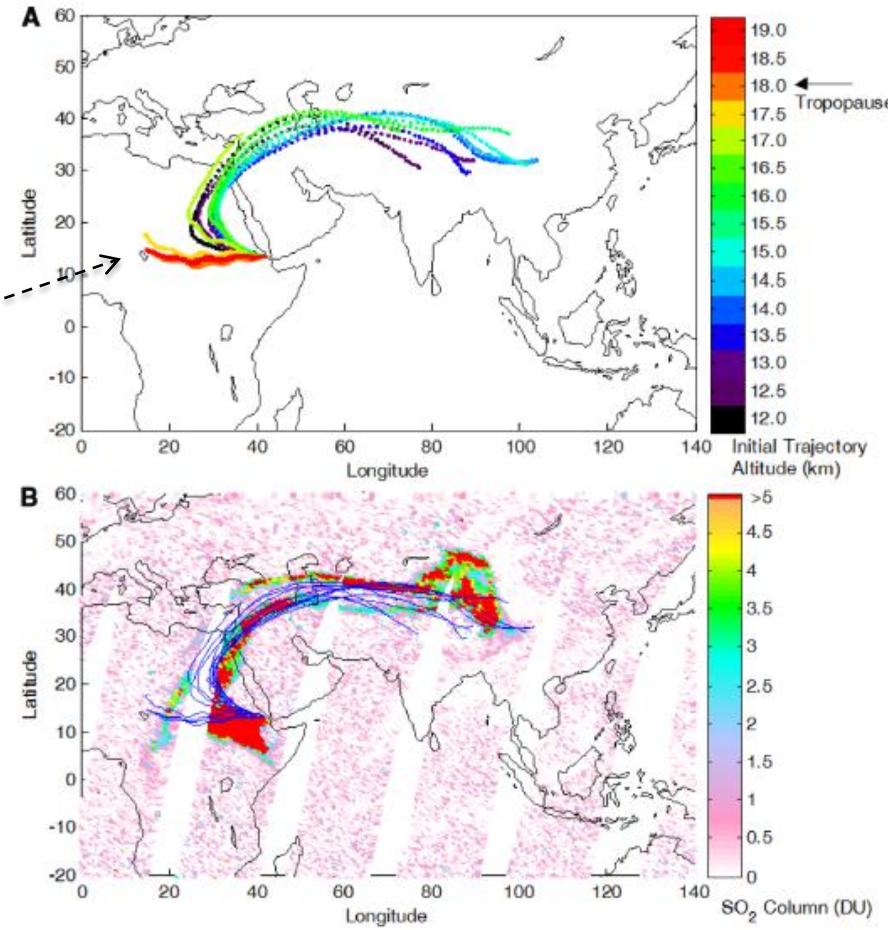


SO_2 plume from Nabro



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

westward movement for 17.5 km and above



