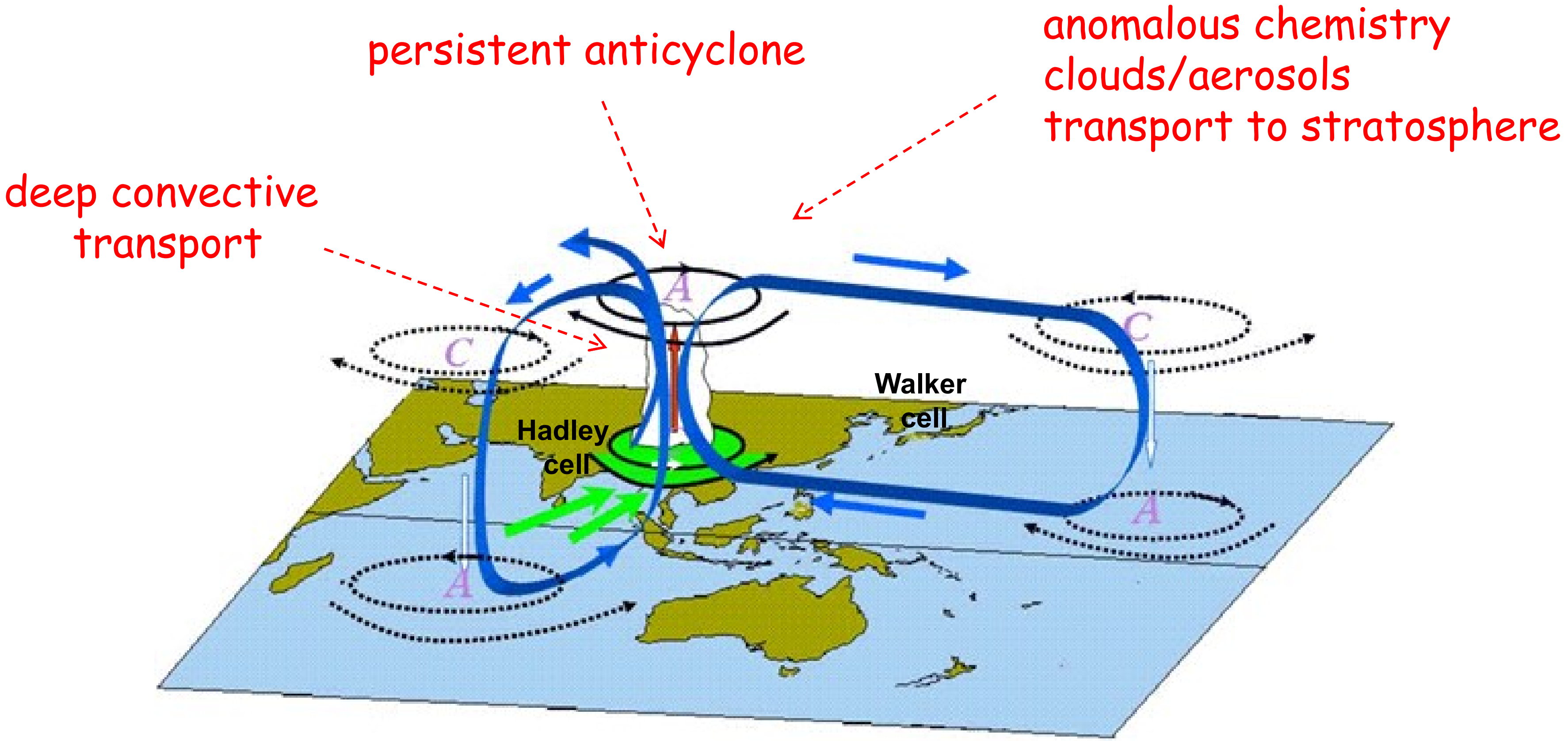
Lecture 5: Monsoon circulations in the UTLS

- 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

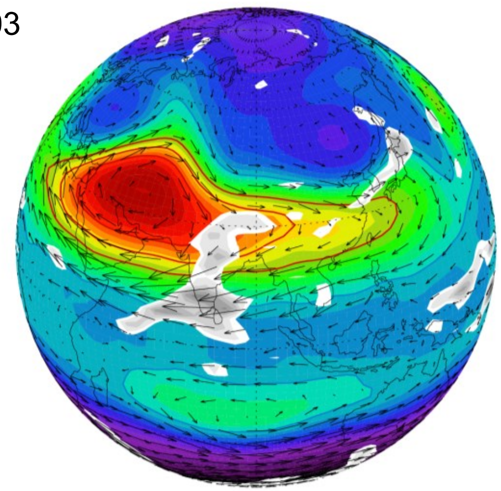
Summer Broad-Scale Circulations



Dynamical Background

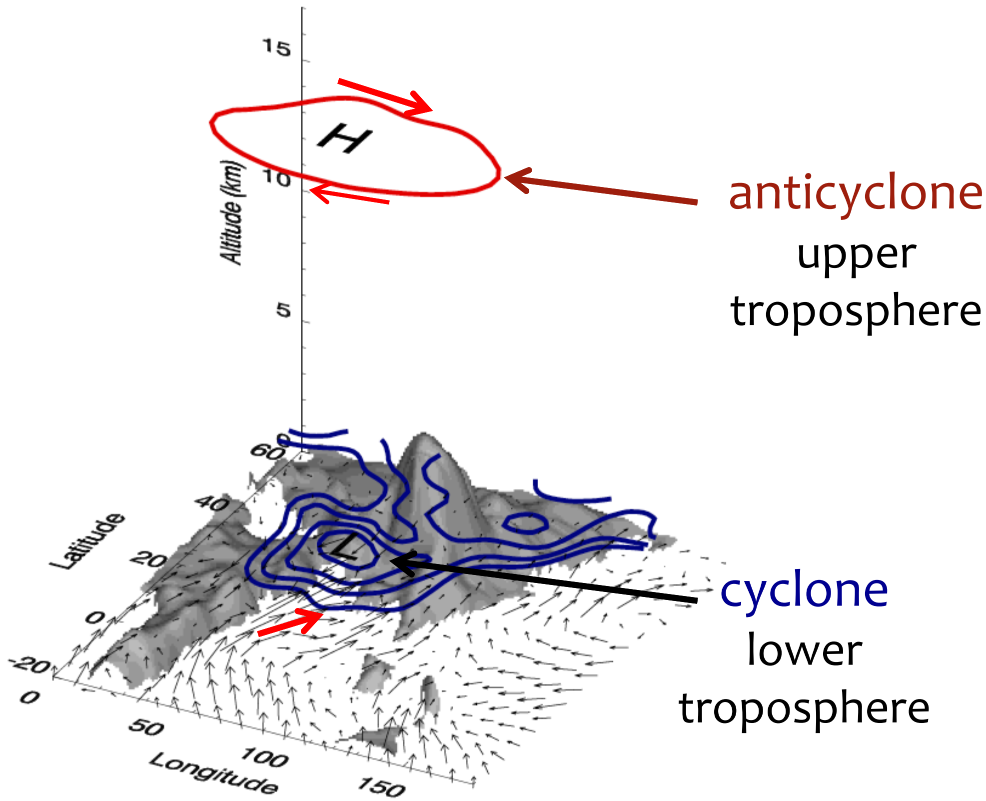
Cyclone at the surface, anticyclone in the upper troposphere

one-day
‘snapshot’
July 10, 2003



Randel and Park, 2006, J. Geophys. Res.

Hoskins and Rodwell, 1995
Highwood and Hoskins, 1998

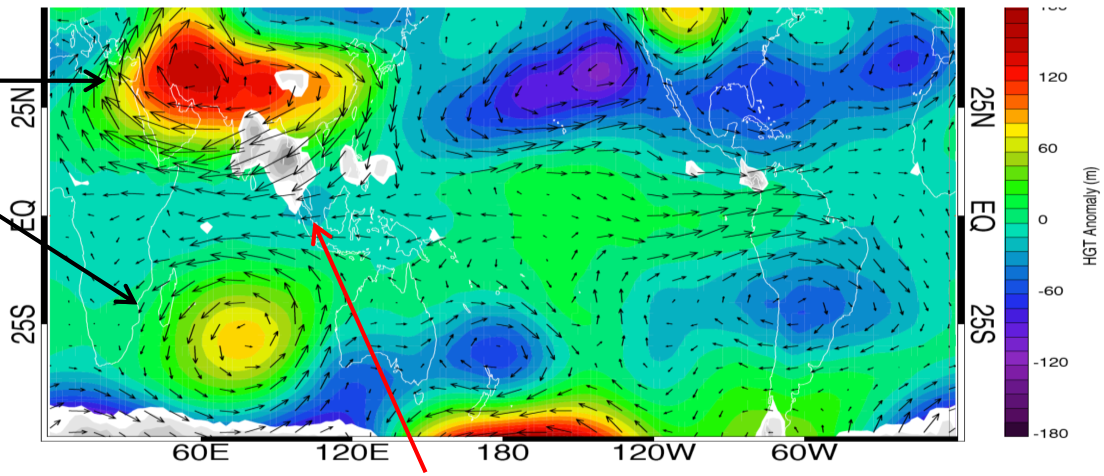


Park et al., 2009, J. Geophys. Res.

Anticyclones in the Upper Troposphere

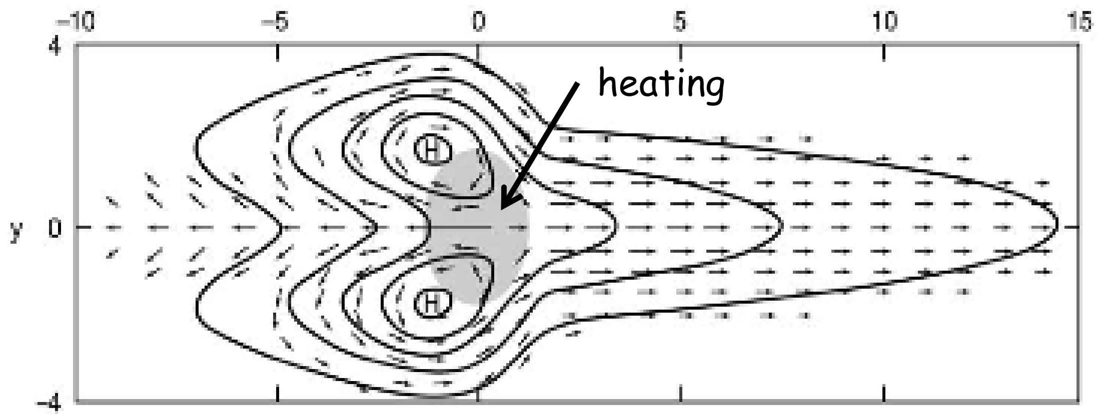
geopotential height and winds 100 hPa

anticyclones



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

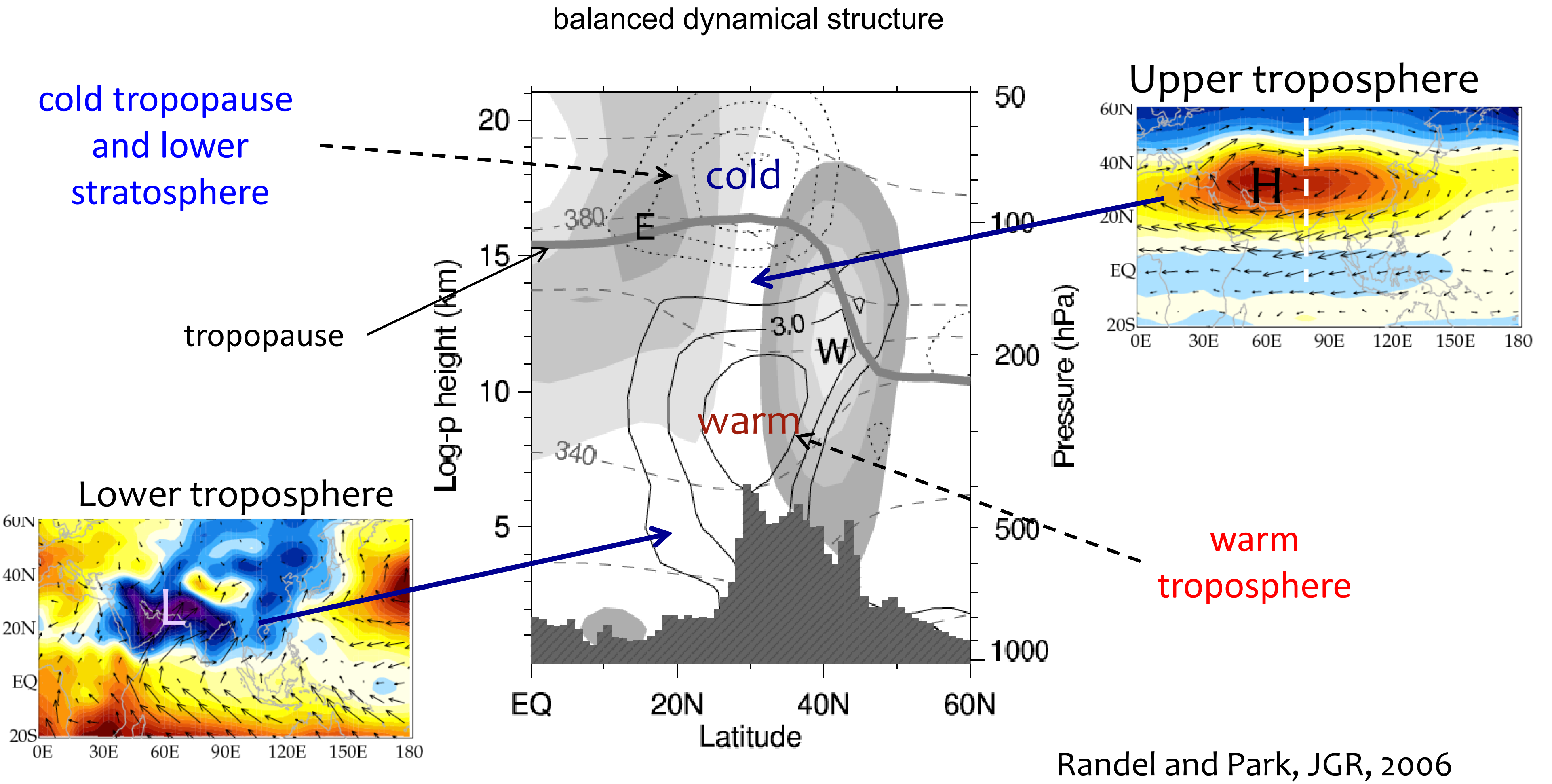
Convection (heating)



Matsuno-Gill Solution

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

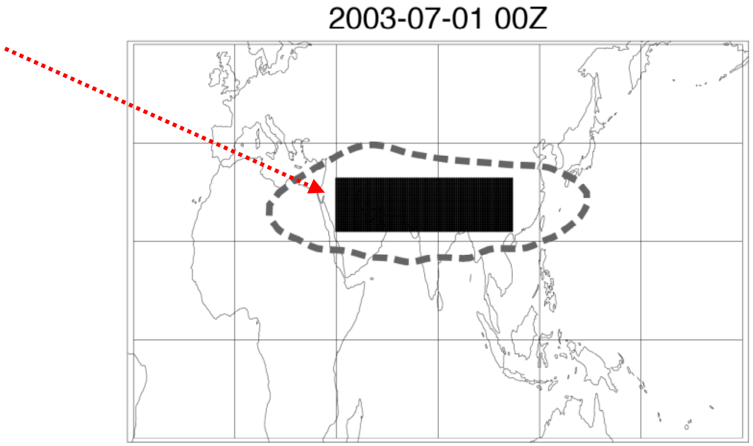
Anticyclonic circulation extends into lower stratosphere



Randel and Park, JGR, 2006

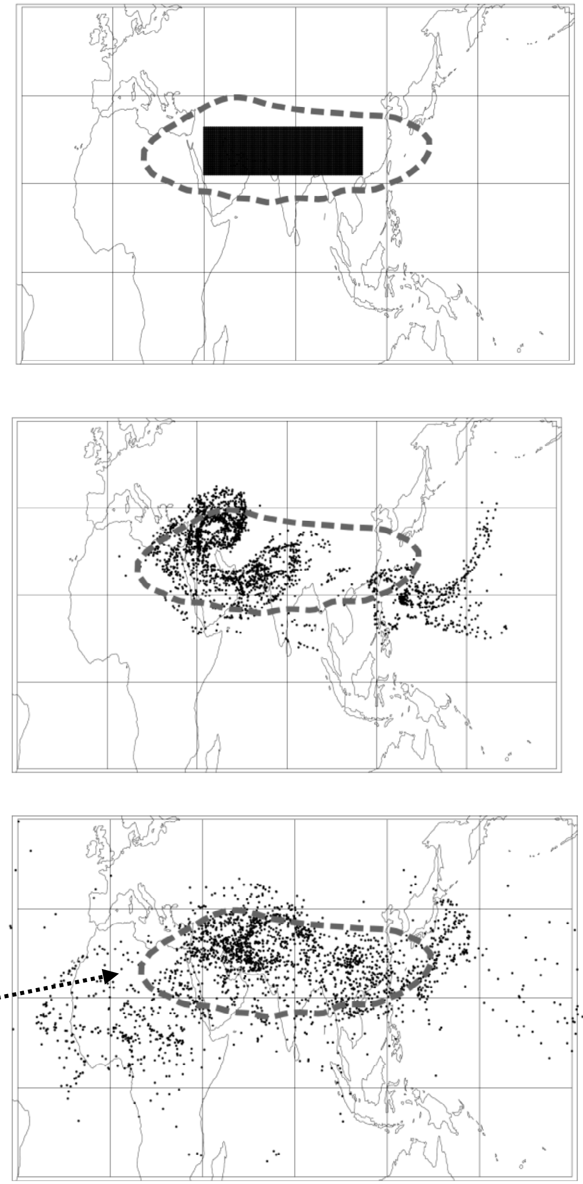
Confinement within the anticyclone: idealized transport experiments

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



Randel and Park, 2006, J. Geophys. Res.

transport simulation at 150 hPa



day 0

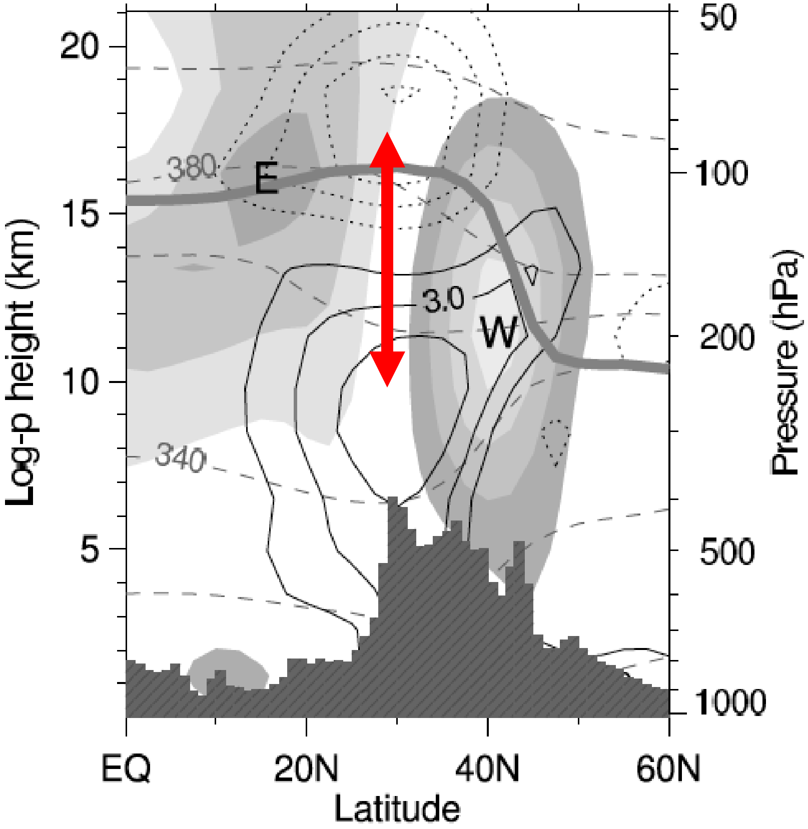
day 10

day 20

large fraction remain inside anticyclone

Randel and Park, 2006, J. Geophys. Res.

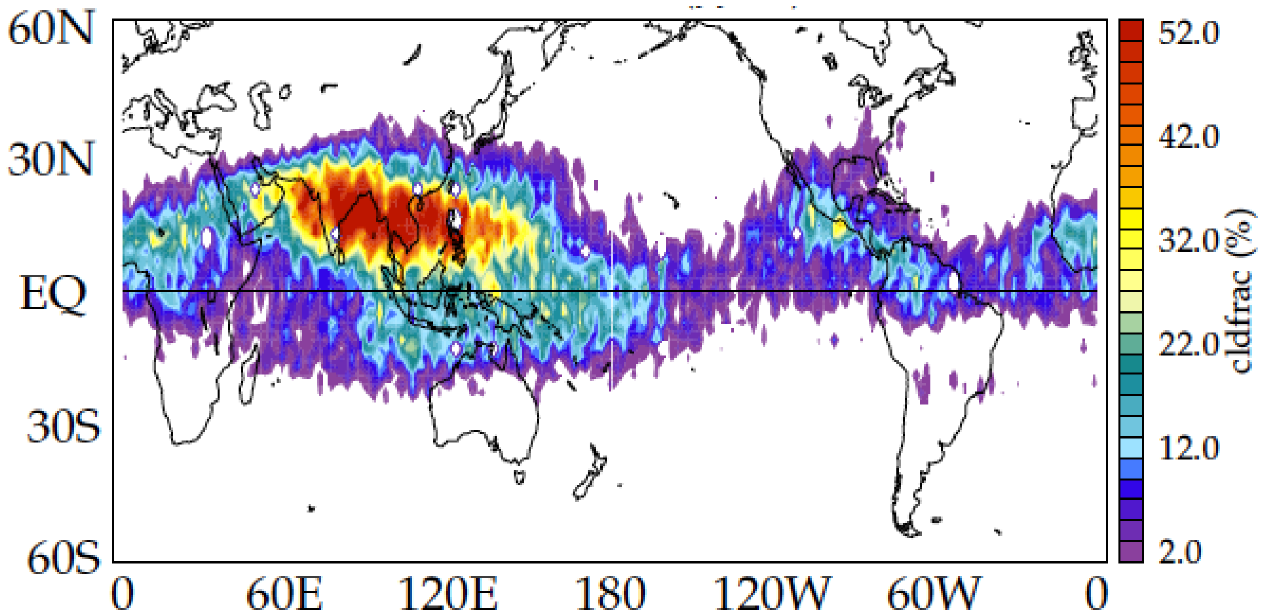
tests at different pressure levels show that confinement mainly occurs over altitudes with strongest winds



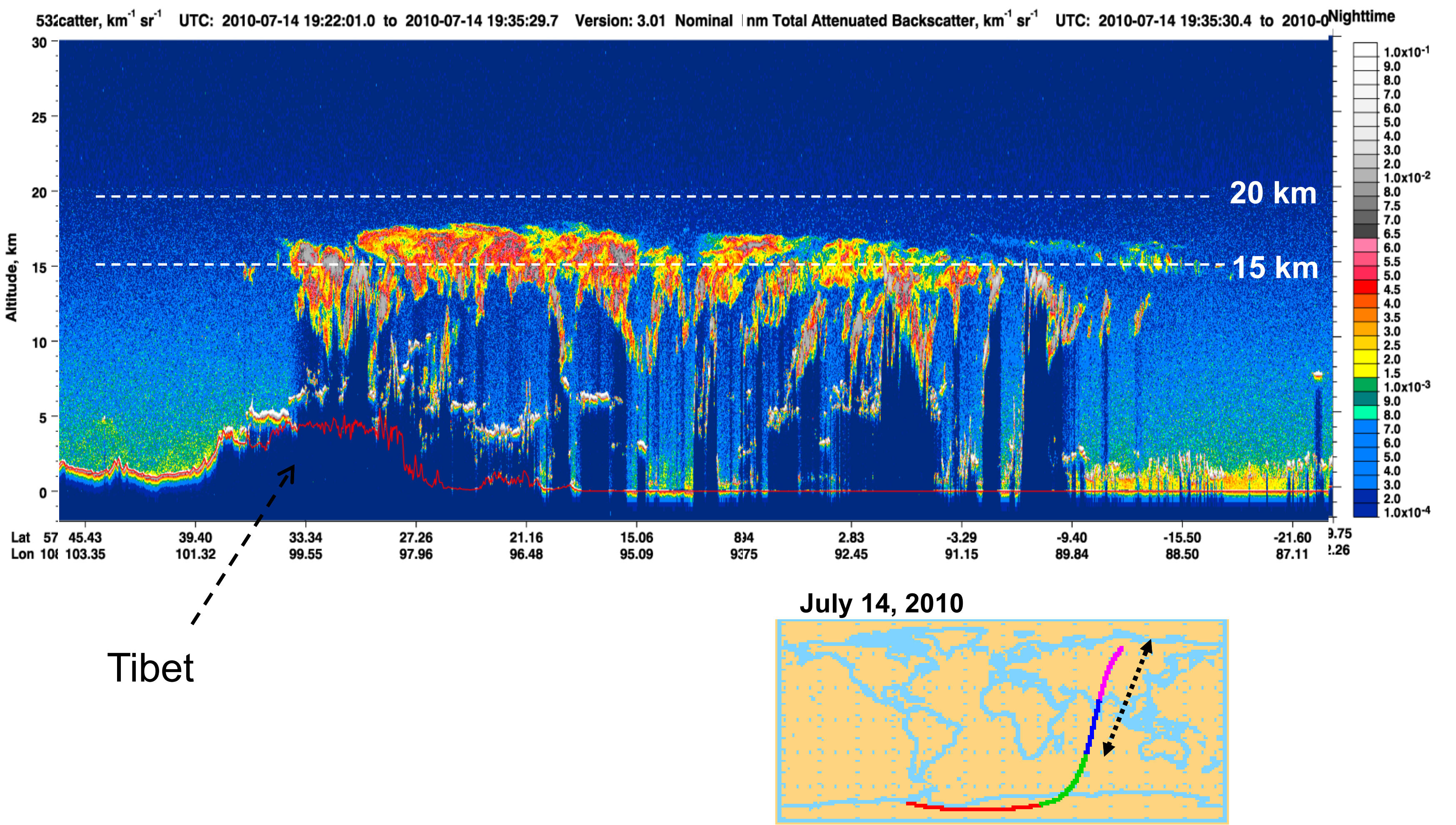
Randel and Park, 2006, J. Geophys. Res.