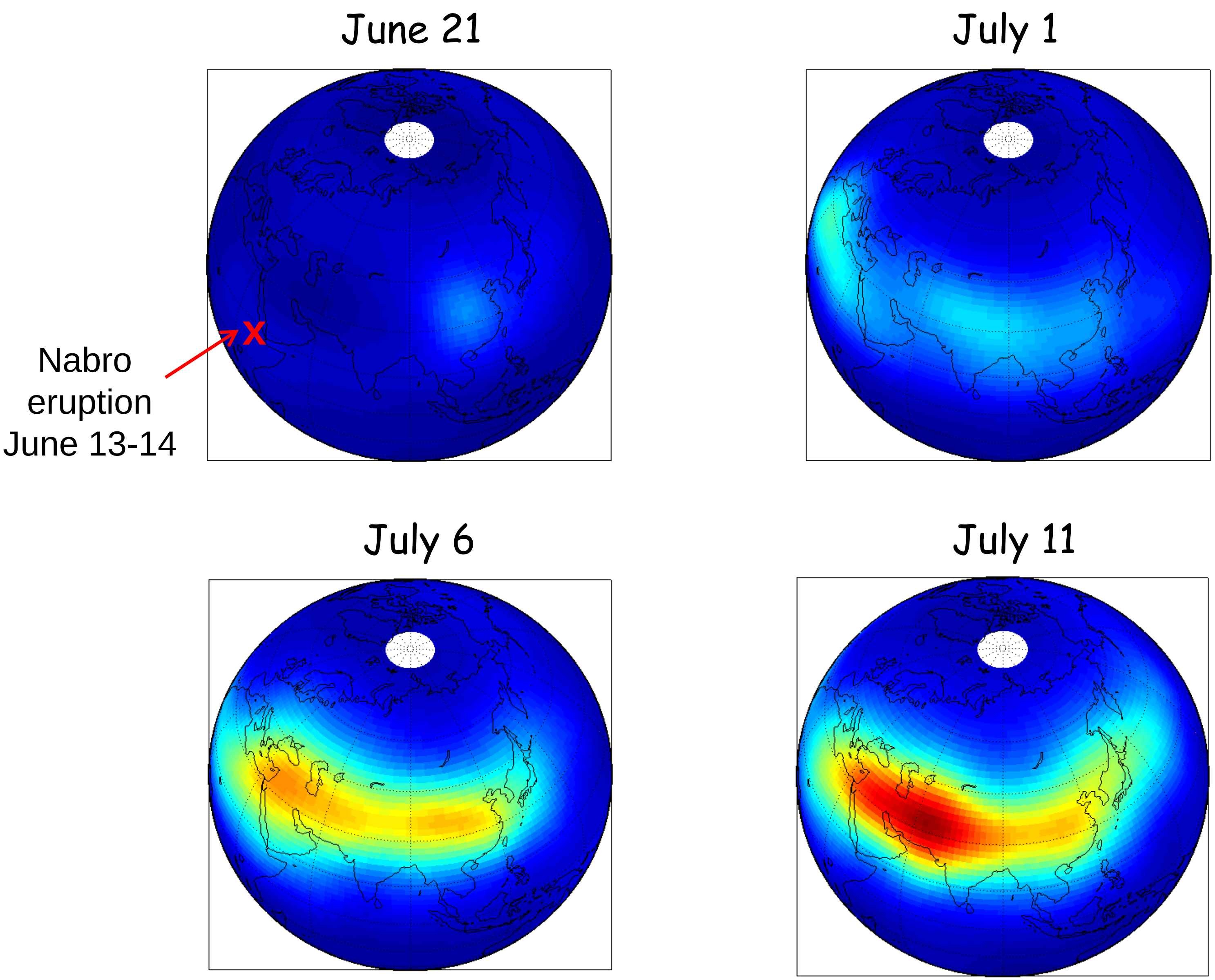
trajectories for June 13-16

trajectories overlaid with GOME SO_2

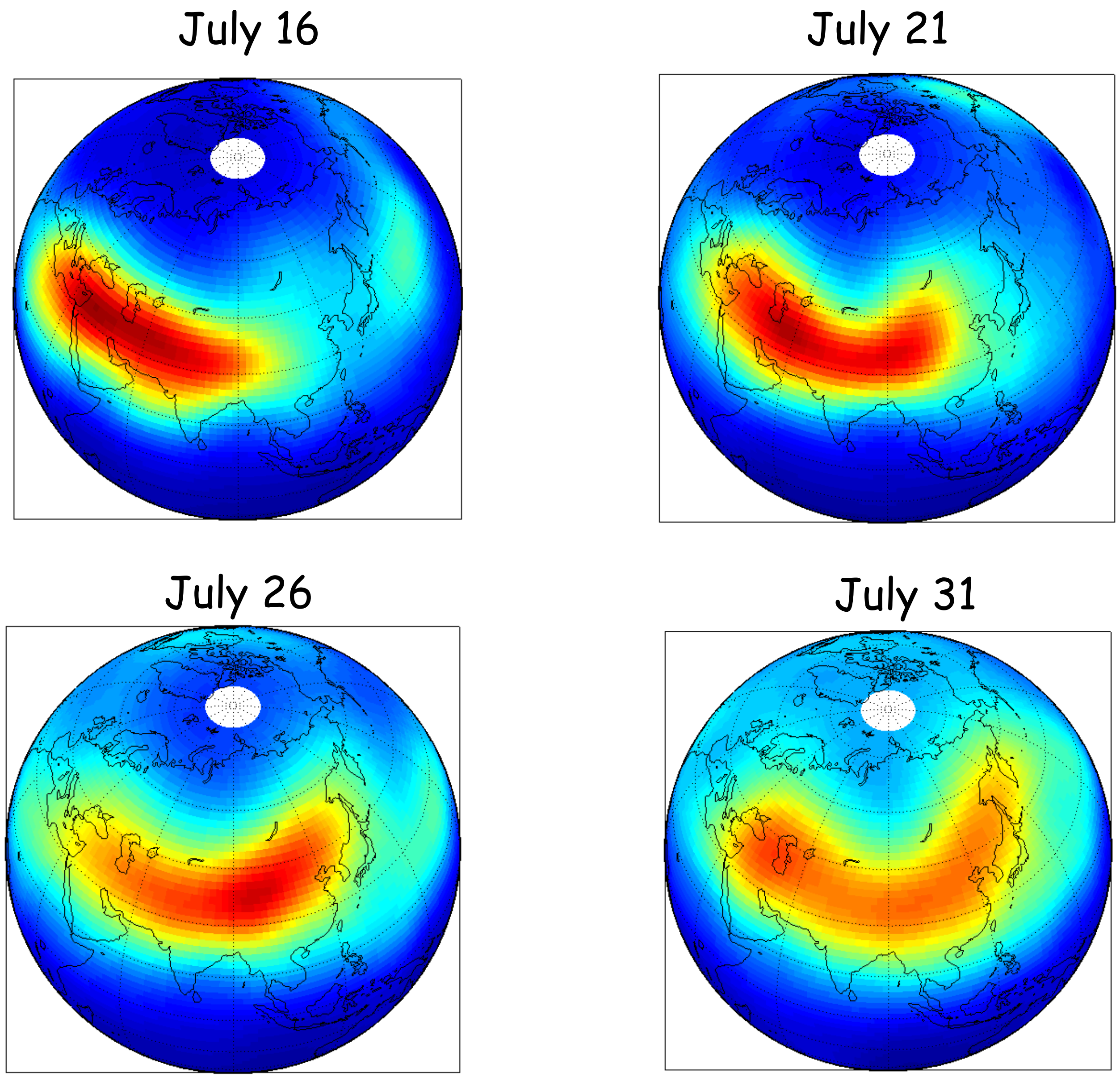
Bourassa et al, 2012

Stratospheric aerosols from OSIRIS satellite

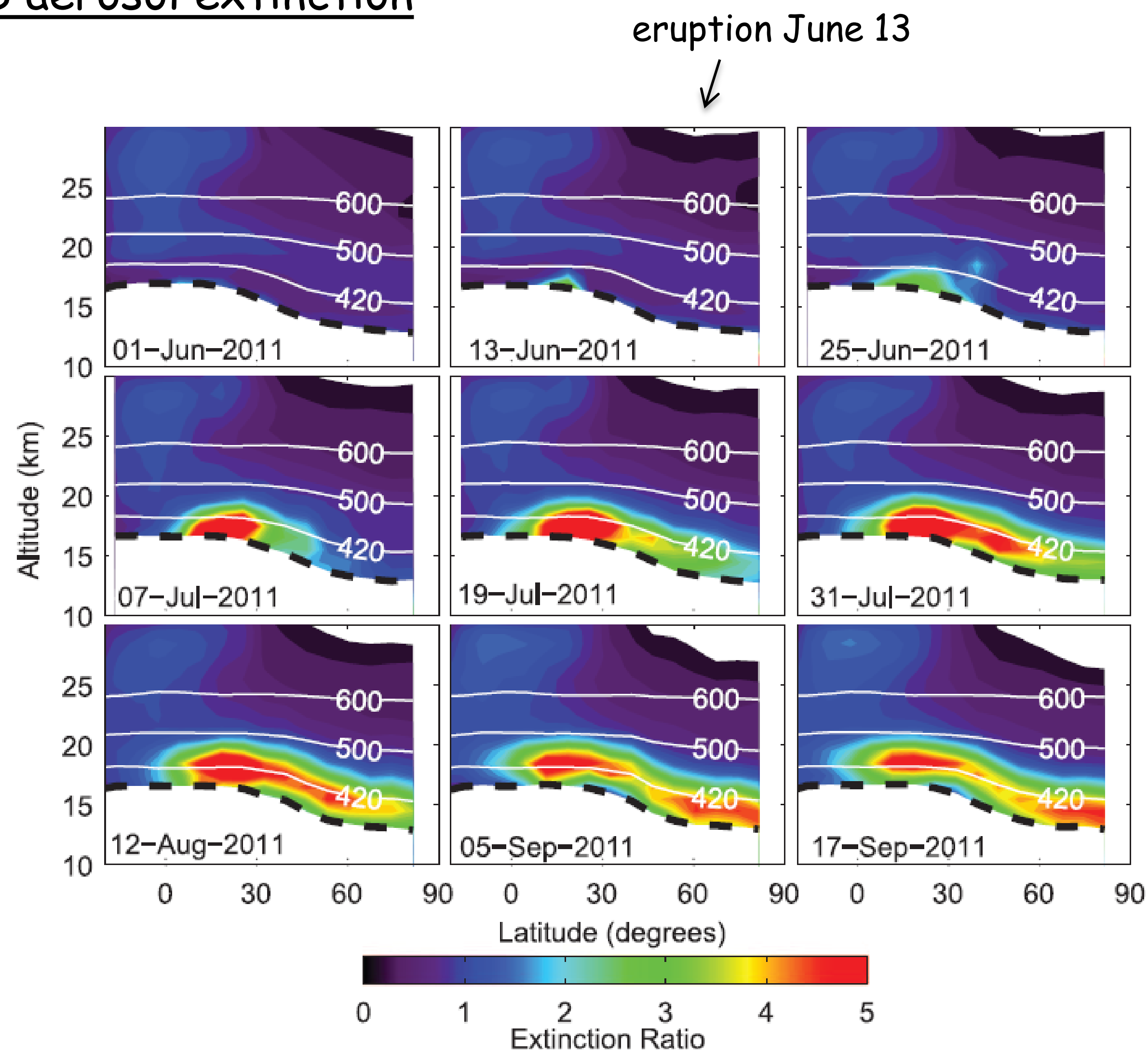
Bourassa et al, 2012



Bourassa et al, 2012



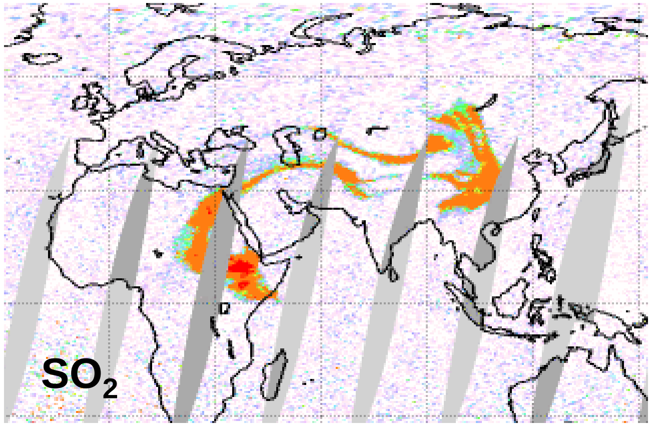
OSIRIS aerosol extinction



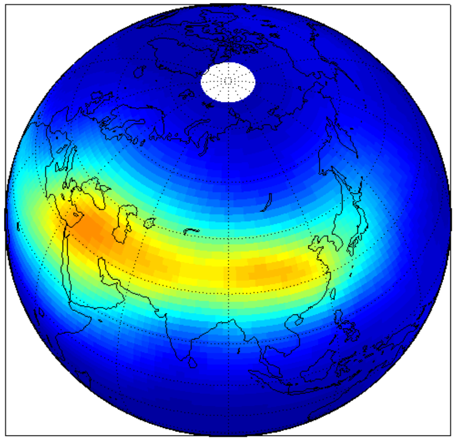
Interpretation:

- 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)