Frequent tropopause-level cirrus clouds in monsoon region

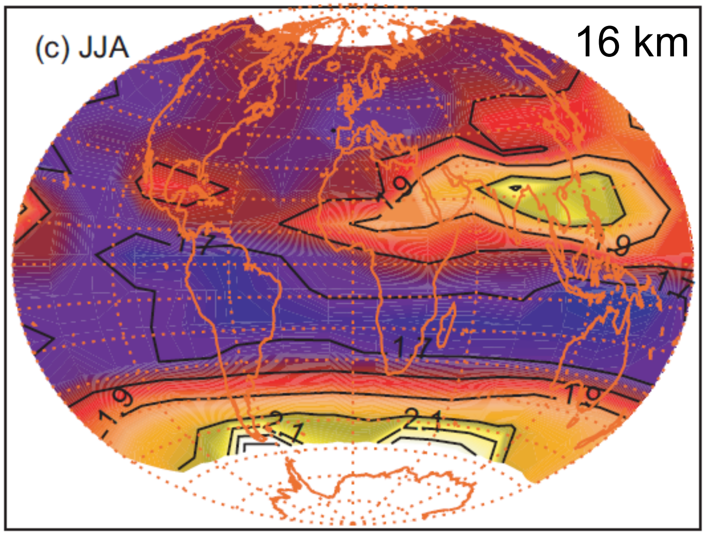
CALIPSO cloud fraction near 16 km



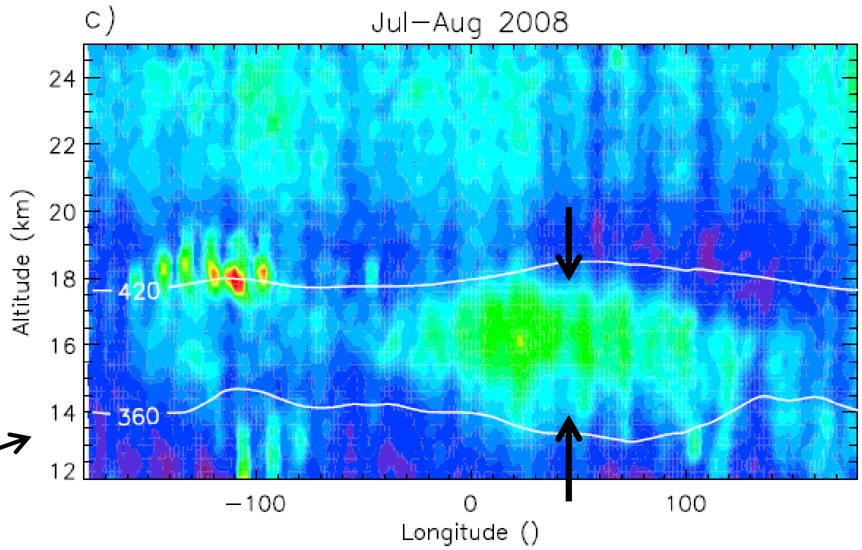
CALIPSO satellite lidar cloud observations



Monsoon aerosol layer near 16 km



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

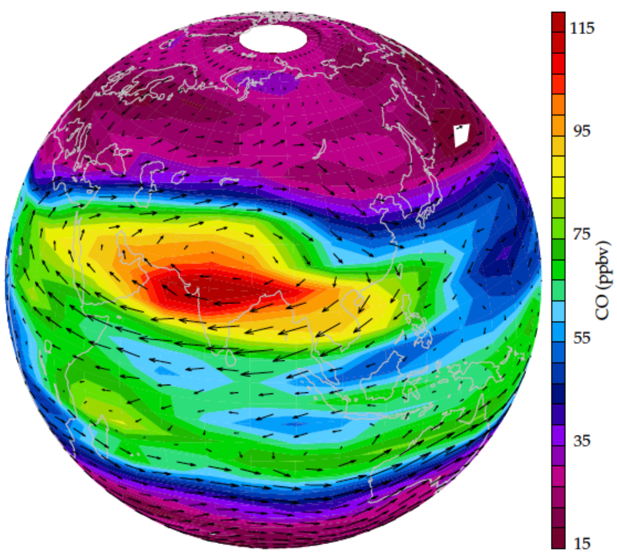


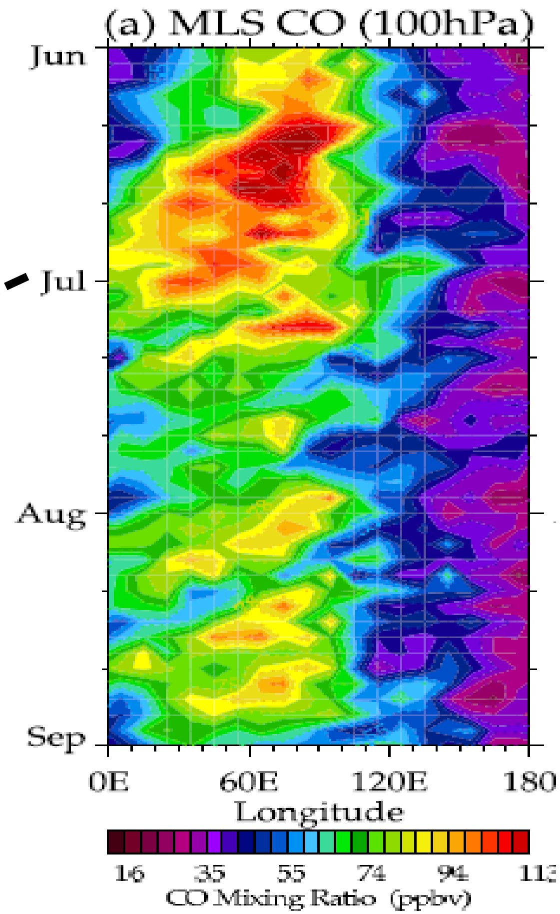
CALIPSO measurements
Vernier et al , GRL, 2011

Narrow layer near tropopause

strong chemical influence on summer UTLS

MLS 100 hPa
carbon monoxide (CO)



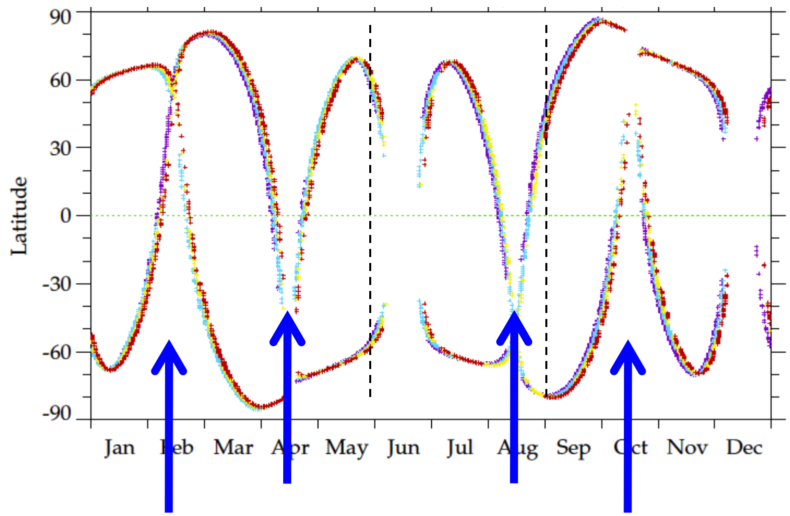


variability linked to monsoon convection

Park et al, JGR, ~~2008~~2007, 2009

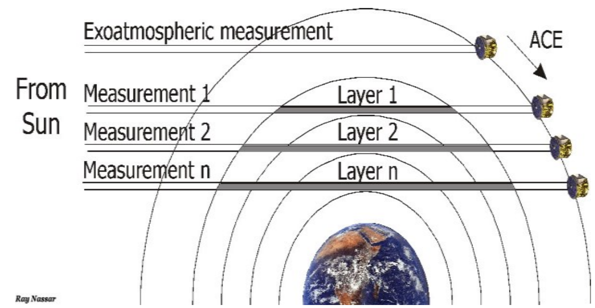
ACE Fourier Transform Spectrometer

ACE occultations, 2004-2006



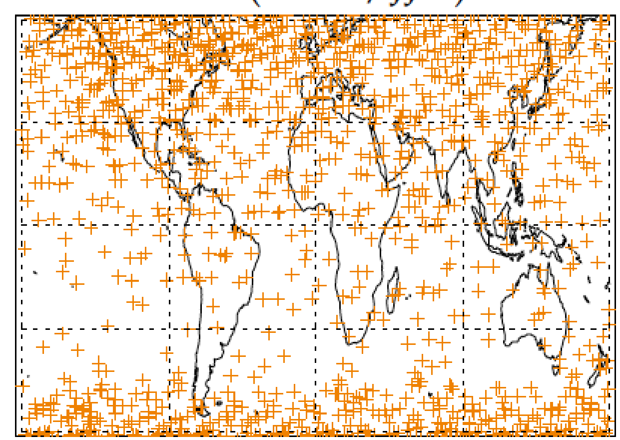
Low latitudes: 4 samples / year

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



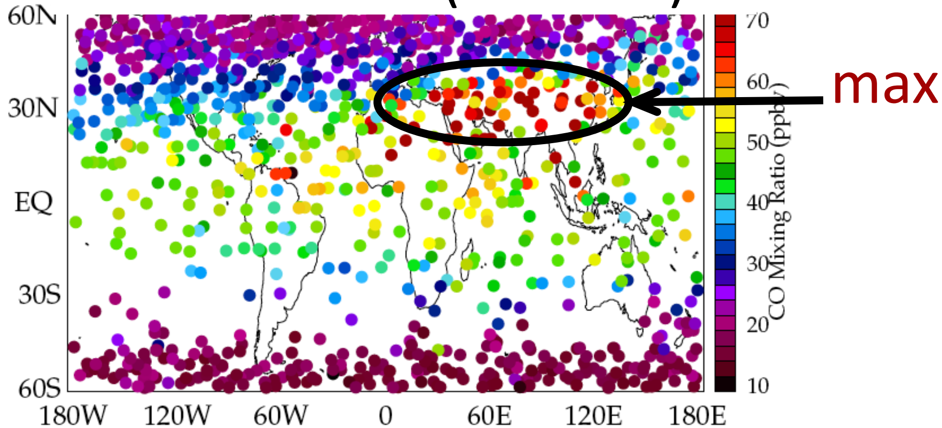
All observations for June-August

ACE-FTS (04-06/JJA) 1233

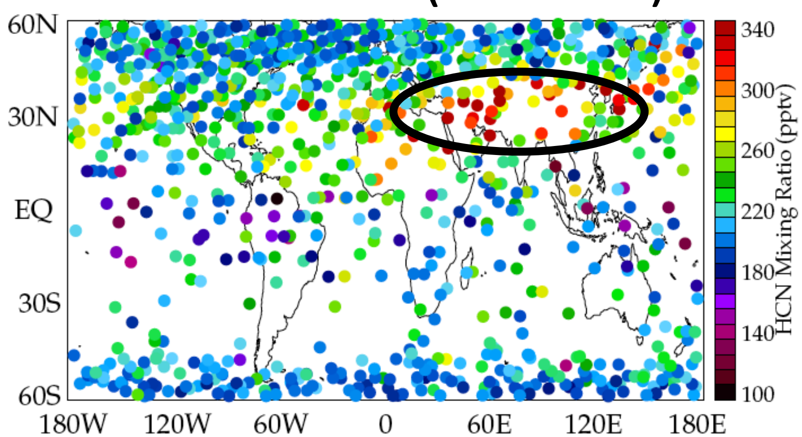


ACE measurements JJA 2004-2006

ACE CO (16.5 km)

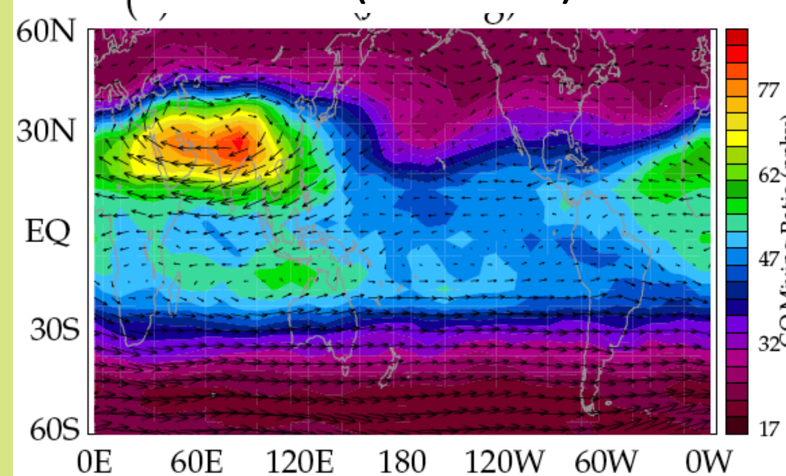


ACE HCN (16.5 km)



Park et al., 2008, Atmos. Chem. Phys.

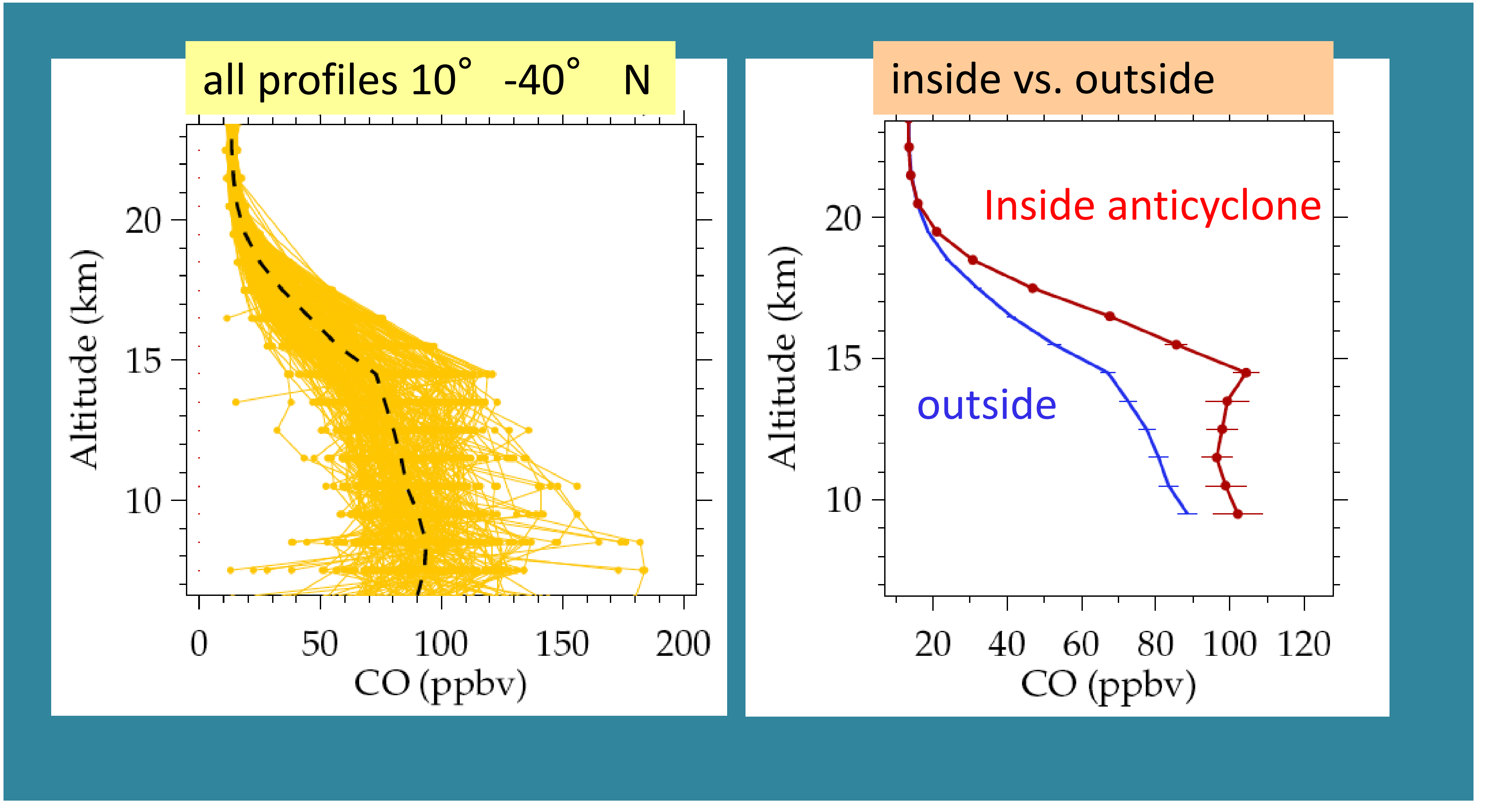
MLS CO (100 hPa)



High CO and HCN are associated with the Asian monsoon anticyclone

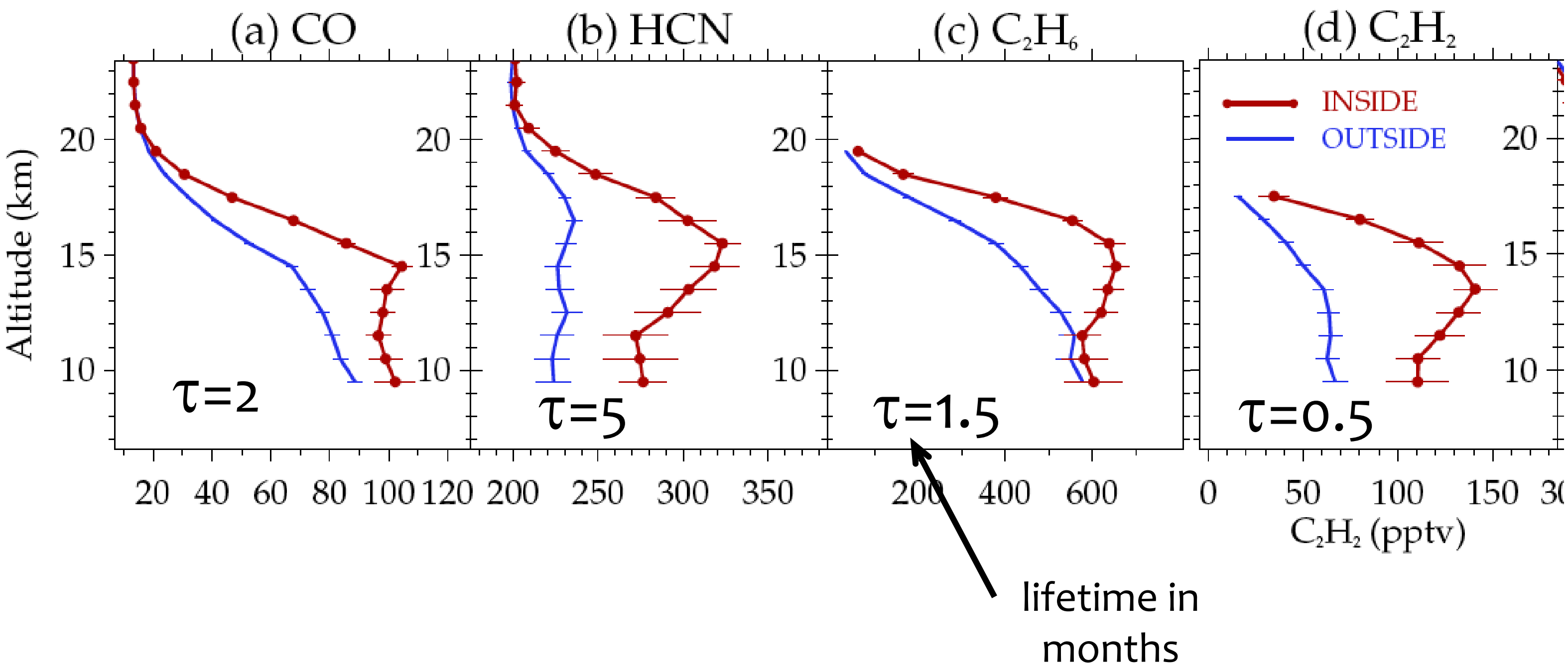
Park et al., 2007, J. Geophys. Res.