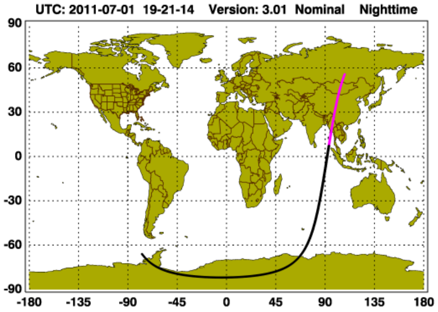
June 17

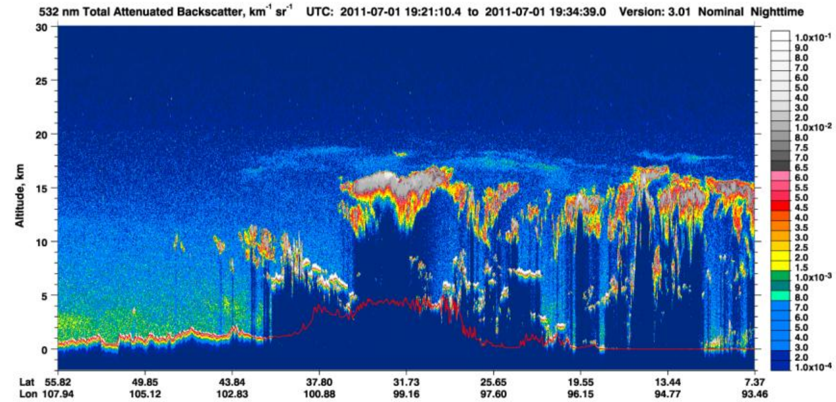


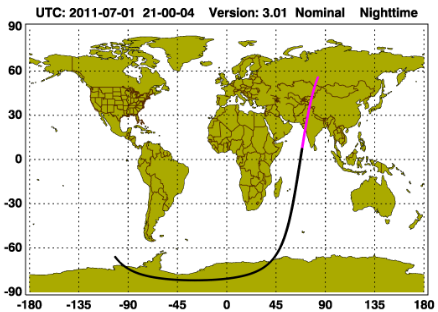
July 6

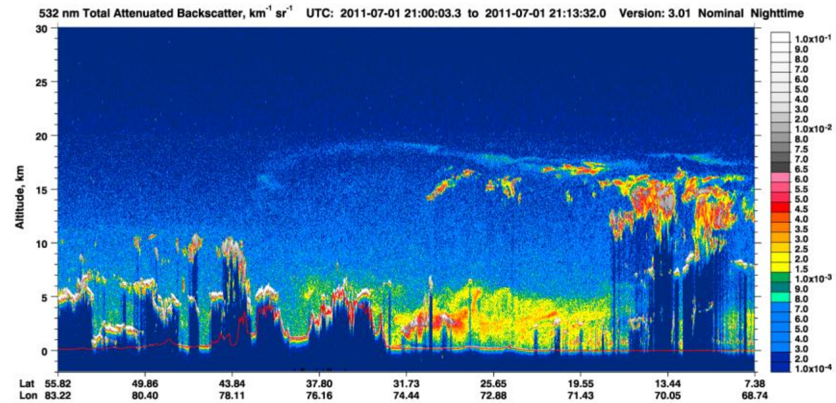


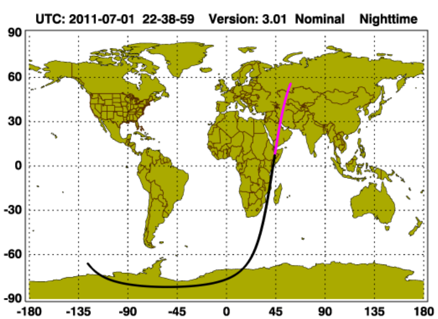
July 1: 18 days after eruption

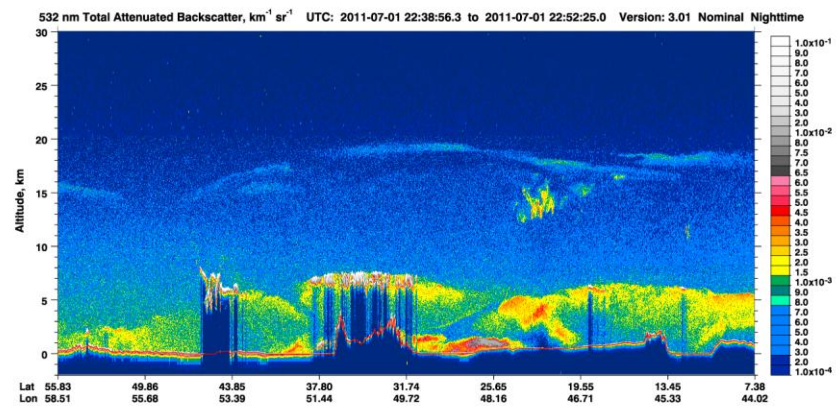