ACE-FTS CO Profiles



other tropospheric tracers

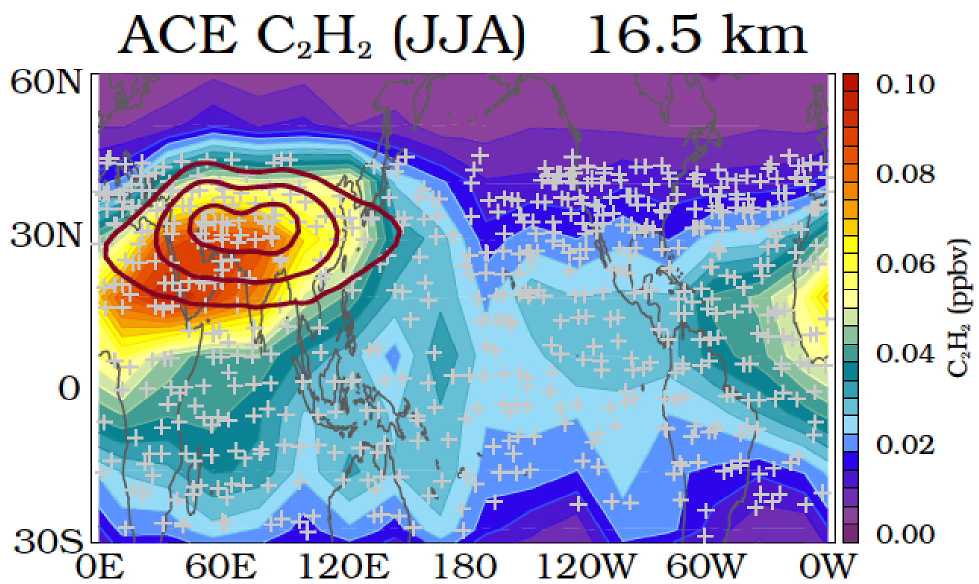
enhancement inside the anticyclone up to ~20 km



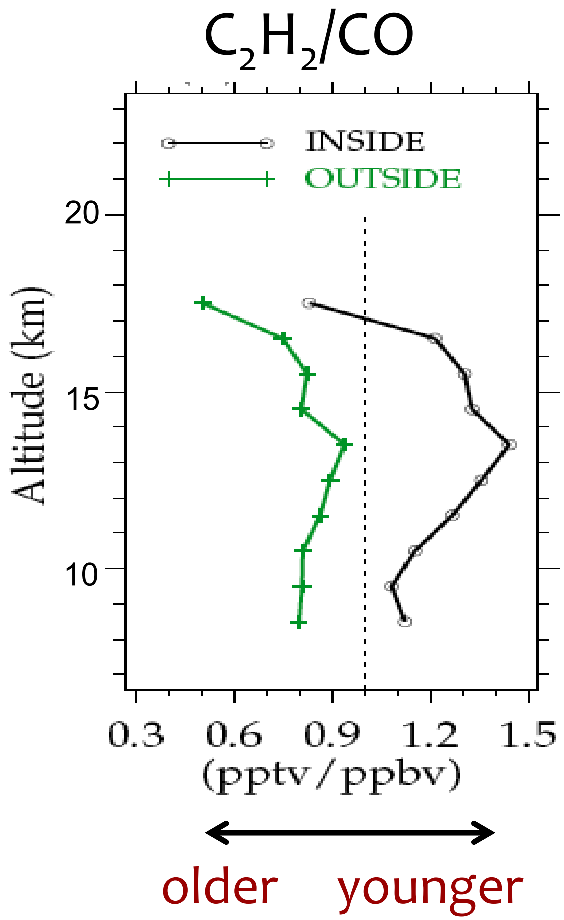
C_2H_2 measurements from ACE-FTS satellite

photochemical lifetime ~ 2 weeks

evidence of relatively rapid transport to the UTLS



C_2H_2/CO ratio ~ measure of photochemical age



relatively young air inside the anticyclone, up to ~17 km

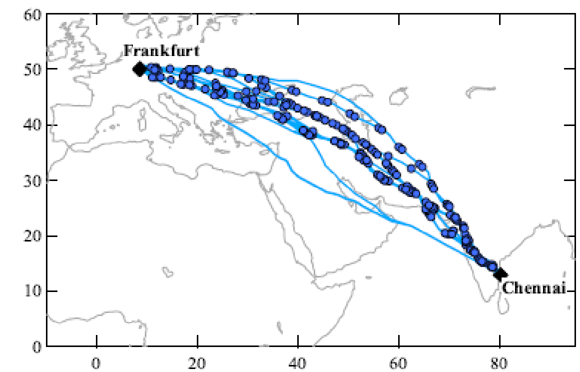
Atmos. Chem. Phys., 10, 3965–3984, 2010
www.atmos-chem-phys.net/10/3965/2010/

Atmospheric Chemistry and Physics

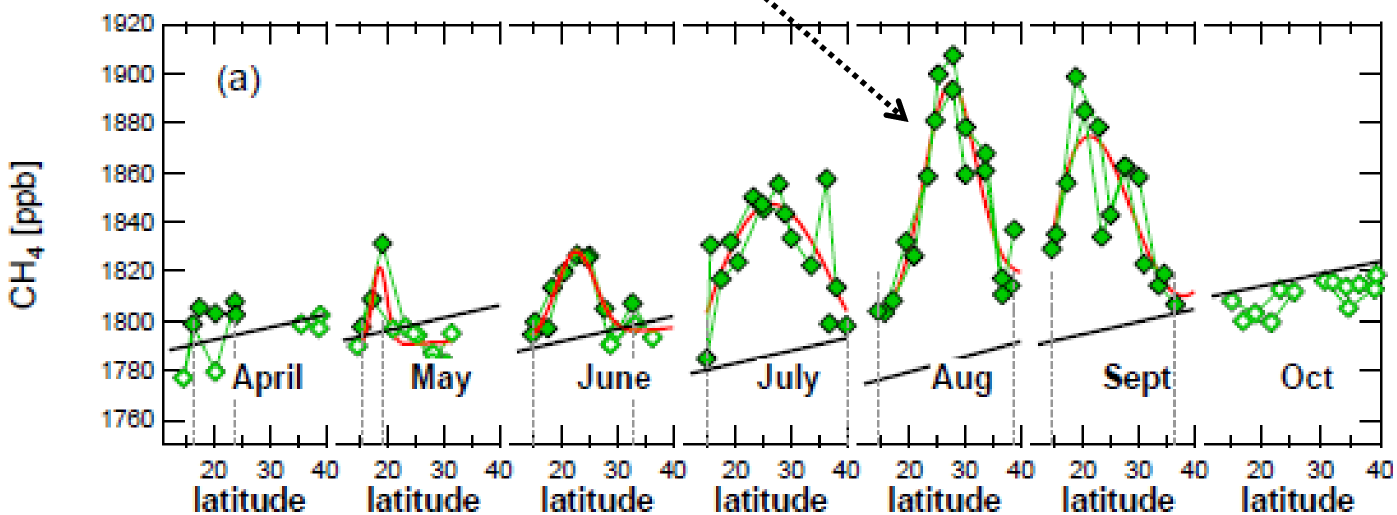
Aircraft measurements

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]



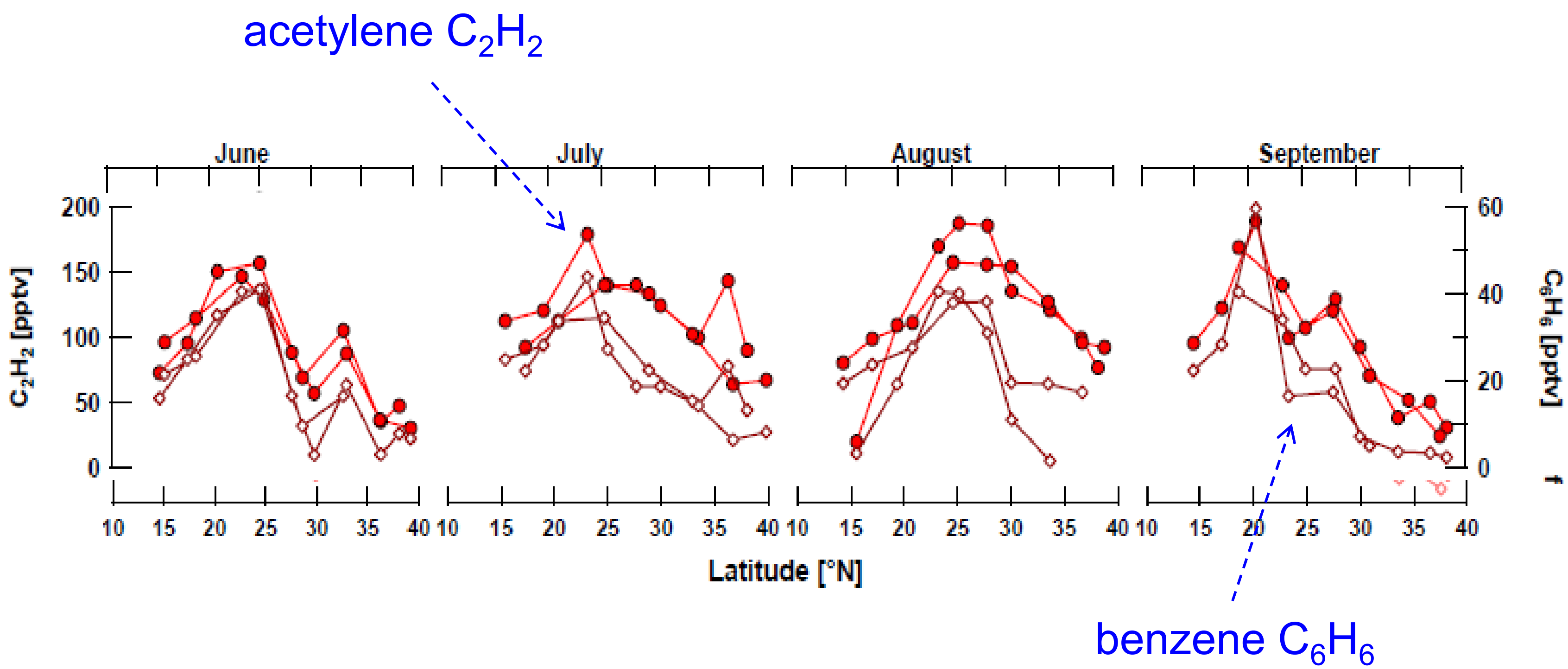
Enhanced CH_4 within anticyclone



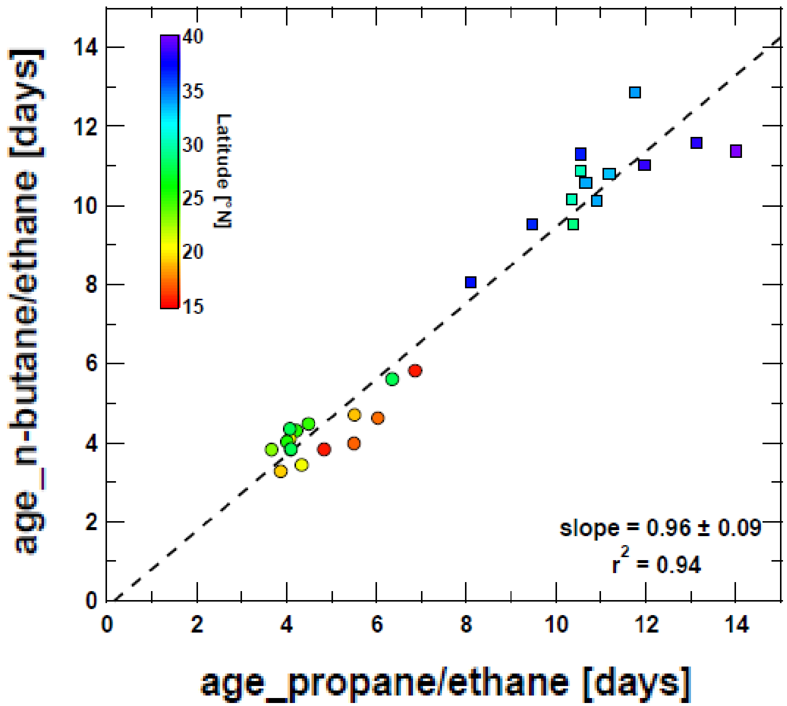
Characterization of non-methane hydrocarbons in Asian summer monsoon outflow observed by the CARIBIC aircraft

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



Age of air estimated from short-lived hydrocarbons



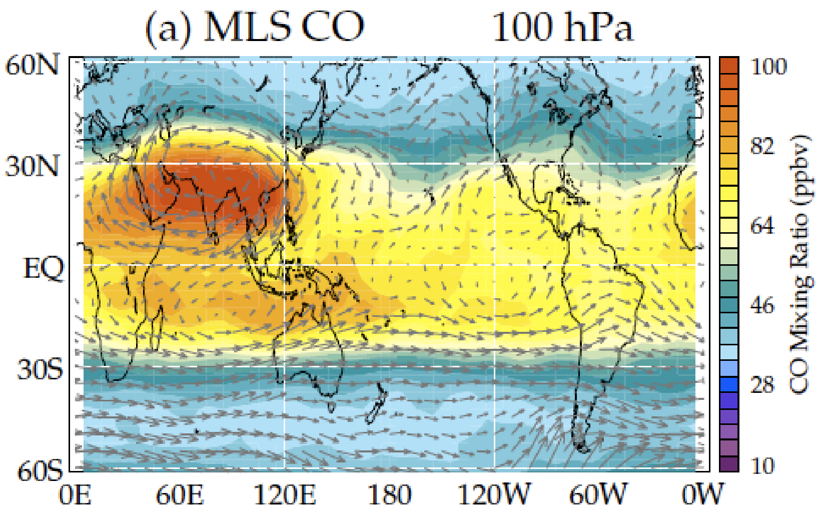
Result: air is relatively young: ~5-12 days

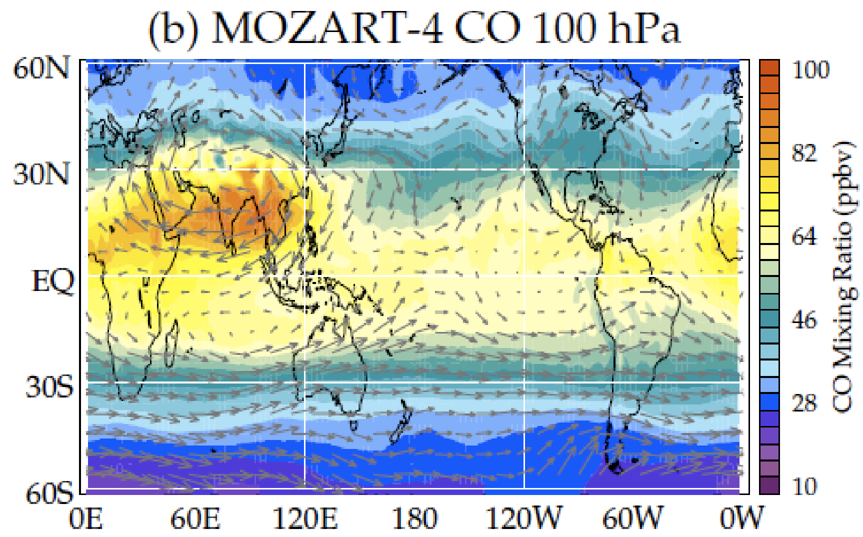
Baker et al, ACP, 2011

chemical transport models can simulate observed large-scale behavior

MLS observations

MOZART simulation



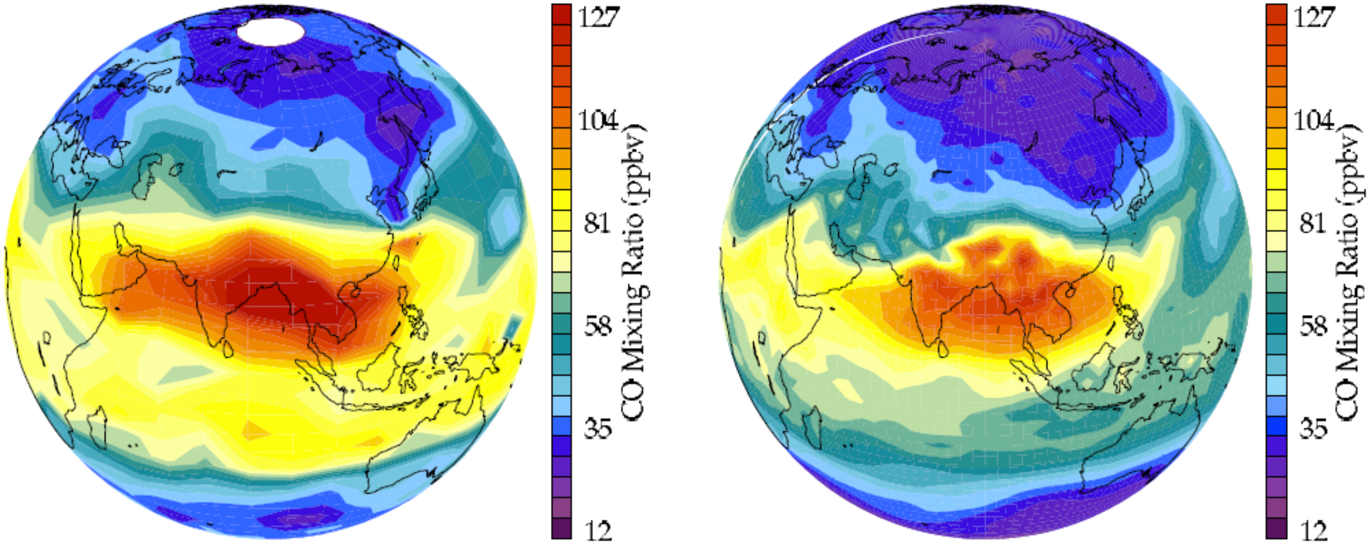


Park et al, JGR, 2009

simulation for one day

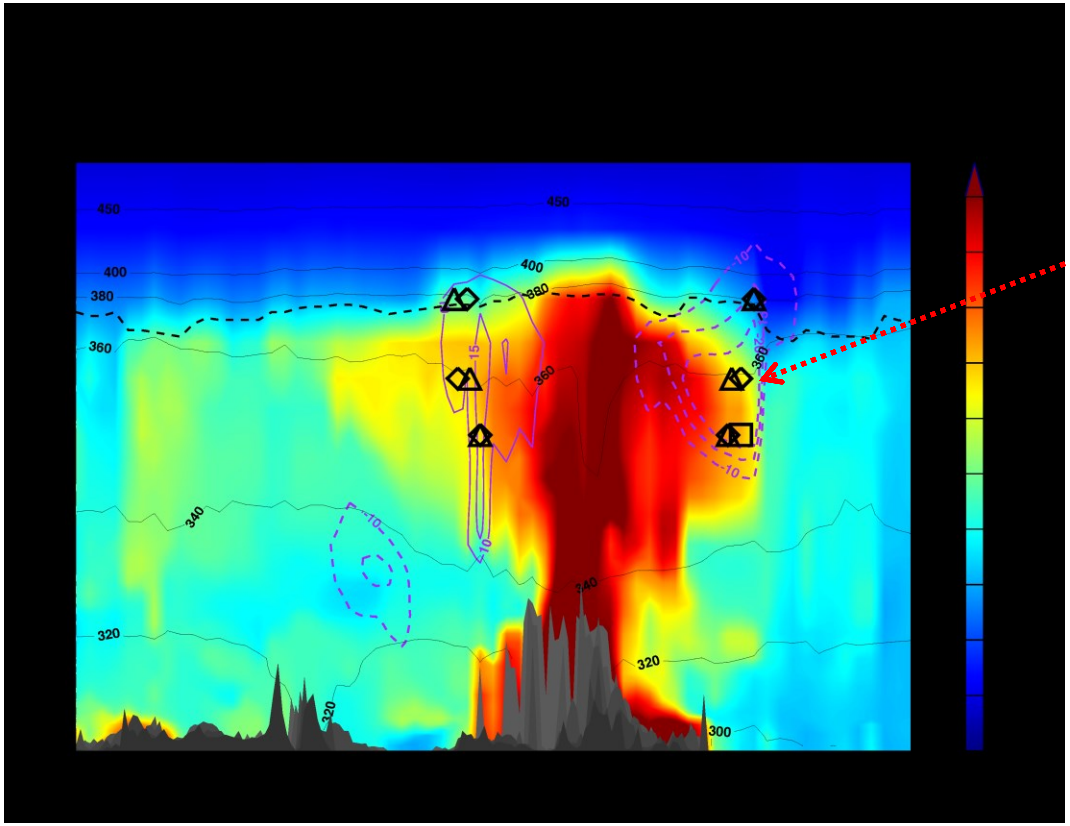
100 hPa

MLS observations **MOZART simulation**



Park et al, JGR, 2009

Vertical structure of CO from model simulation

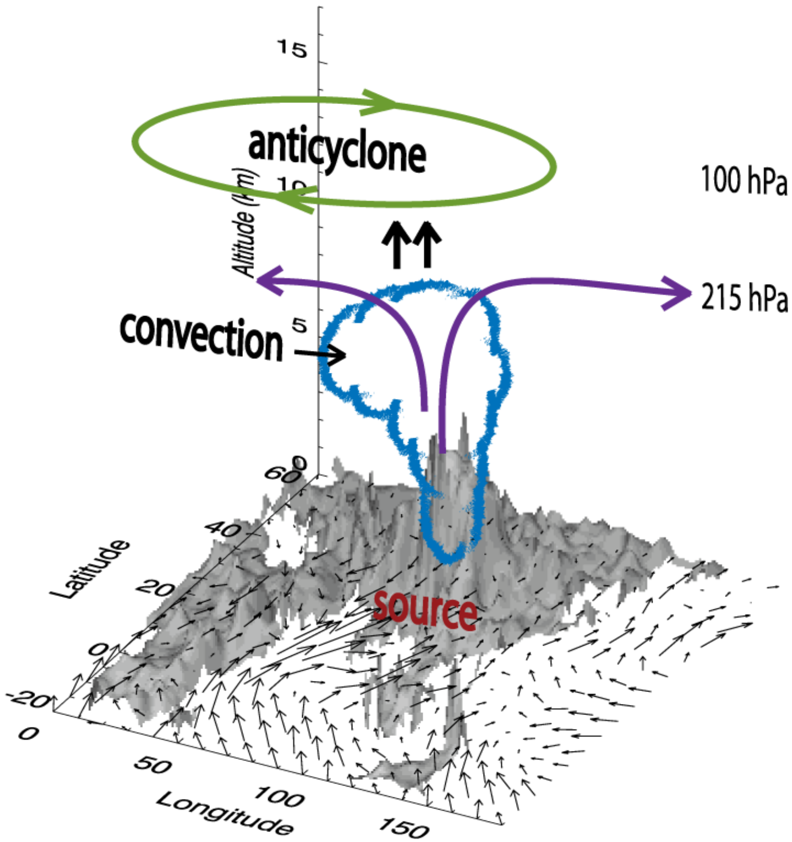


dynamical 'edge' of anticyclone

<u>Questions:</u>

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

Transport pathways derived from observations and models



Park et al, JGR, ~~2008~~2007, 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

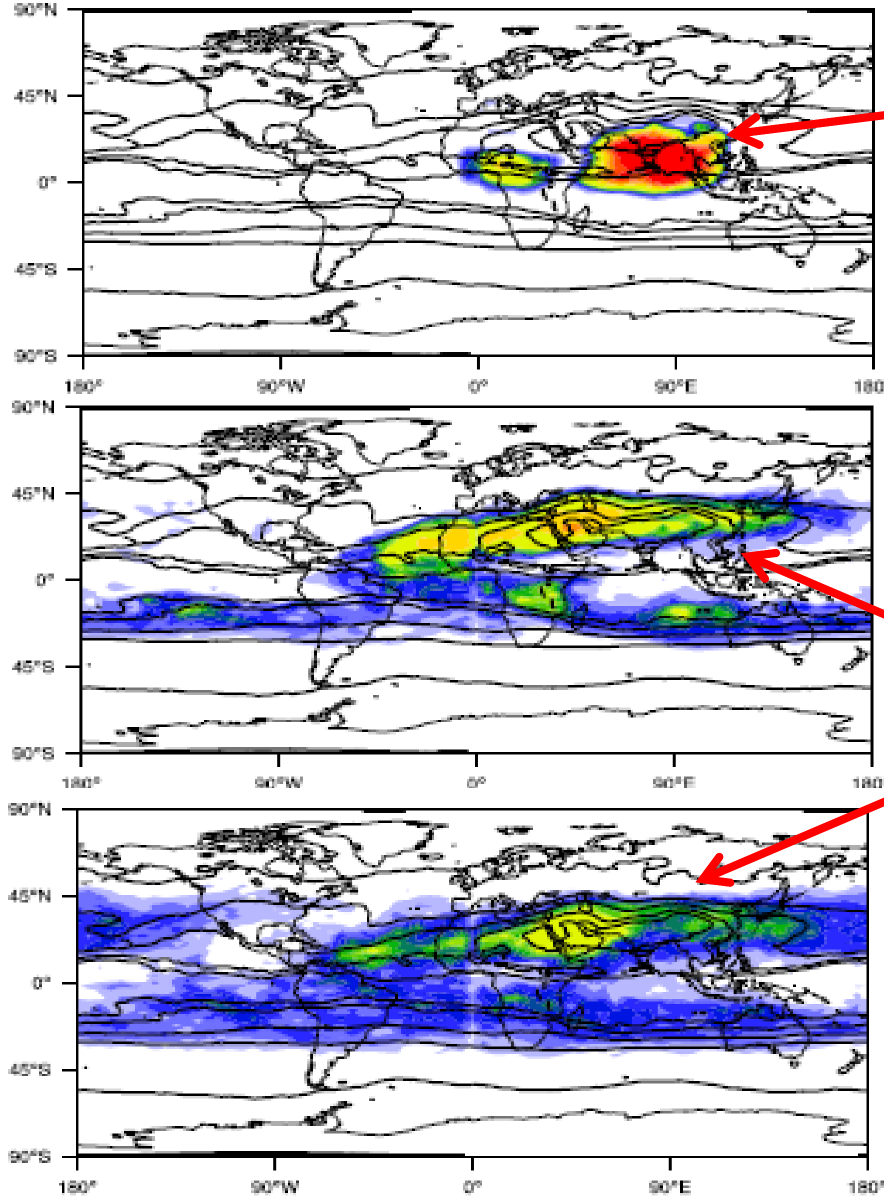
•cold tropopause, frequent clouds, aerosol layer

•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?

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



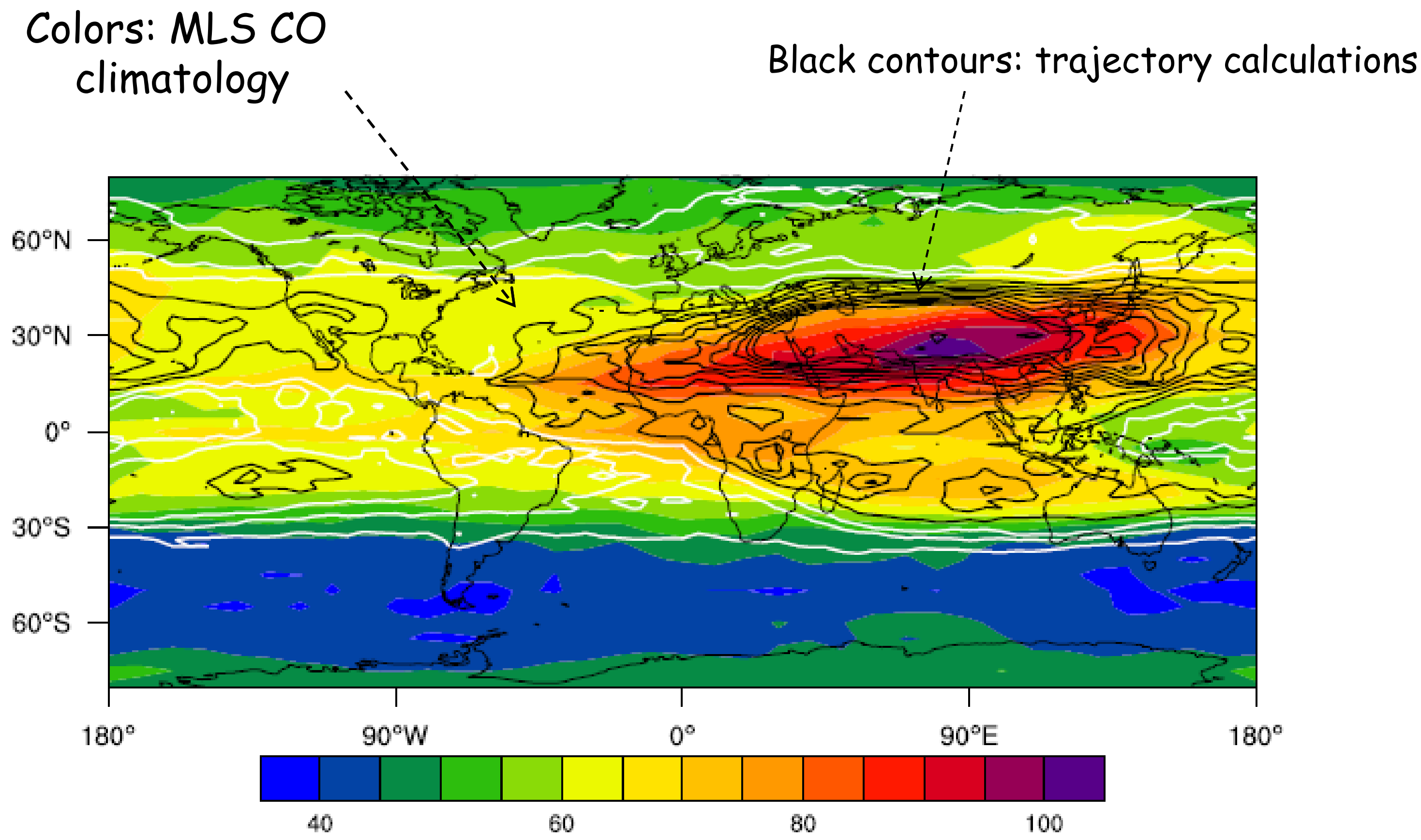
+ 10 days

+ 20 days

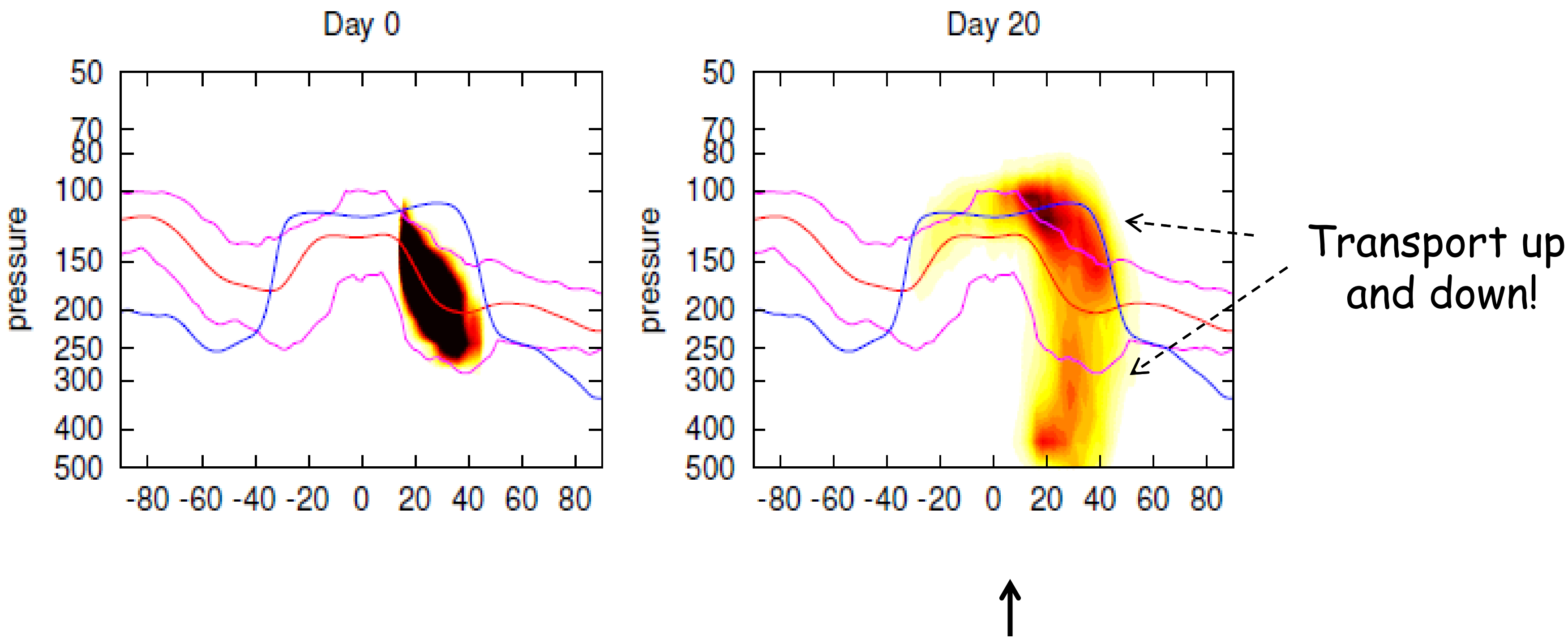
confinement within anticyclone

from Hella Garney

Comparison of trajectory calculations with MLS CO climatology



Three-dimensional diabatic trajectories



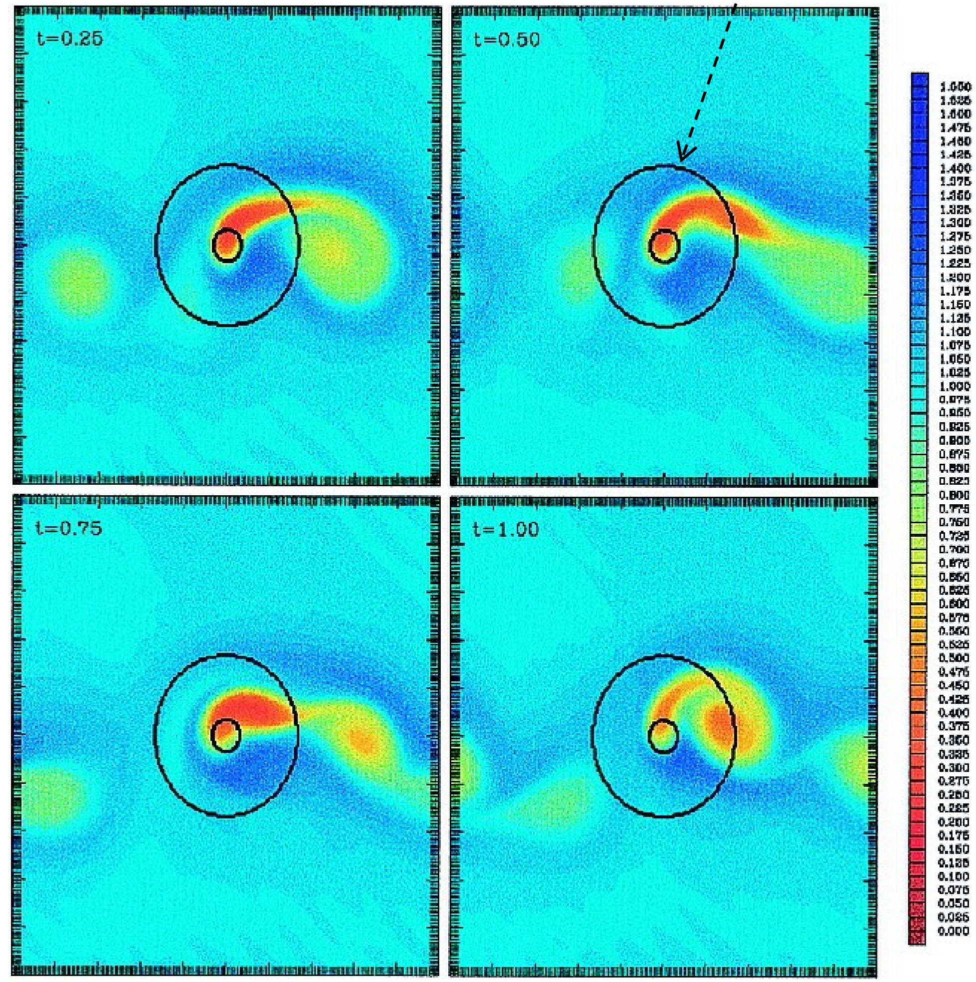
Note: this is work in progress, and not well understood yet

Monsoon circulation is inherently unstable

Hsu and Plumb 2000 JAS

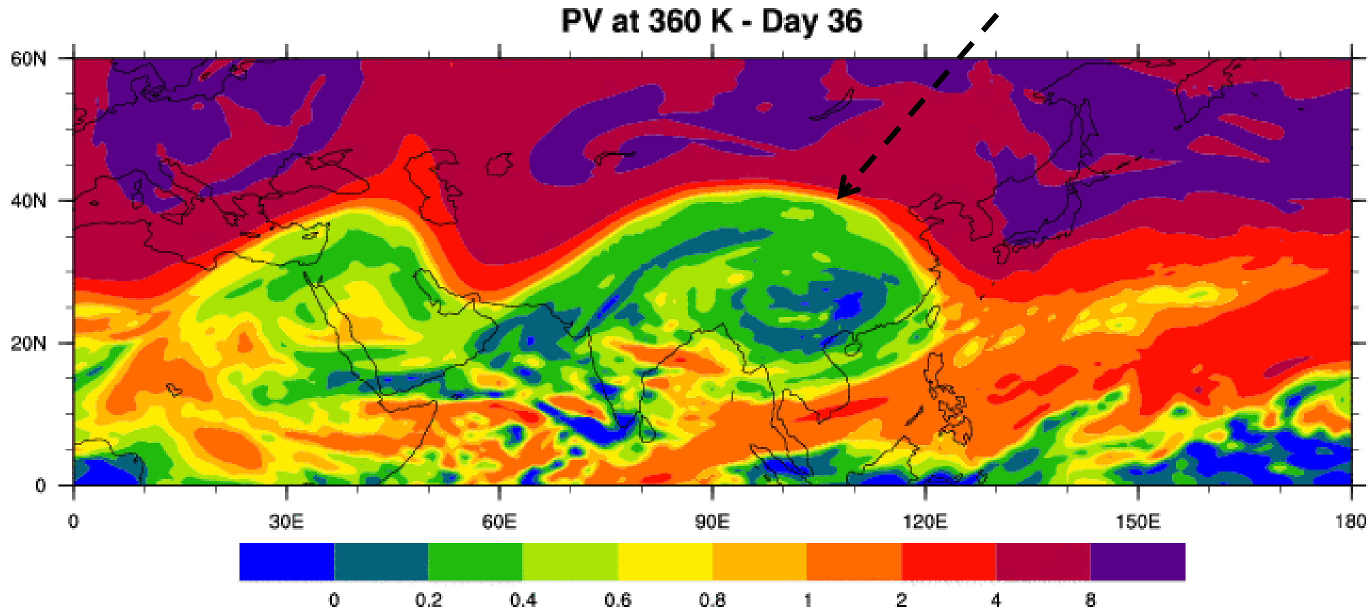
'eddy shedding' from monsoon circulation

time-independent divergence forcing



Anticyclone viewed in potential vorticity

relatively low PV

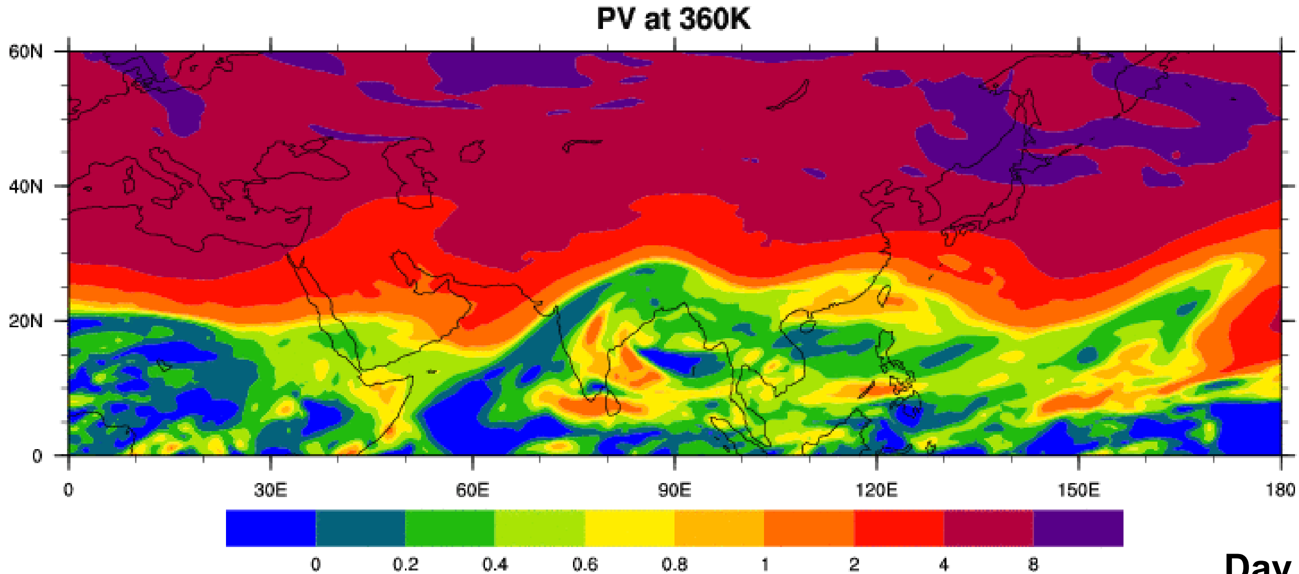


Dynamic variability of the Asian monsoon anticyclone observed in potential vorticity and correlations with tracer distributions

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

JGR 2013

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

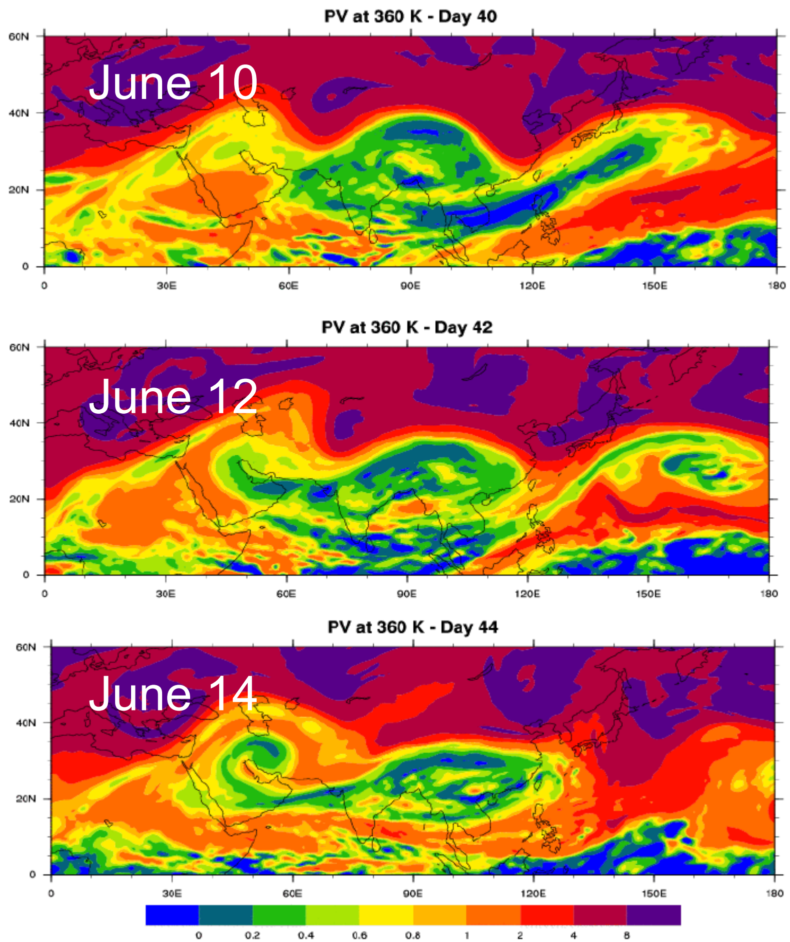


Day 1 = May 1
32 June 1
62 July 1
93 Aug 1
123 Sept 1

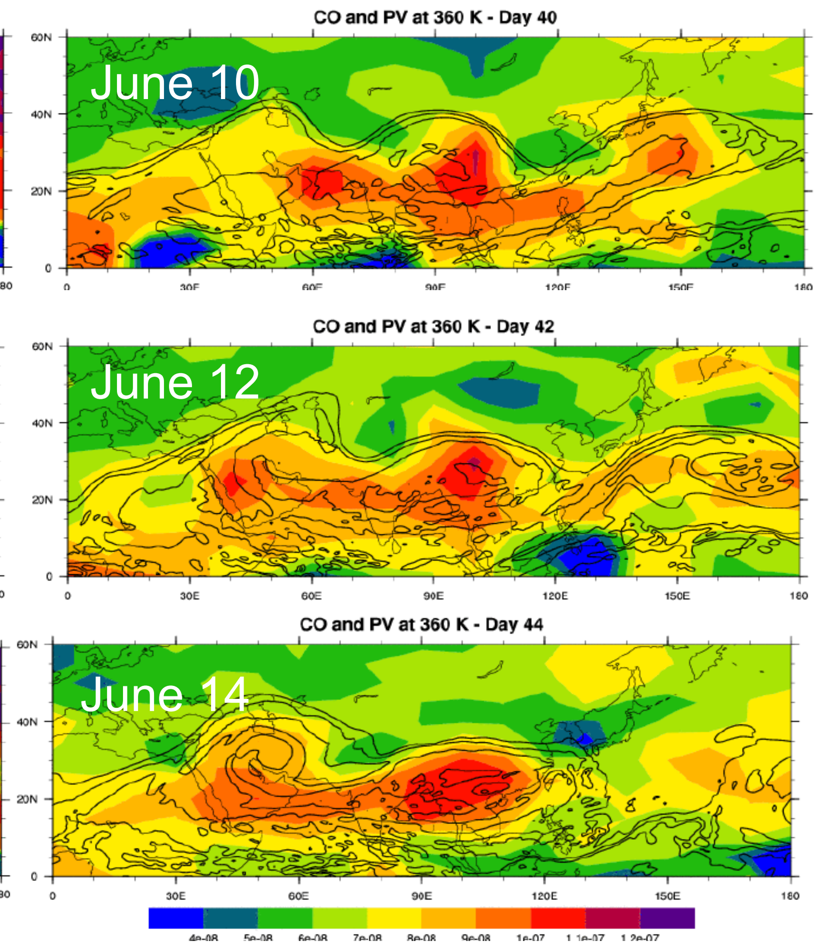
Garny and Randel, 2013, J. Geophys. Res.