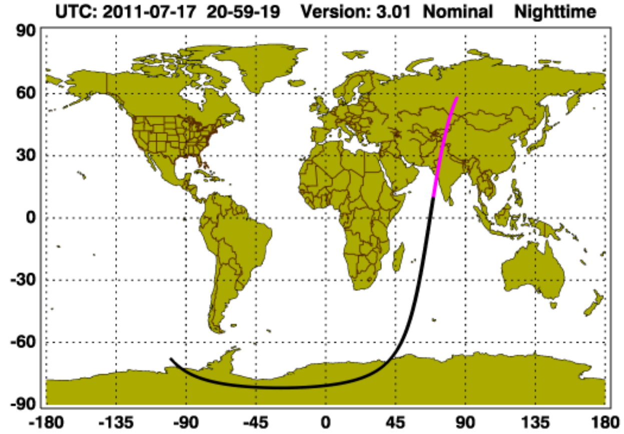


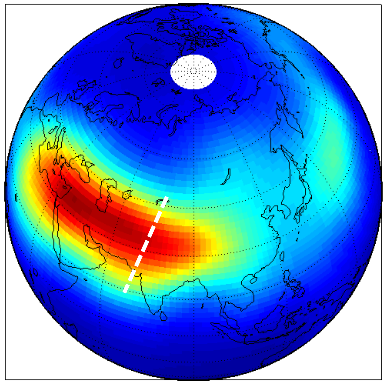


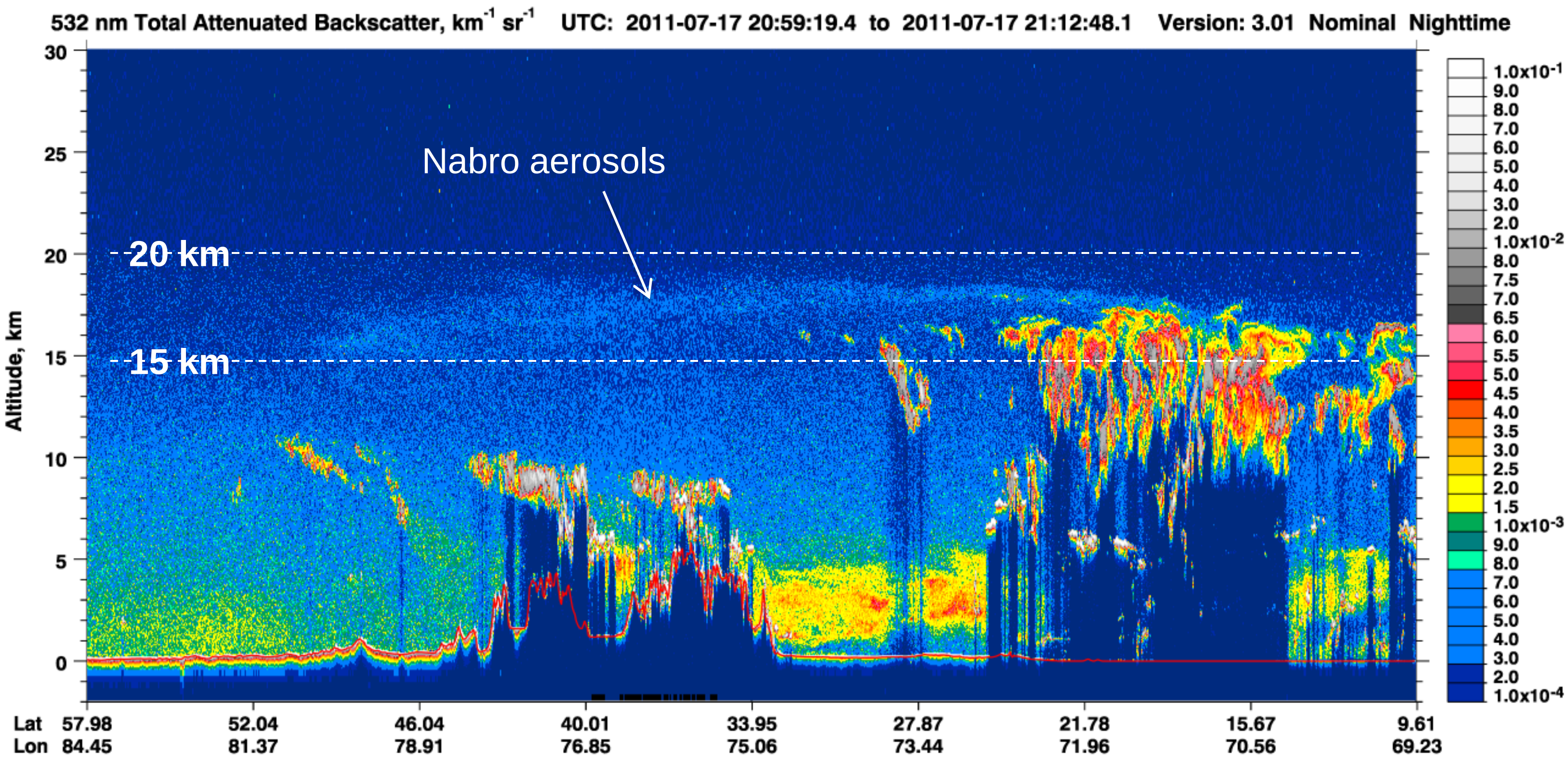




July 17
34 days
after eruption







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

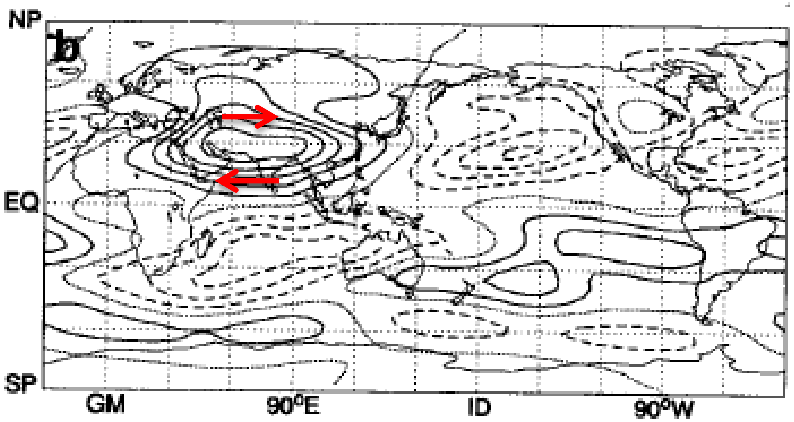
200 hPa streamfunction JJA

A Model of the Asian Summer Monsoon.