Dynamical variability echoed in tracers

PV at 360 K



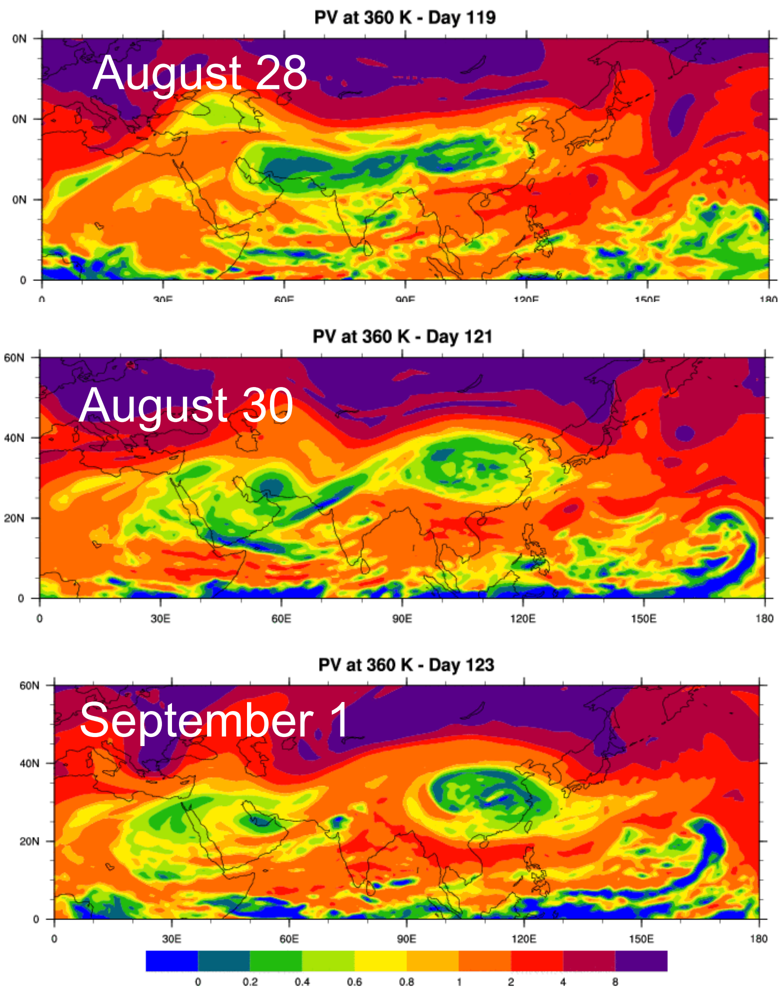
CO from Aura MLS



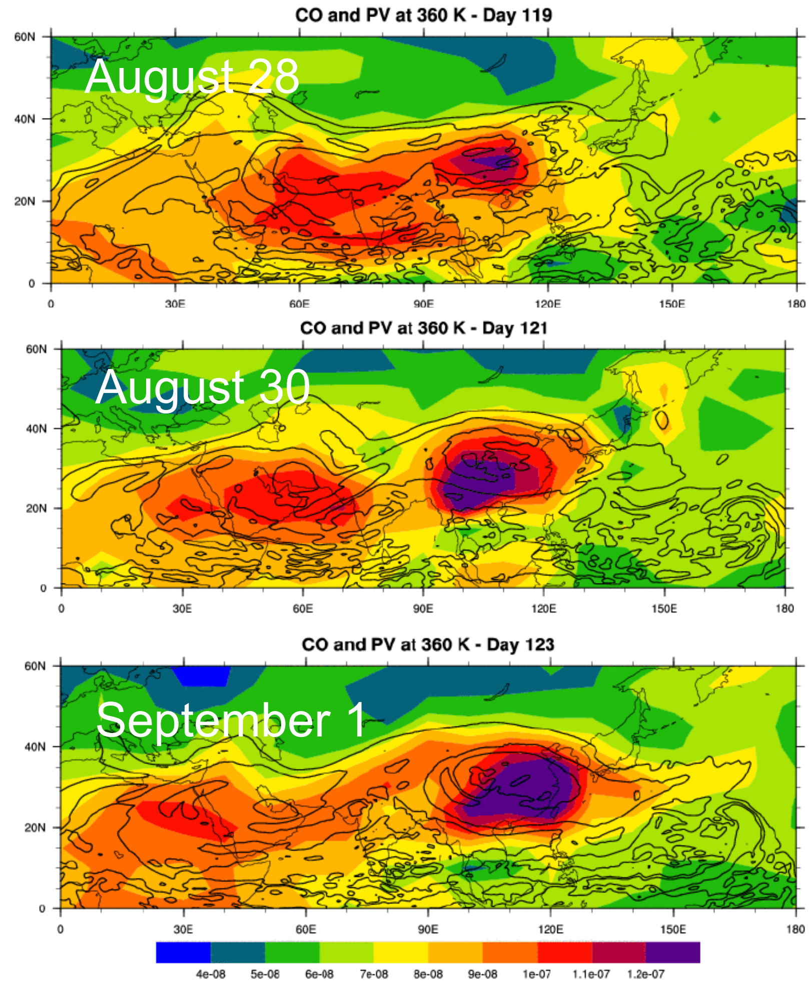
Garney and Randel, 2013, JGR

Another example

PV at 360 K



CO from Aura MLS

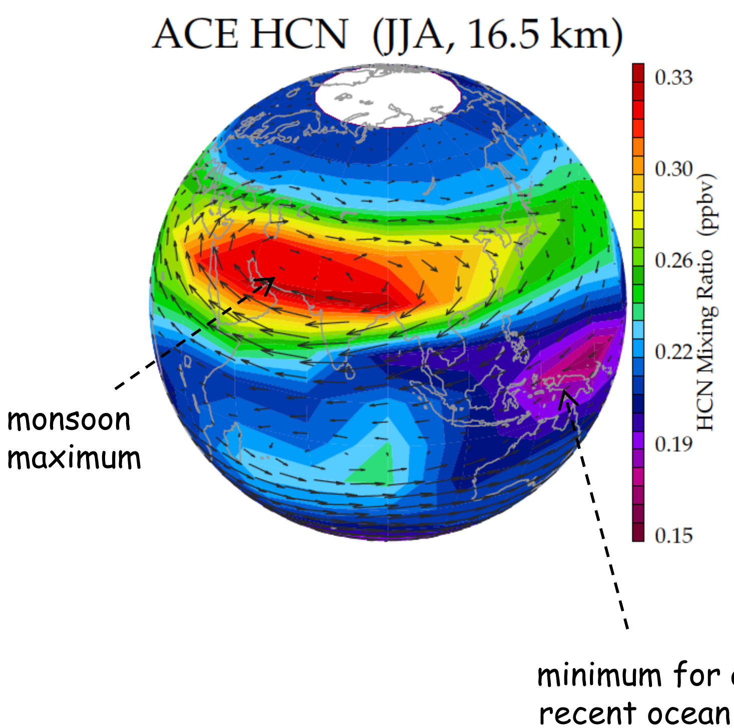


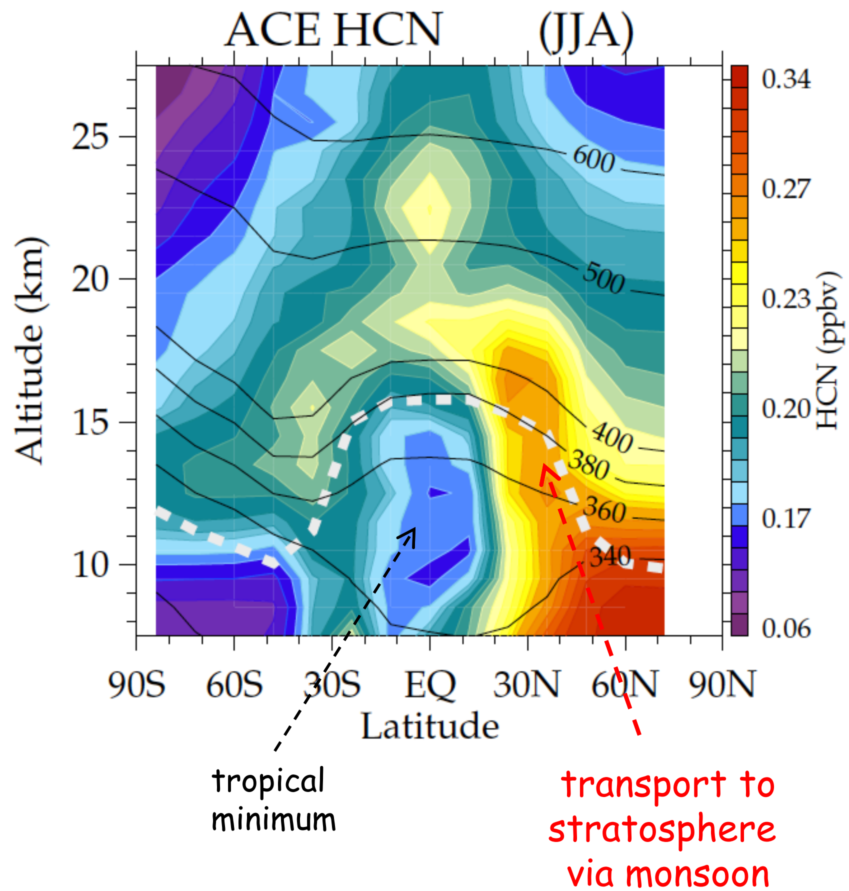
Garny and Randel, 2013, J. Geophys. Res.

Transport to the stratosphere via the monsoon anticyclone

<u>HCN – biomass burning tracer</u>

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

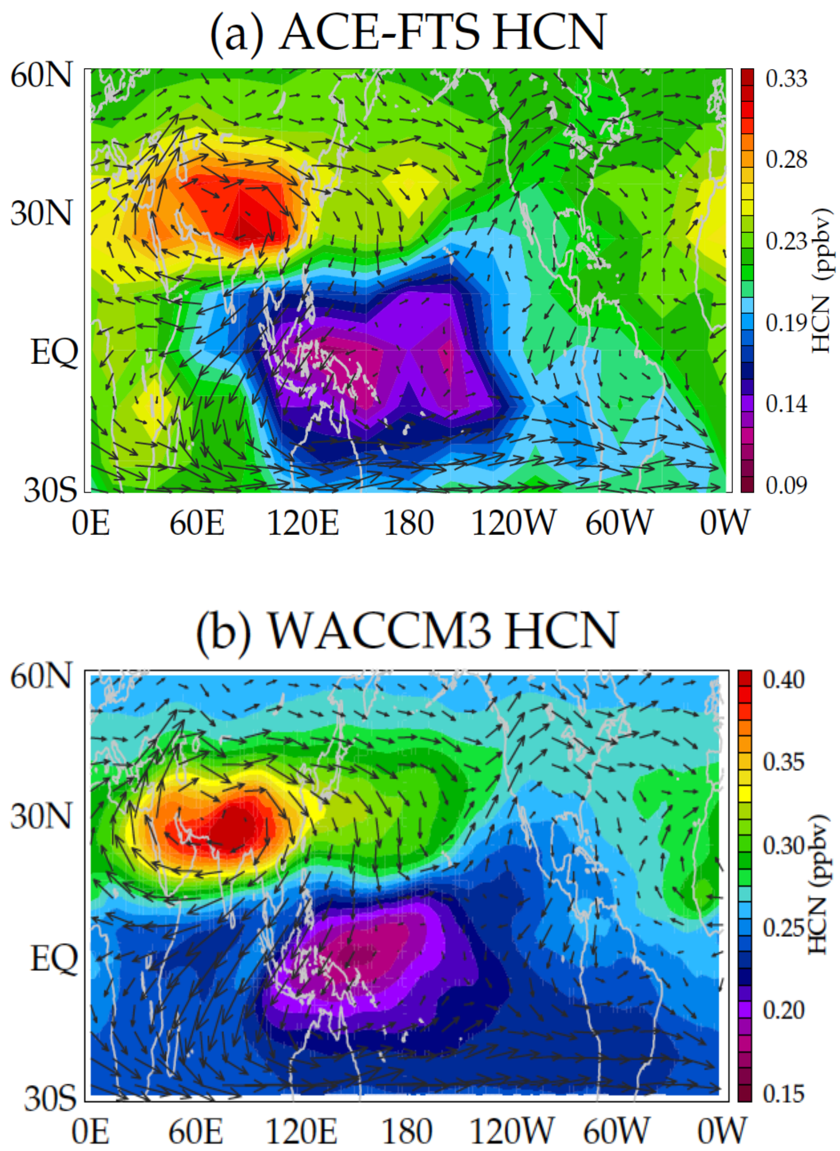




JJA

WACCM simulation of HCN

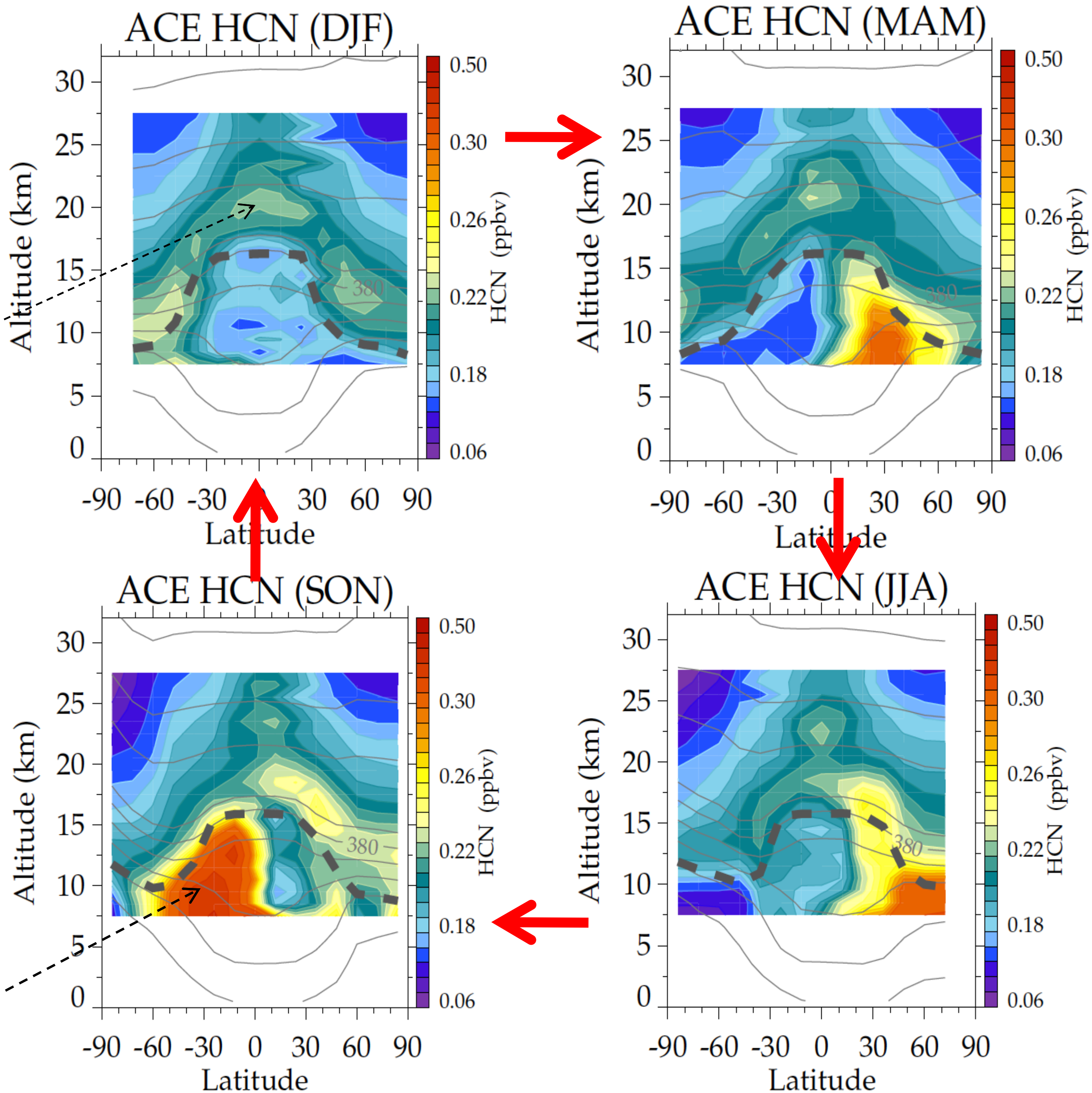
- climatological emission sources
- parameterized ocean sink



ACE

WACCM

Seasonal cycle of HCN from ACE-FTS

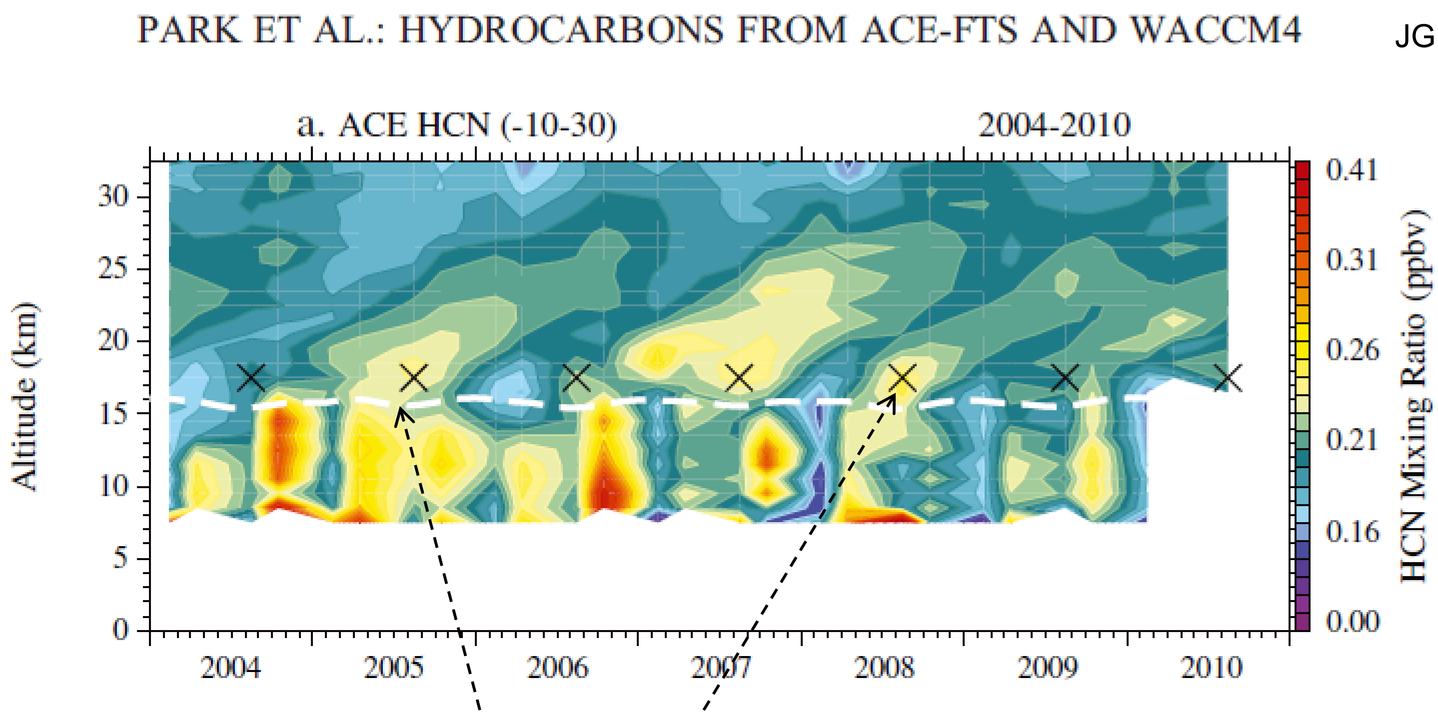


maxima persist in stratosphere because of long HCN lifetime

Africa and S. America biomass burning

HCN 'tape recorder' from ACE-FTS measurements

JGR, 2013

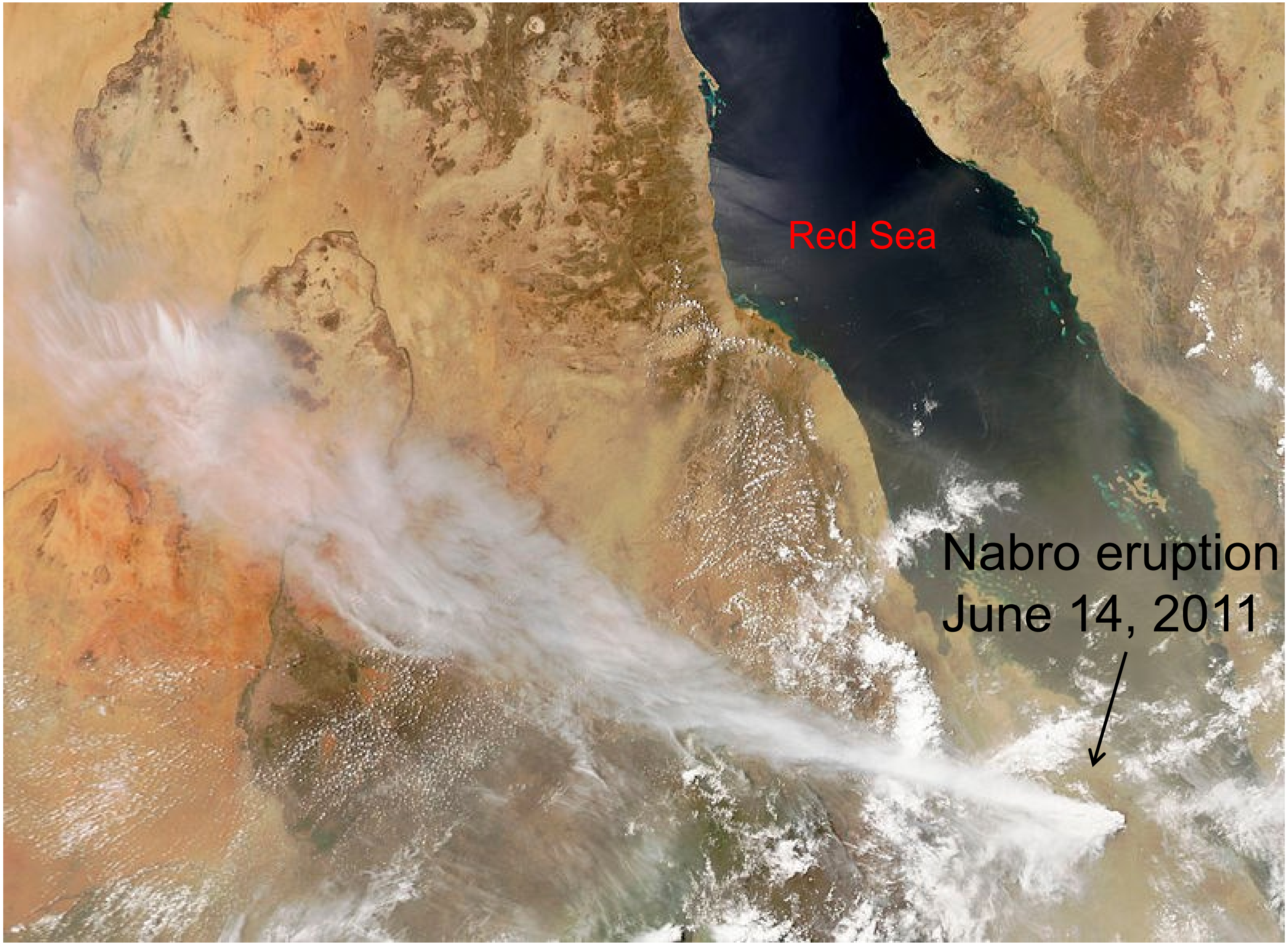


boreal summer maxima from
Asian monsoon circulation

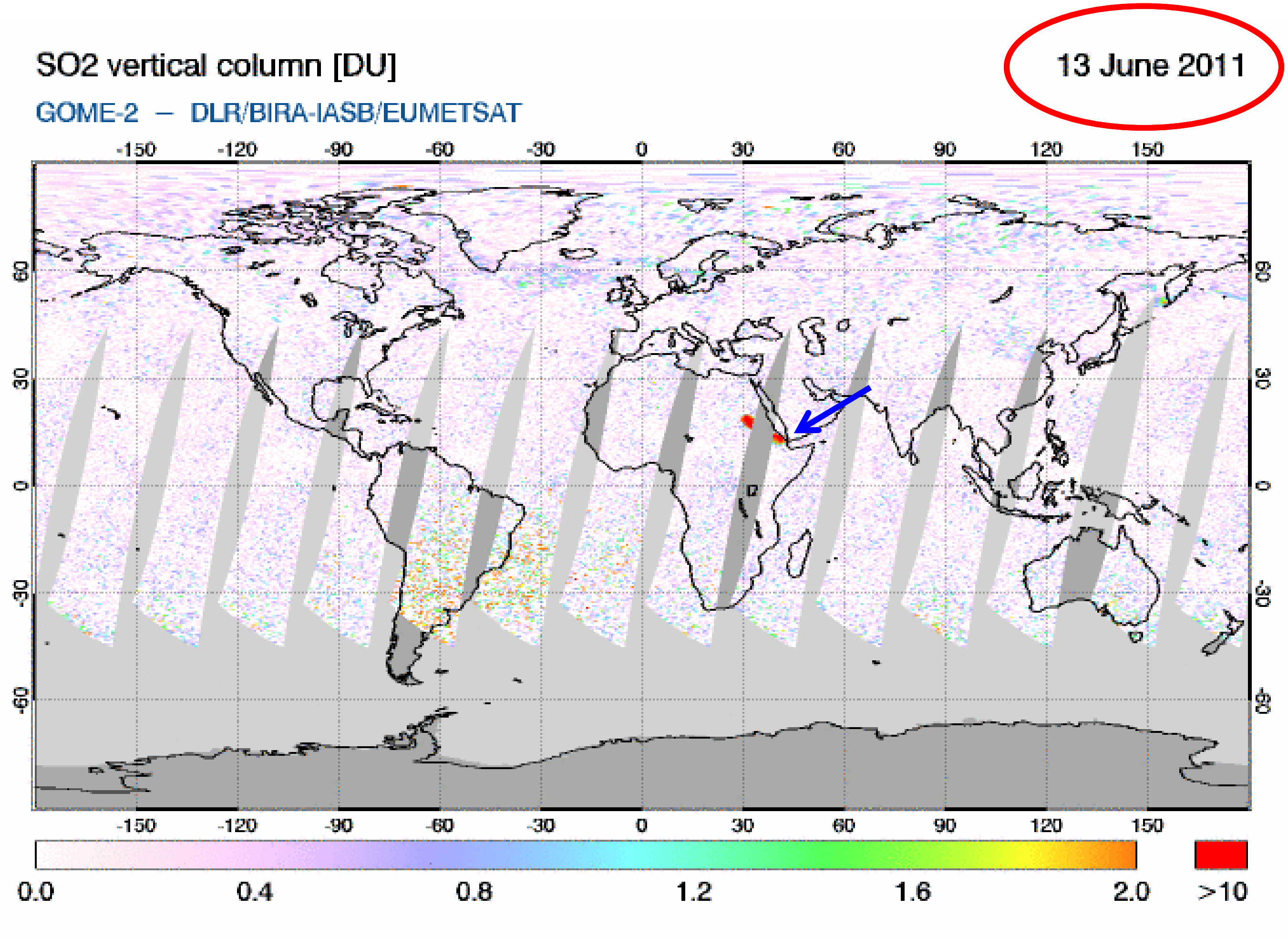
Key points:

- Trajectory studies valuable for understanding fate of convective outflow
- Fundamental instability of anticyclone: eddy shedding
- HCN provides evidence for monsoon transport to stratosphere

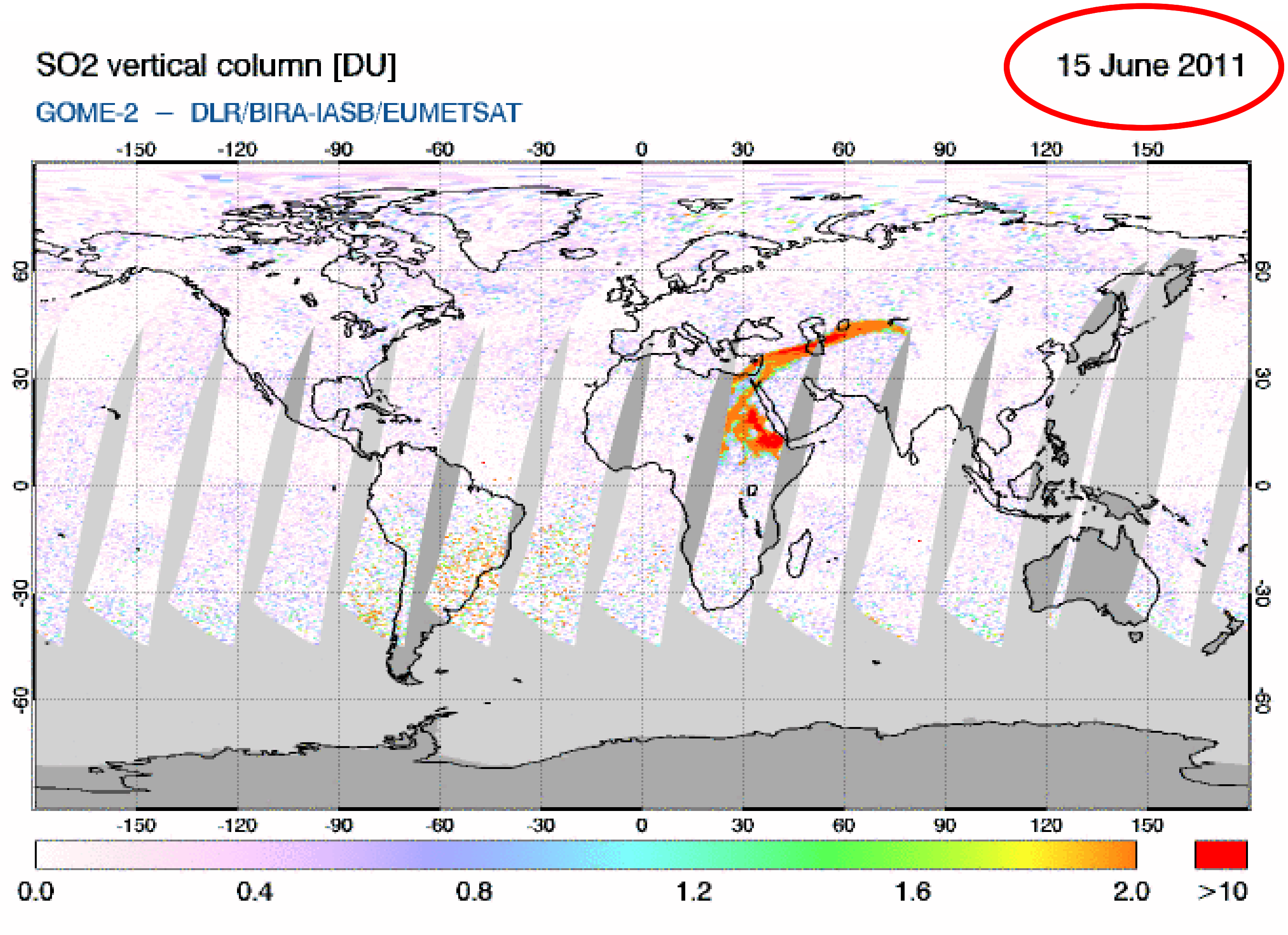
Eruption of Mt. Nabro June 13, 2011 Eritria, Africa