Part I: The Global Scale

JAS 1995

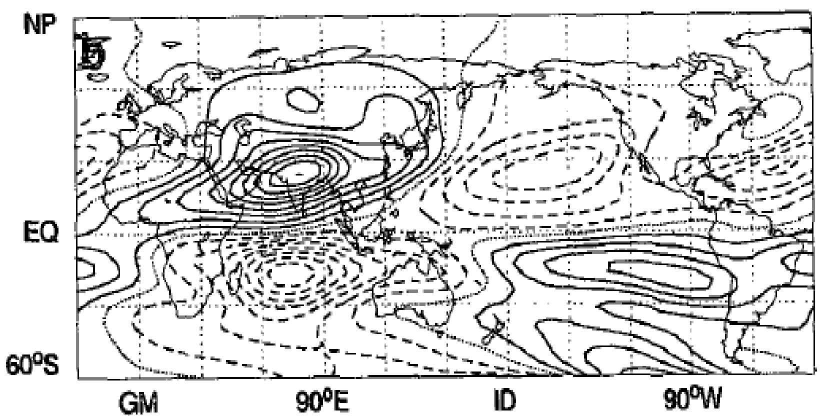
Brian J. Hoskins and Mark J. Rodwell

observations

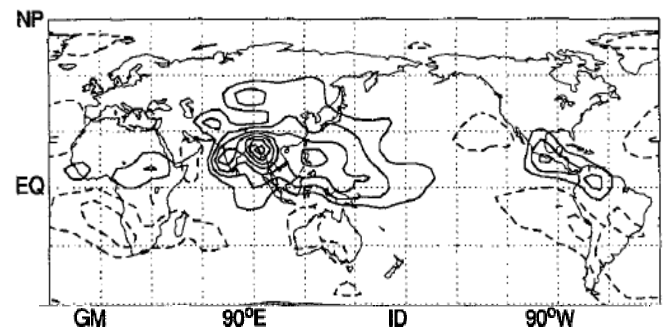


reasonable agreement

linear model with heating



diabatic heating from reanalyses



Result: heating from convection mainly forces monsoon anticyclone