Red Sea
Nabro eruption
June 14, 2011

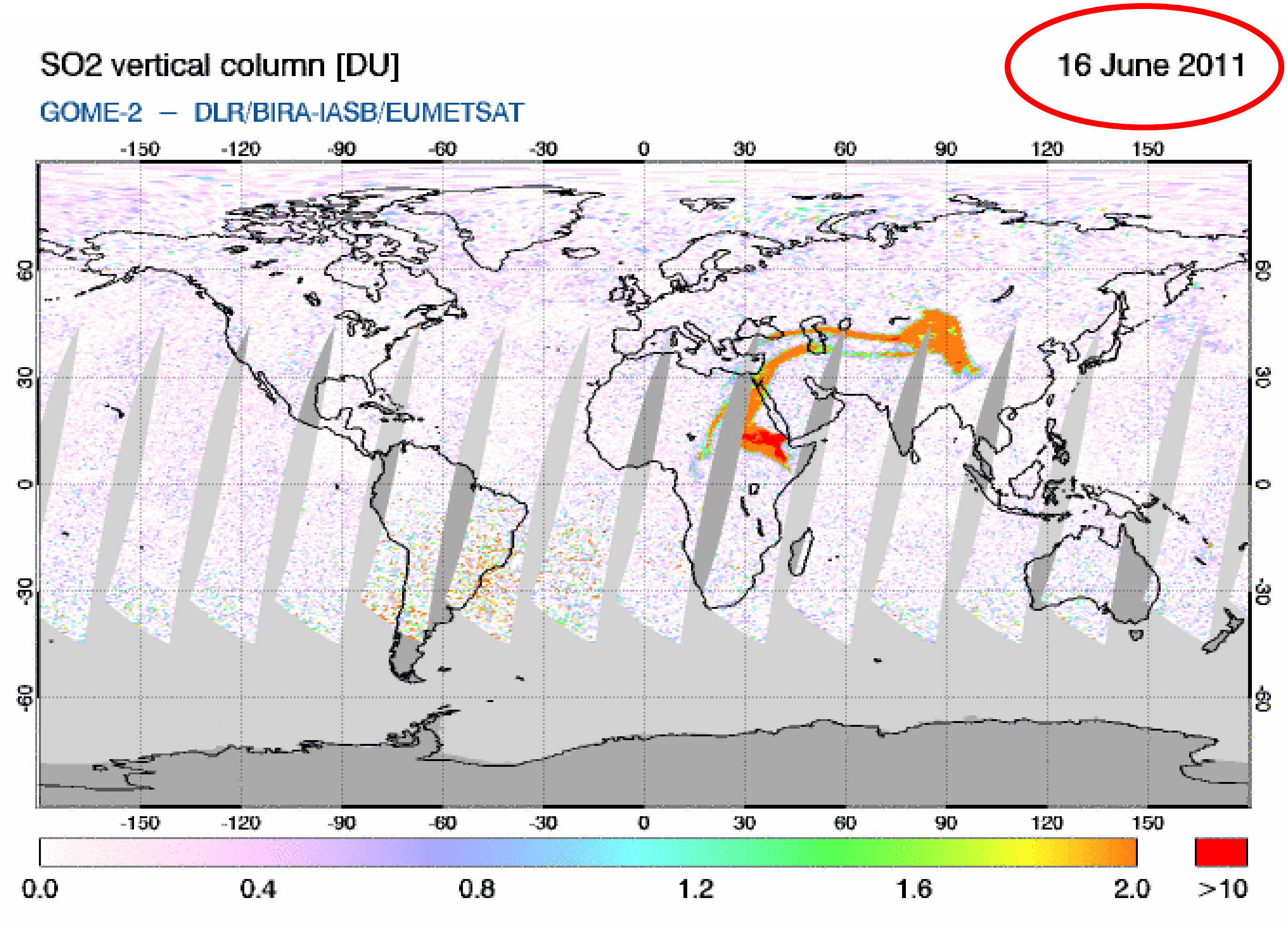
SO_2 plume from Nabro



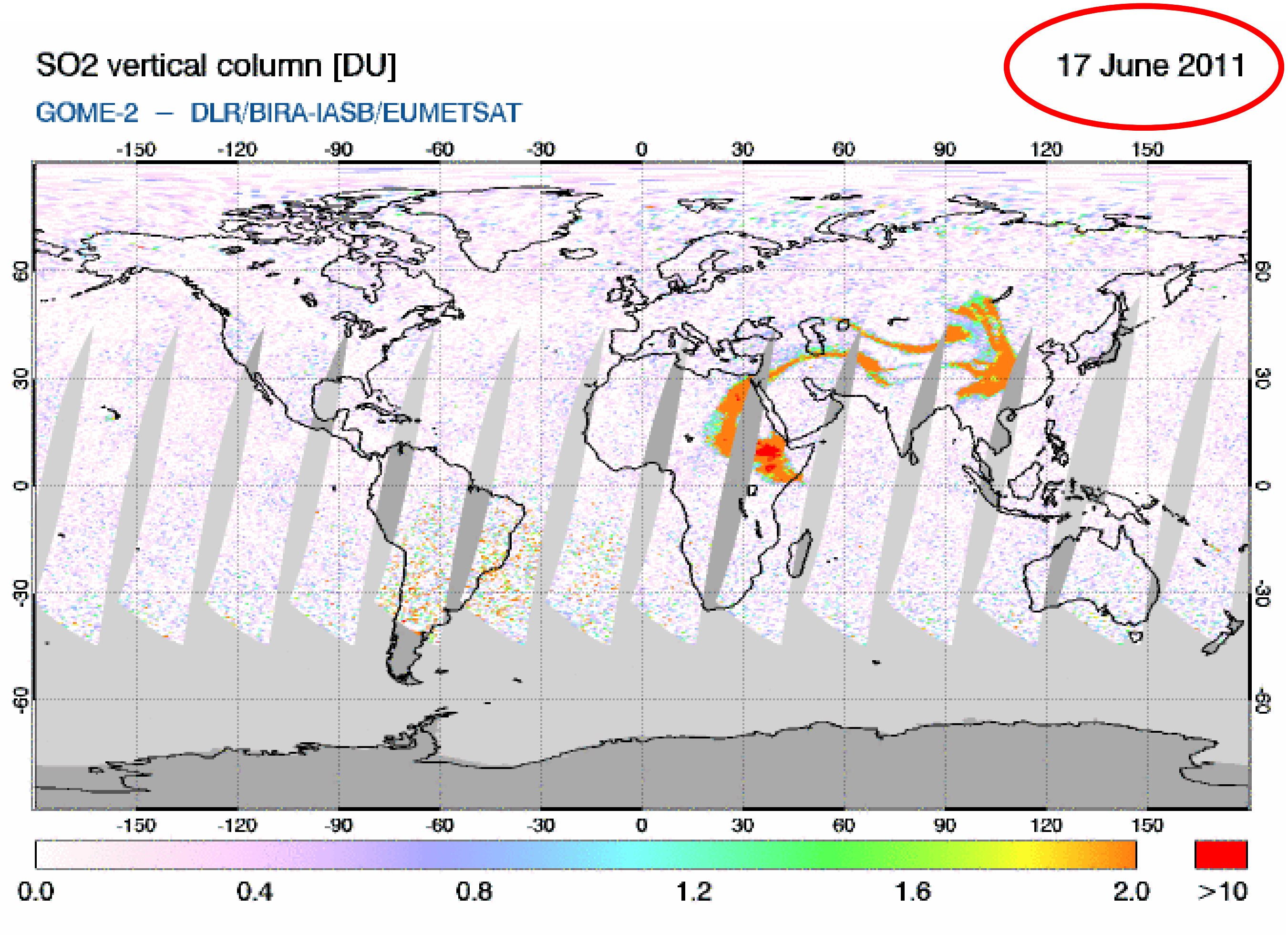
SO_2 plume from Nabro



SO_2 plume from Nabro

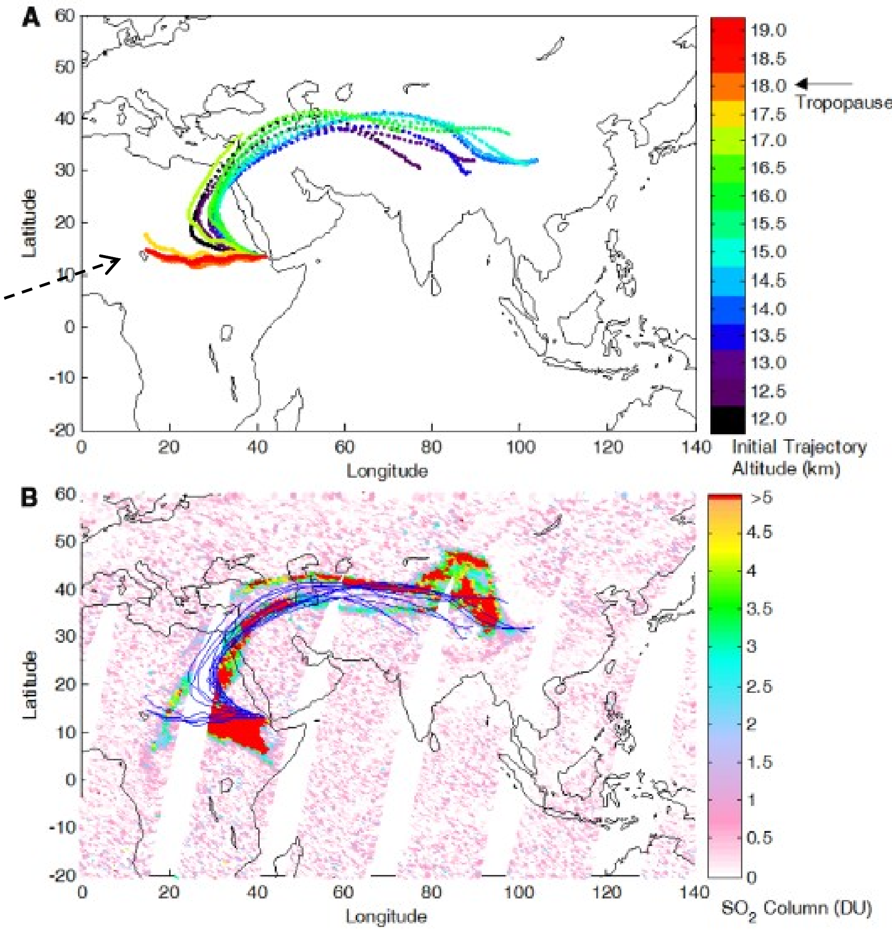


SO_2 plume from Nabro



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



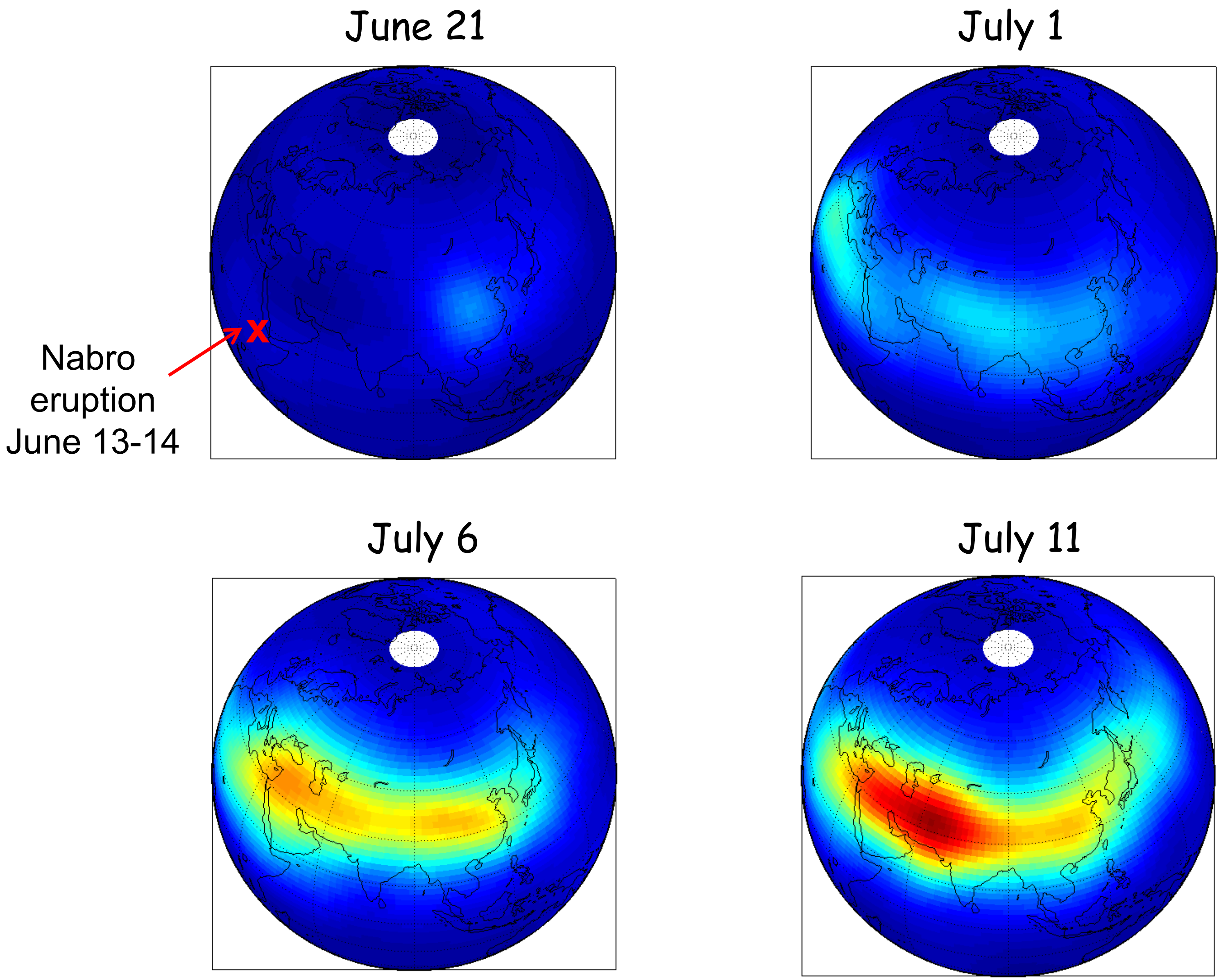
trajectories for
June 13-16

trajectories overlaid
with GOME SO_2

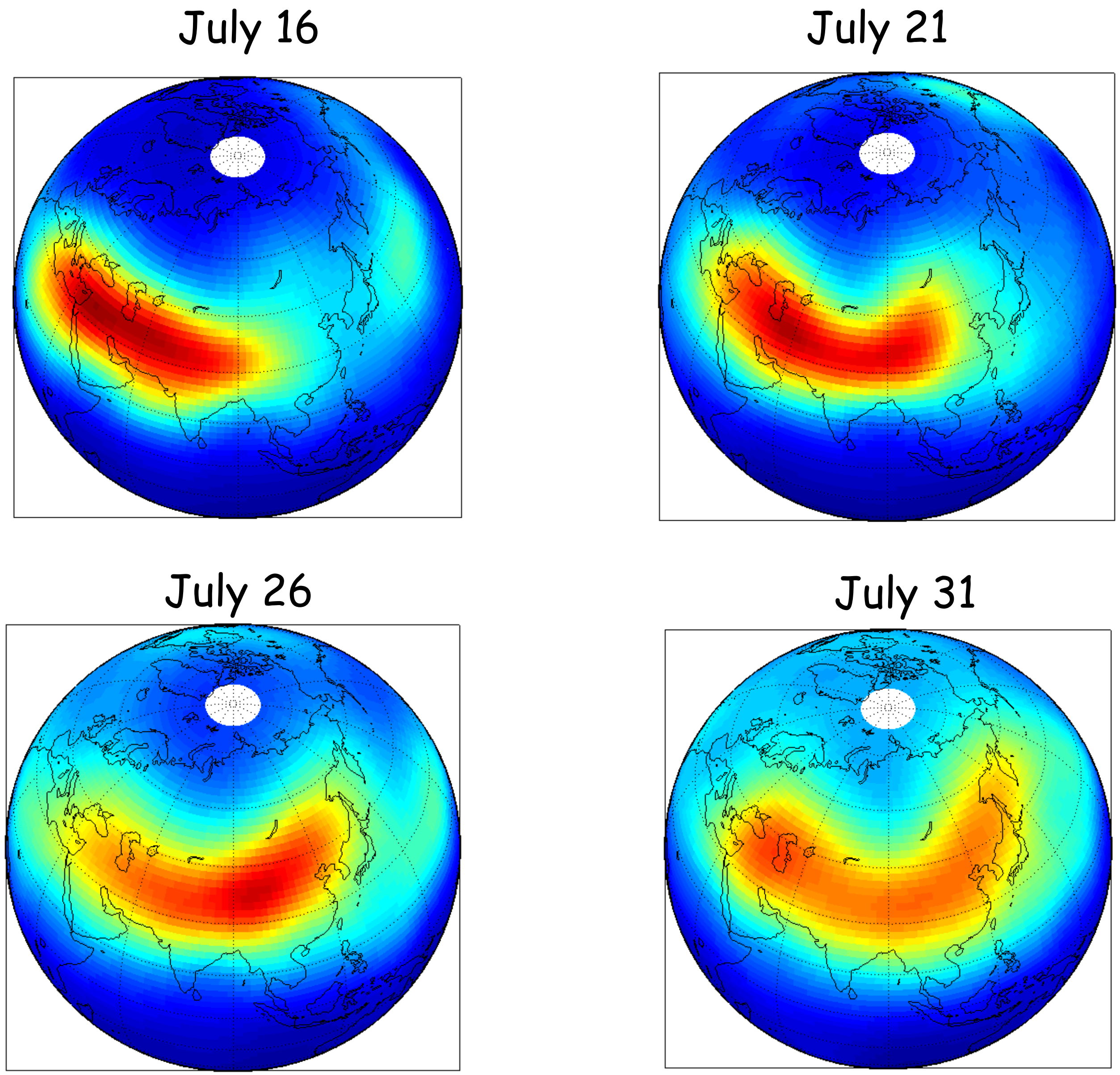
Bourassa et al, 2012

Stratospheric aerosols from OSIRIS satellite

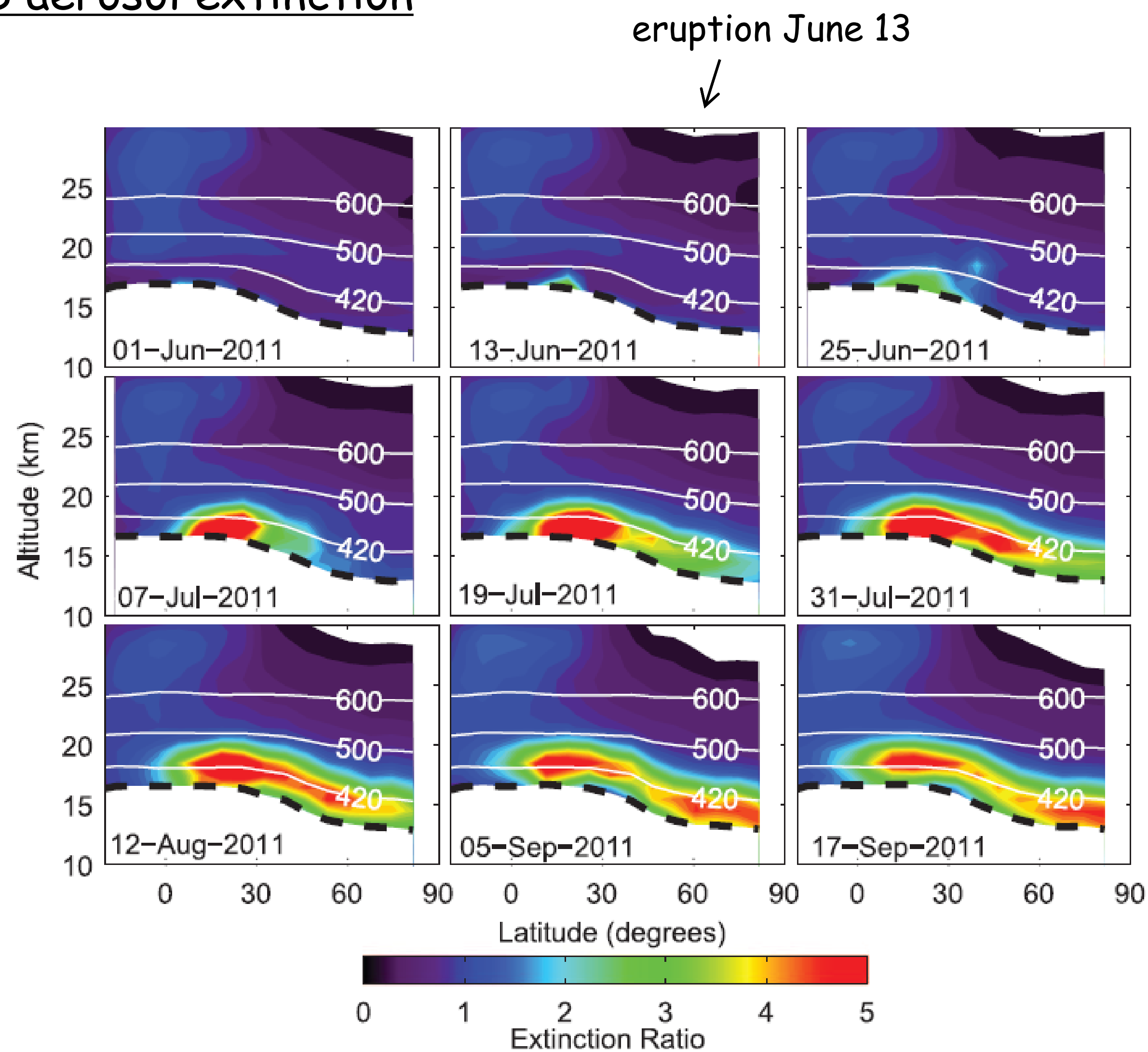
Bourassa et al, 2012



Bourassa et al, 2012



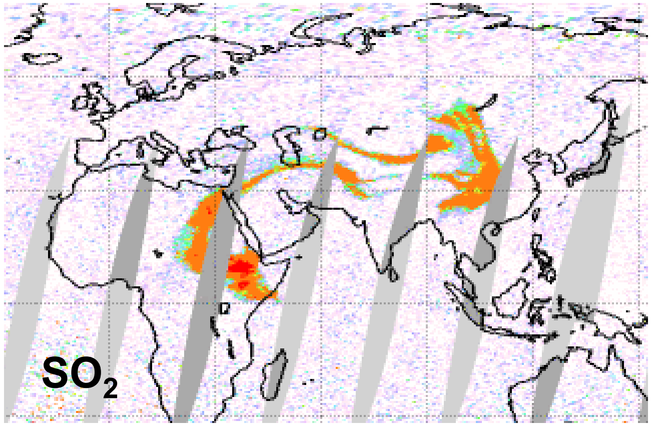
OSIRIS aerosol extinction



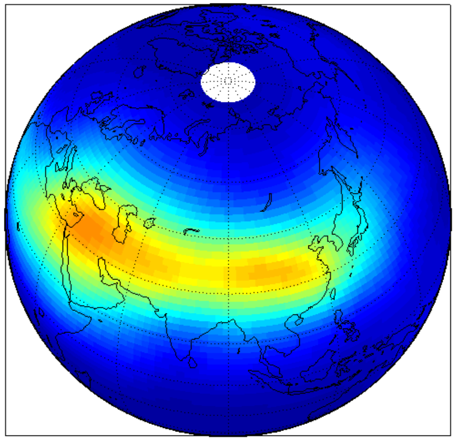
Interpretation:

- 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

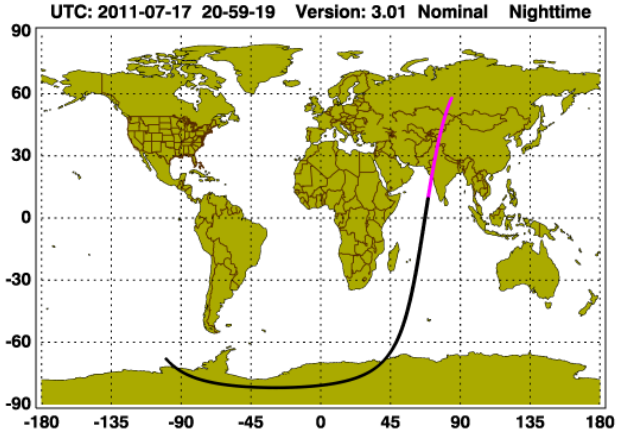


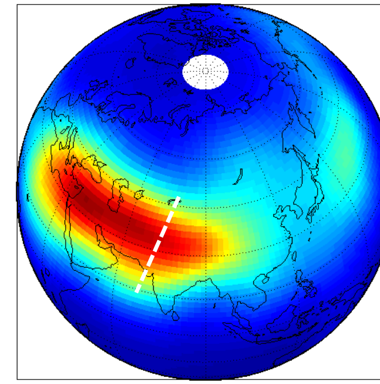
July 6



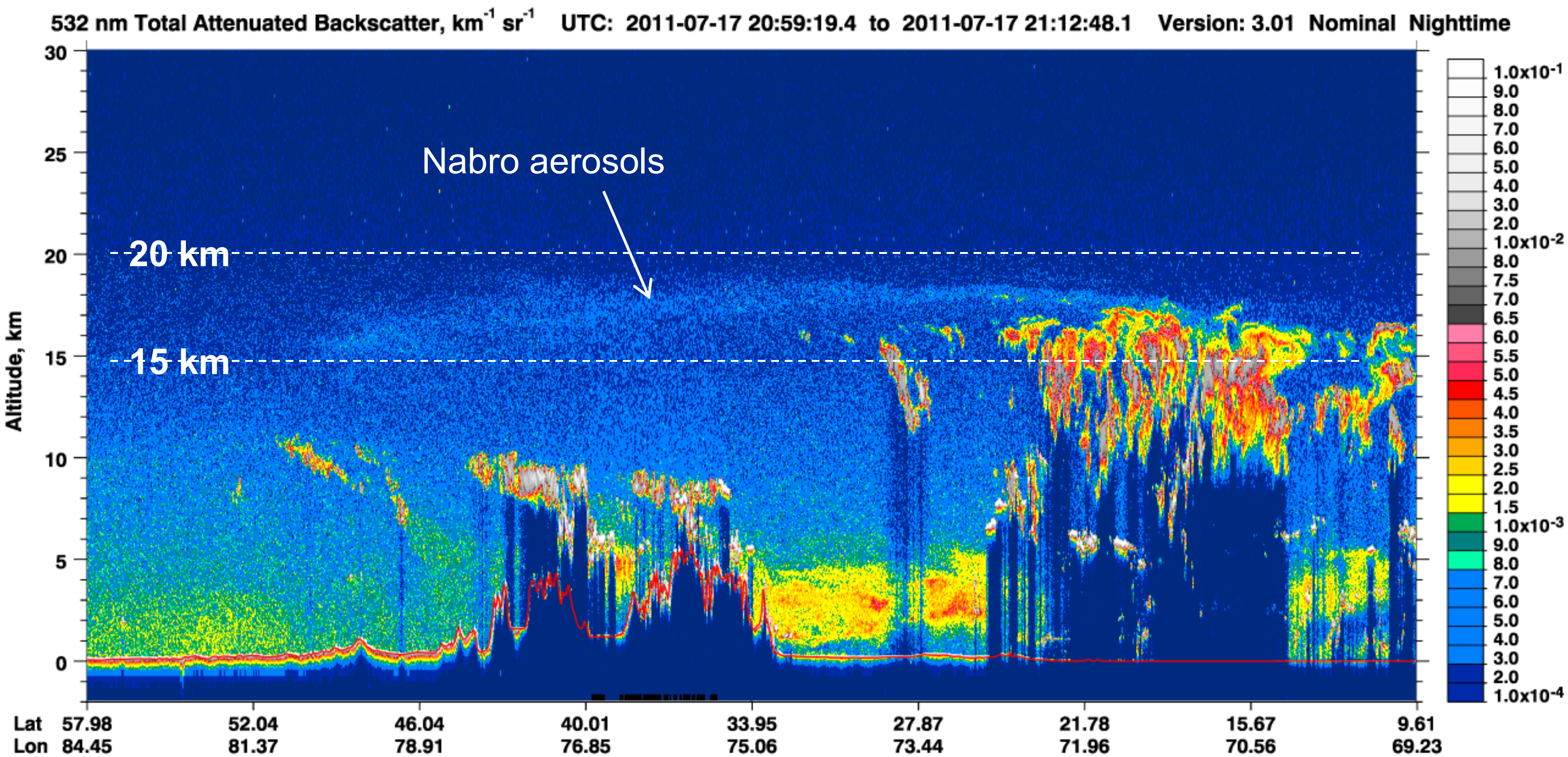
Bourassa et al., 2012, Science

July 17
34 days
after eruption





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

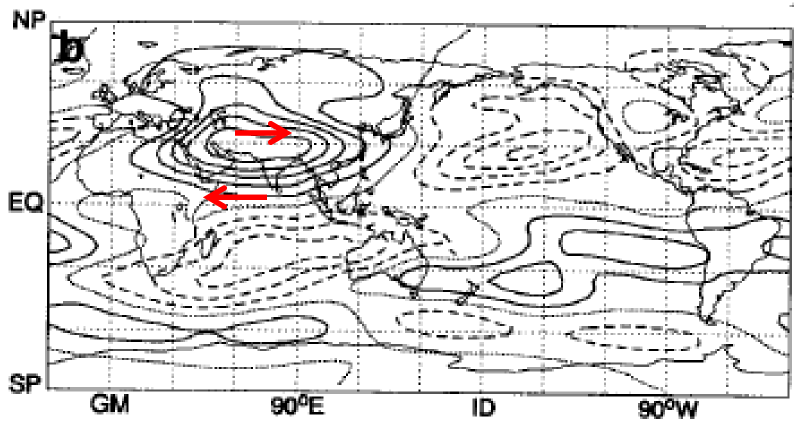
200 hPa streamfunction JJA

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

JAS 1995

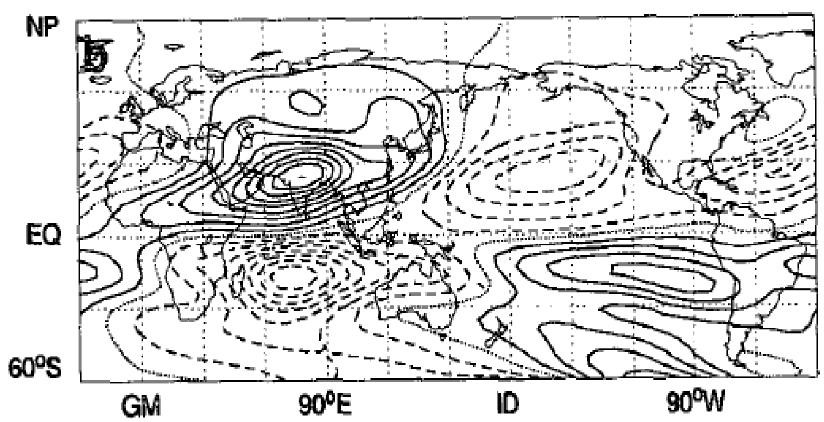
BRIAN J. HOSKINS AND MARK J. RODWELL

observations

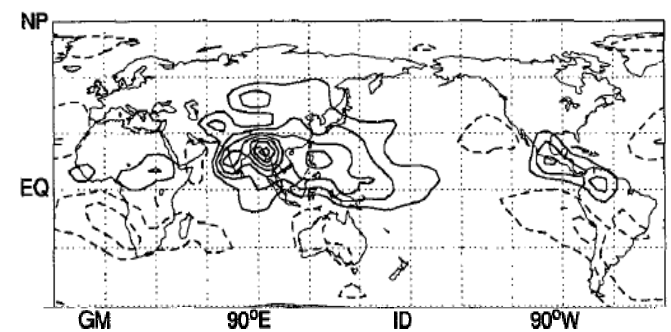


reasonable agreement

linear model with heating

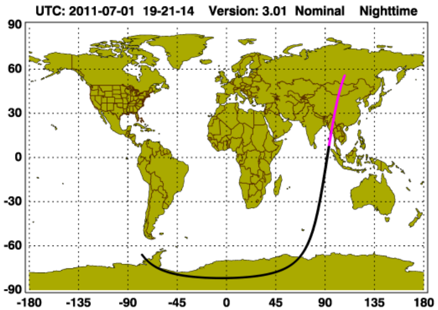


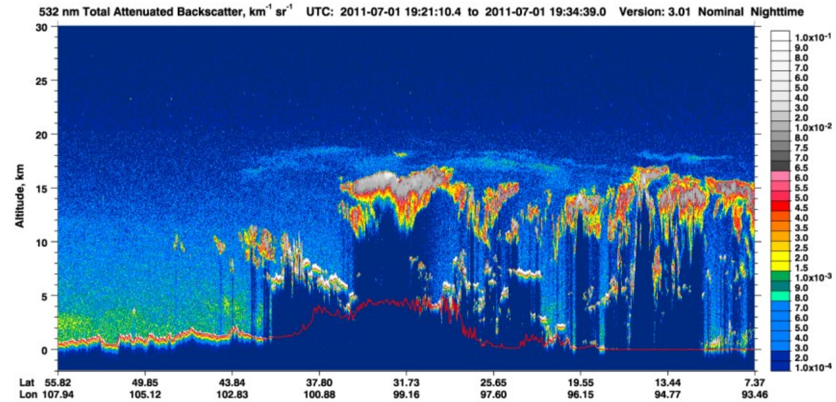
diabatic heating from reanalyses

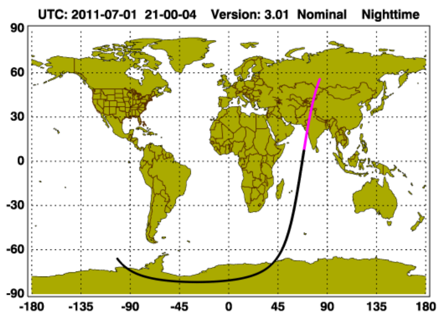


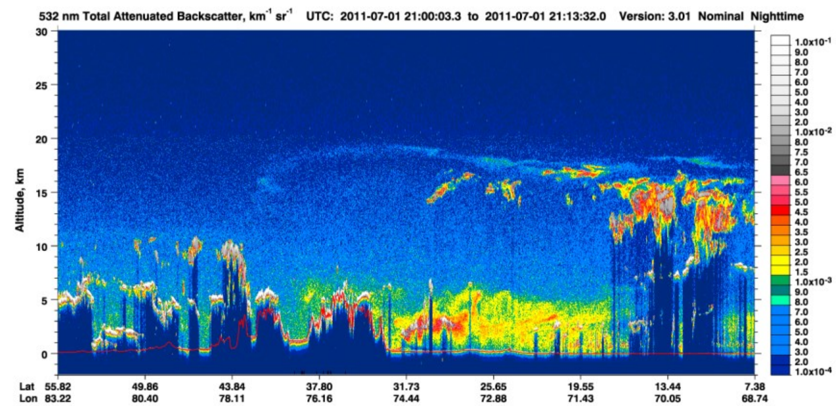
Result: heating from convection mainly forces monsoon anticyclone

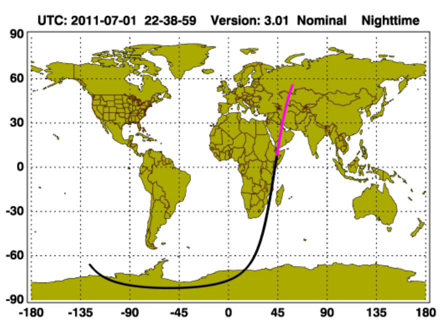
July 1: 18 days after eruption

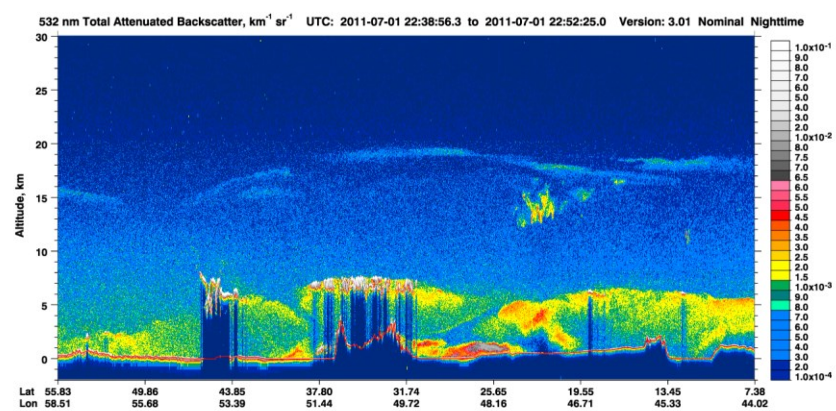




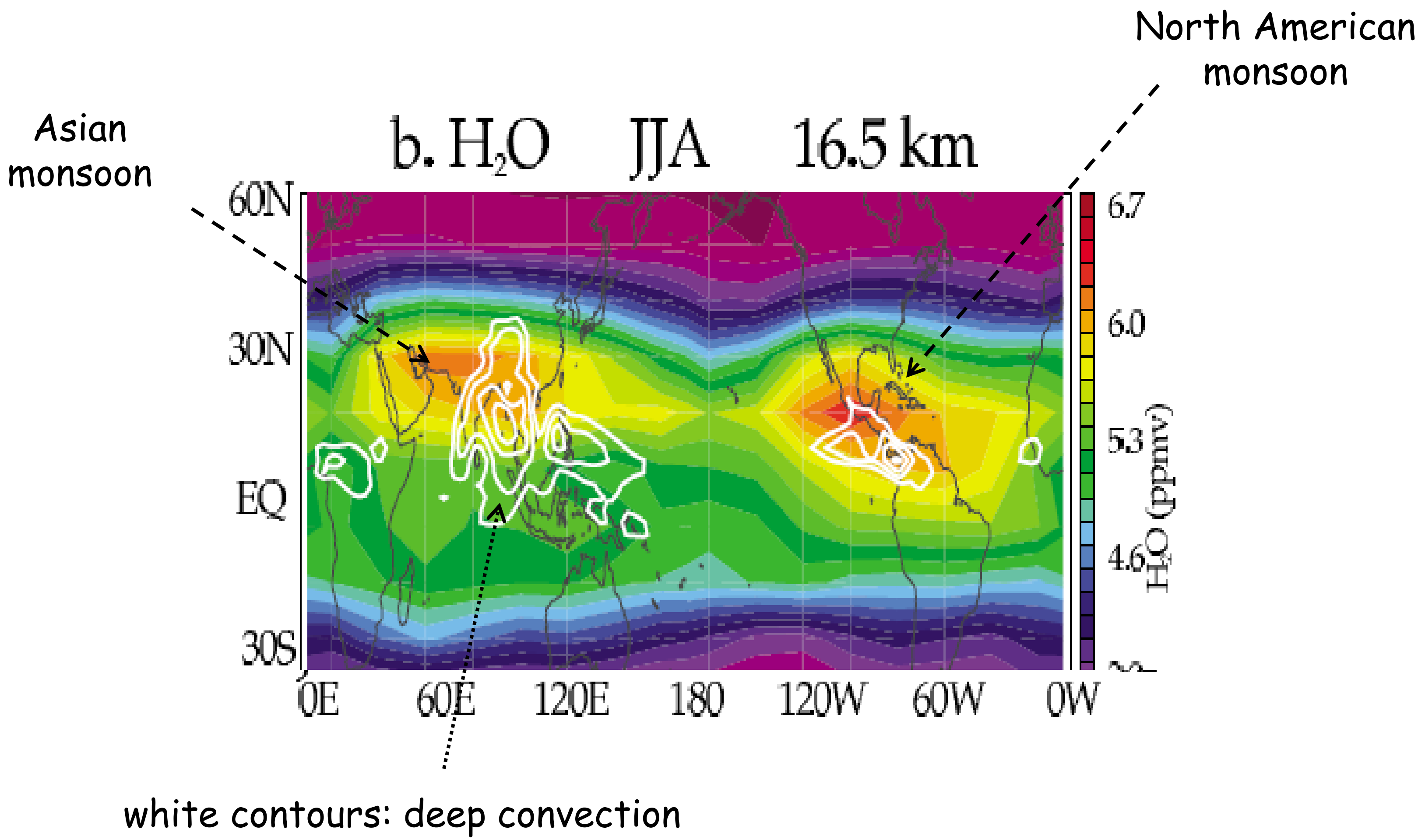




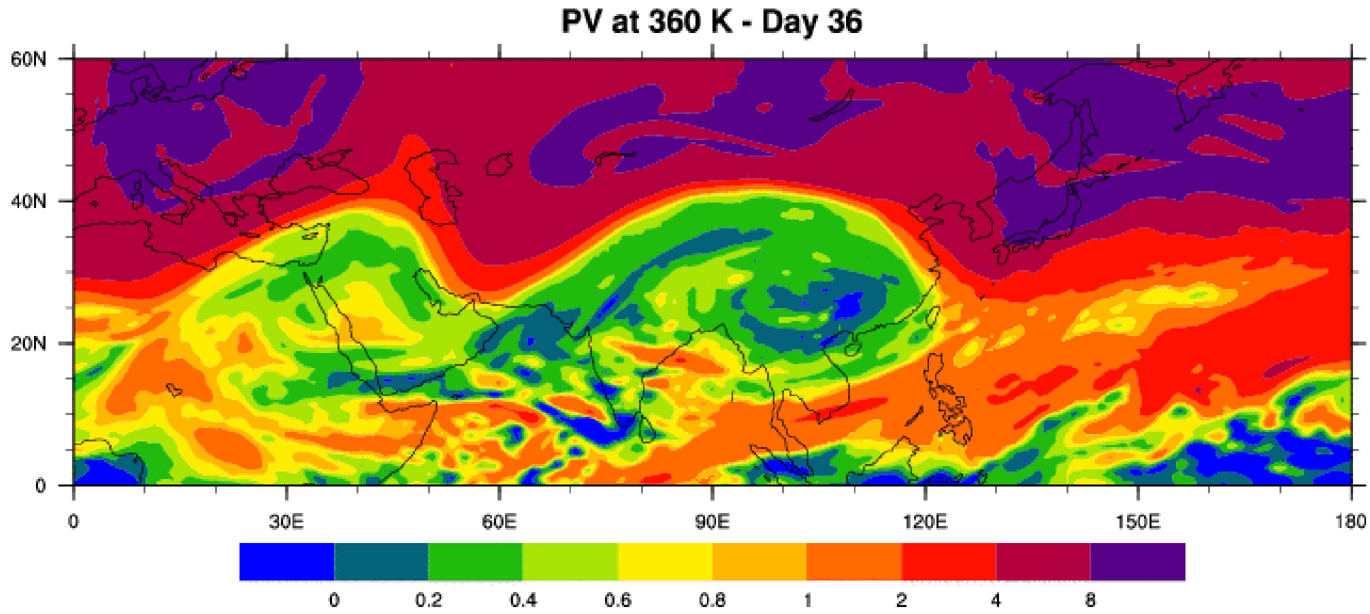




Also enhanced water vapor in monsoon regions

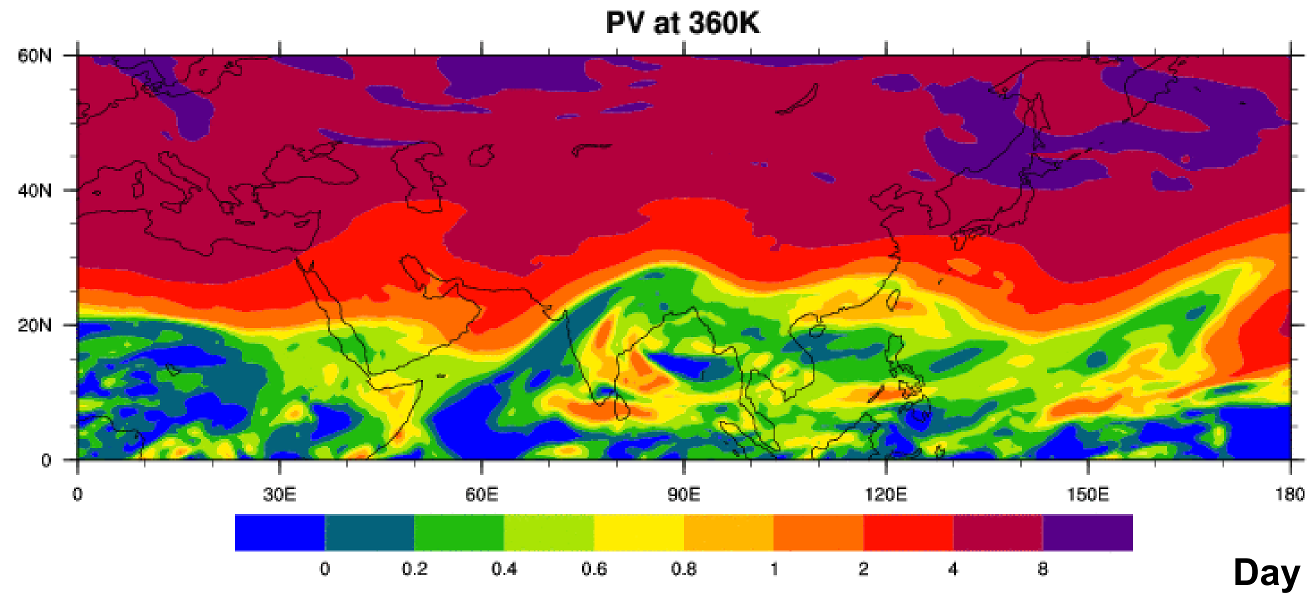


Anticyclone viewed in potential vorticity



Garny and Randel, 2013, J. Geophys. Res.

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

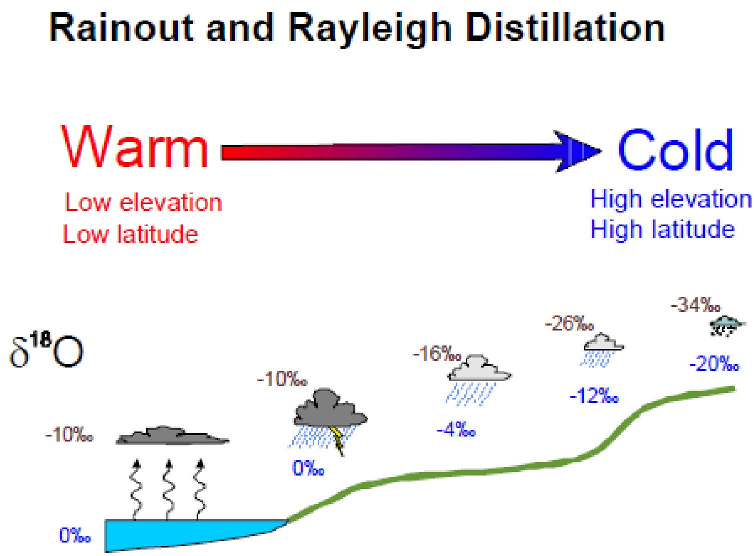


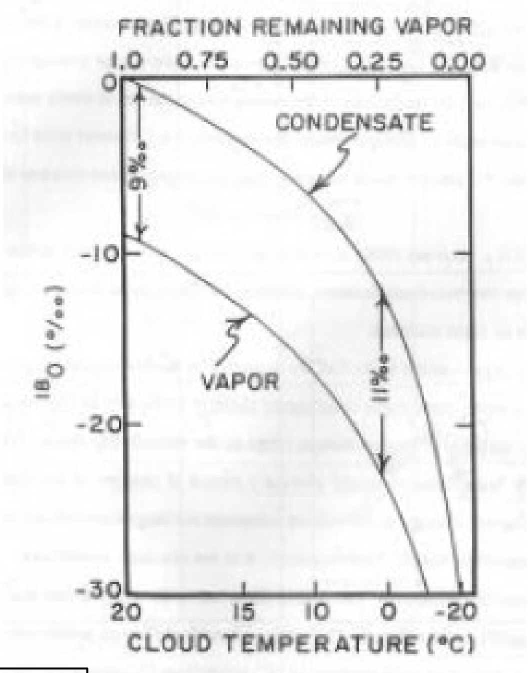
Day 1 = May 1
32 June 1
62 July 1
93 Aug 1
123 Sept 1

Garny and Randel, 2013, J. Geophys. Res.

Global variations of Water Vapor Isotopes from ACE-FTS satellite data

Water vapor isotopes: H_2O^{16}, HDO, H_2O^{18}, H_2O^{17}





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

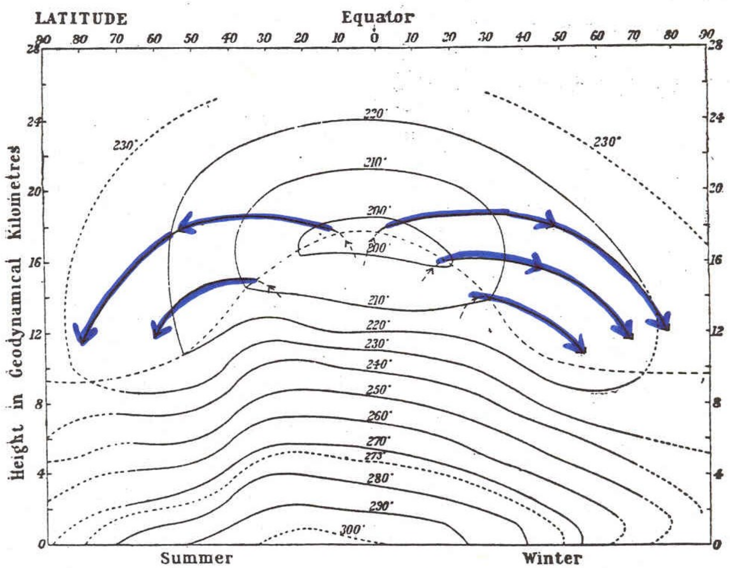
values often expressed in delta notation:

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

'per mil'

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

Brewer, 1949



Isotherms over the Globe

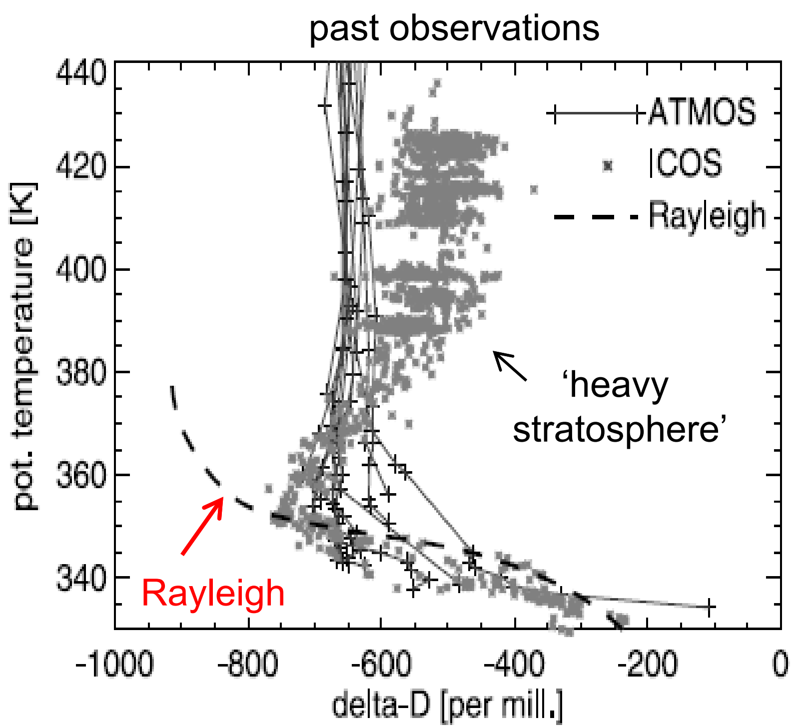
FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

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

Very small HDO/H_2O

But observations show a different story:

persistent increase in TTL region, heavy stratosphere

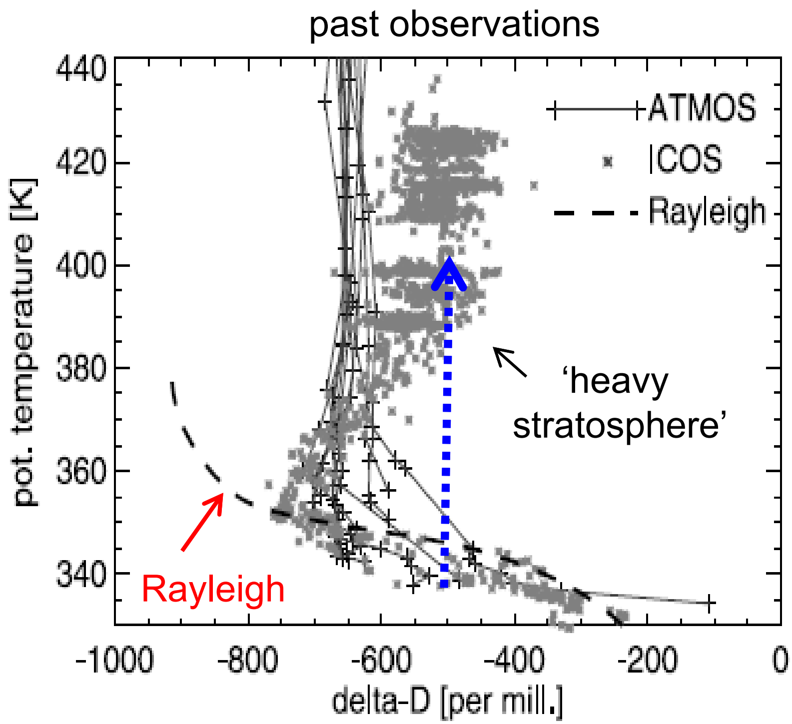


Moyer et al 1997
Hanisco et al 2007
Fueglistaler et al, 2009

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

But observations show a different story:

persistent increase in TTL region, heavy stratosphere



transport of ice in overshooting deep convection ?

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

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

ACE-FTS water isotopologues

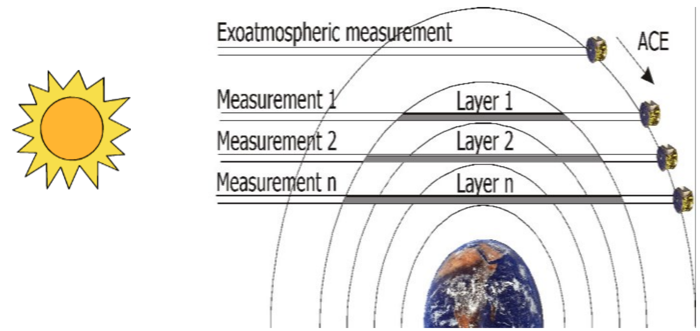
FTS measurements: *2.2 – 13.3 µm*

5+ years of data (Feb. 2004 – present)

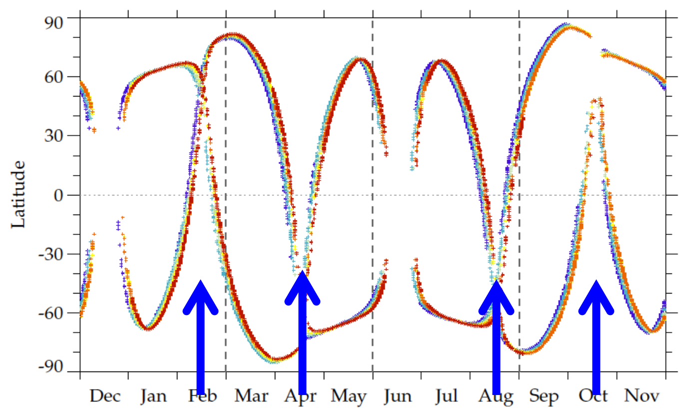
~ 3,500 occultations /year

All major isotopologues of water and methane

Resolution: ~300 km horizontal, 3 km vertical



ACE occultations, 2004-2009



Low latitudes: 4 samples / year

Data presented here:

~20,000 occultations

(entire V2.2 dataset 2004-2009)

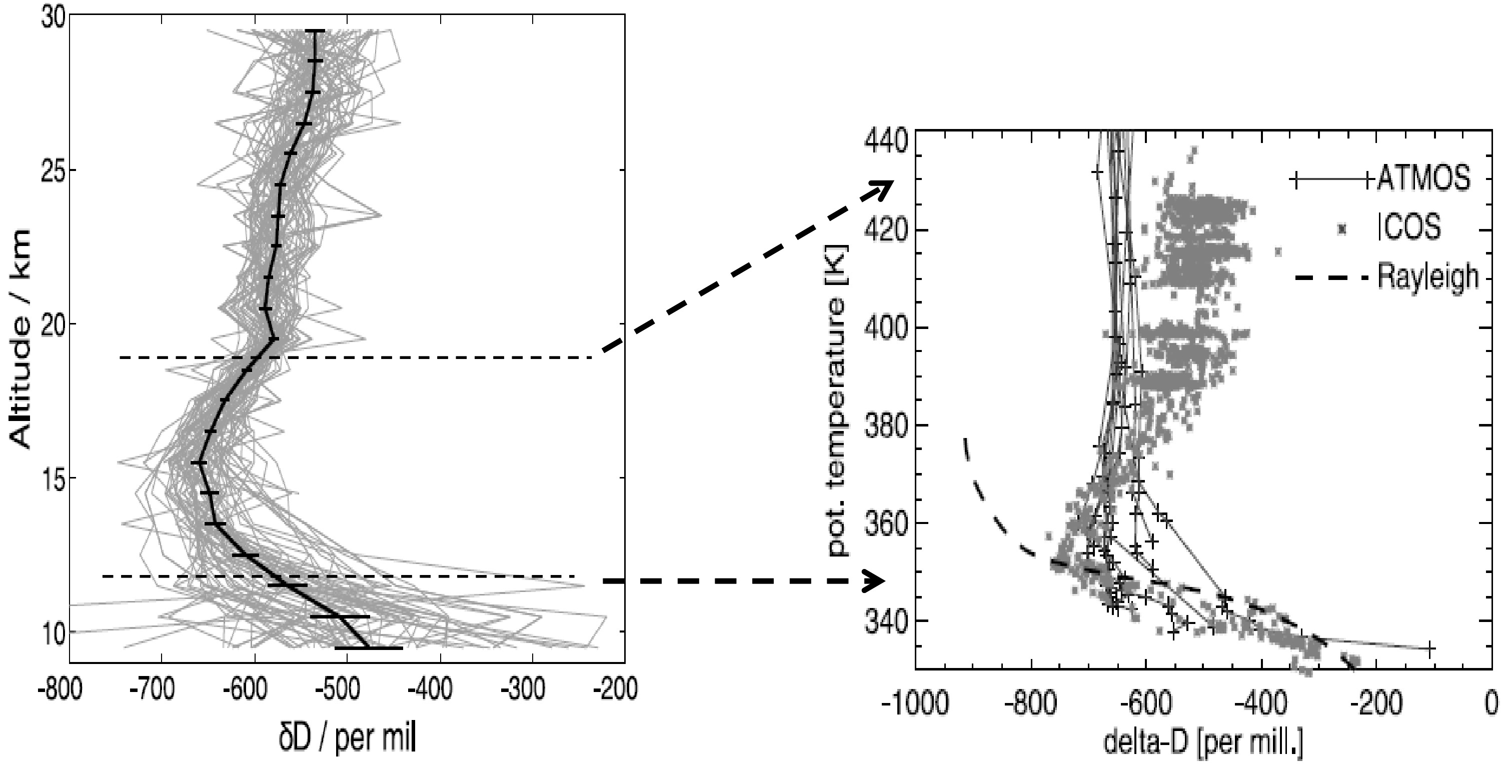
3-month seasonal averages DJF, …

(~ global coverage)

Randel et al 2012

ACE-FTS δD profiles show similarities to previous measurements

persistent increase in TTL region, heavy stratosphere



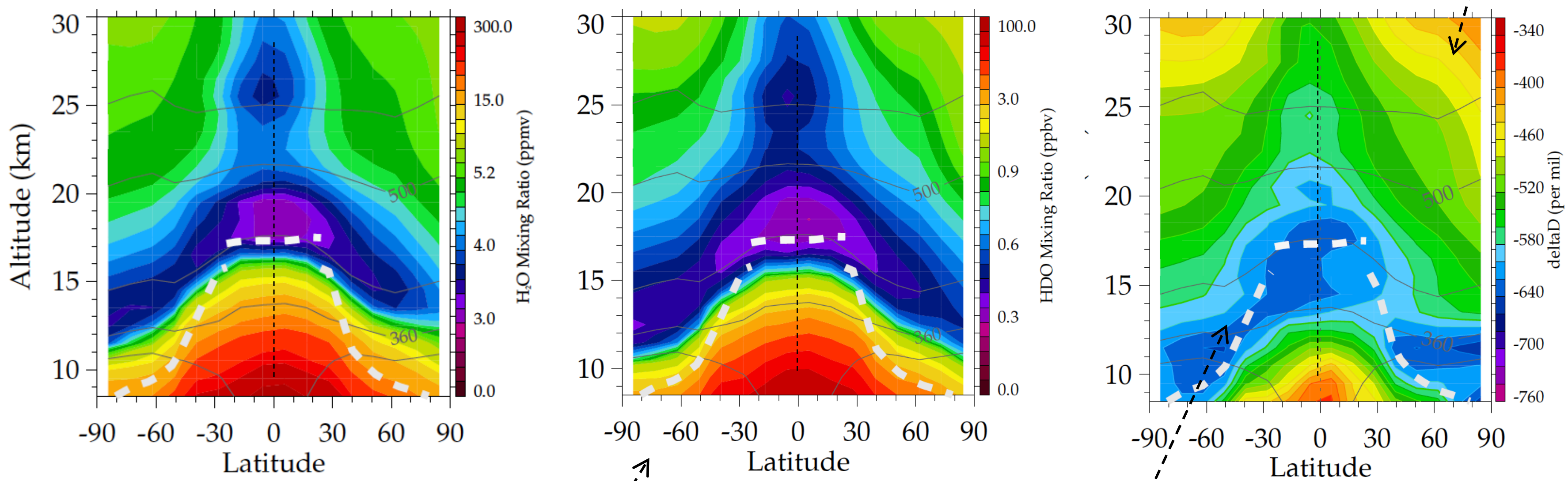
Nassar et al, JGR 2008

Global behavior derived from ACE-FTS

Climatologies for March-May

increase due to methane oxidation

H_2O HDO δD



max depletion near global tropopause

Note HDO ~ 10,000 times smaller than H_2O

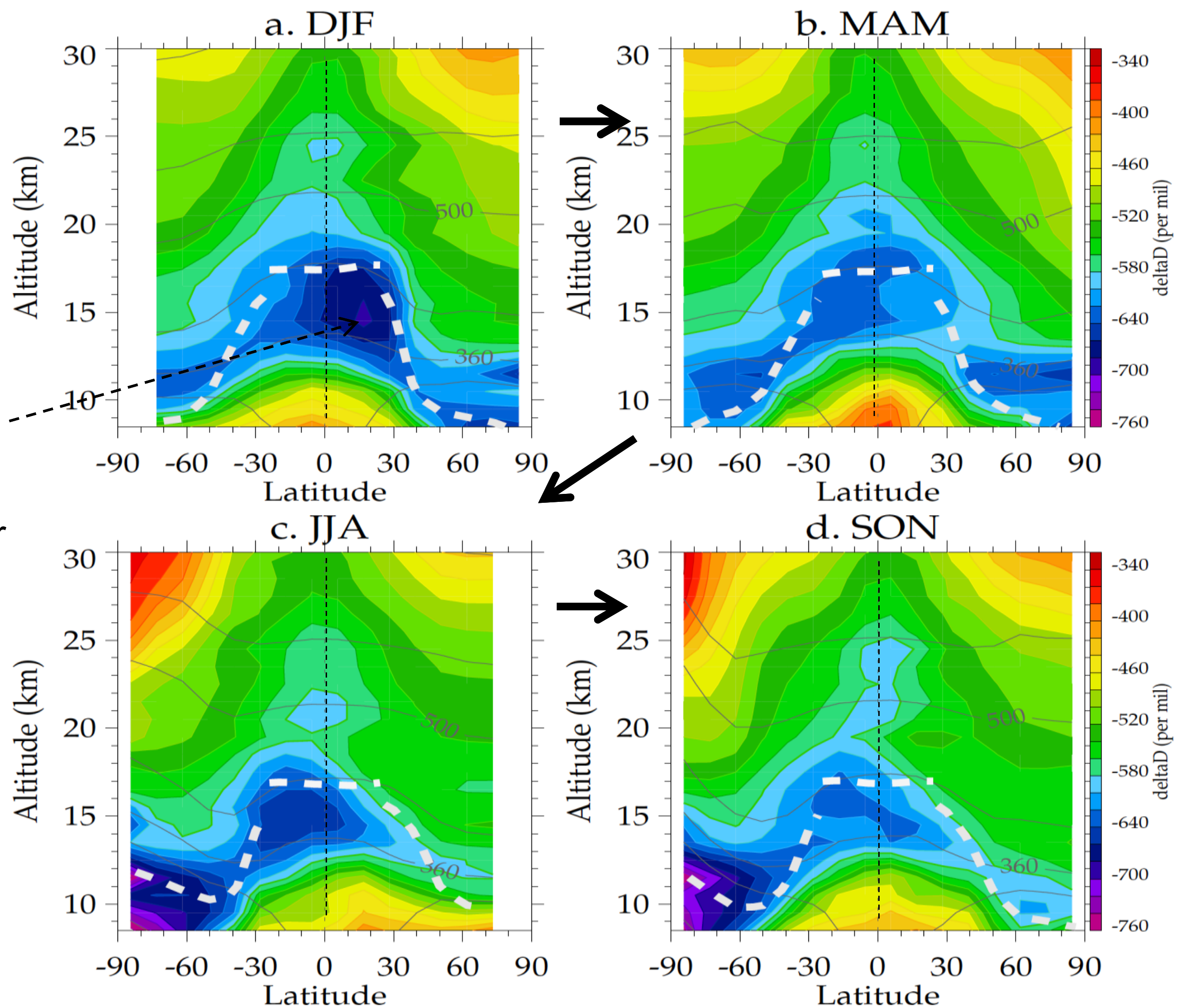
very difficult measurement!

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

Seasonal variation of δD

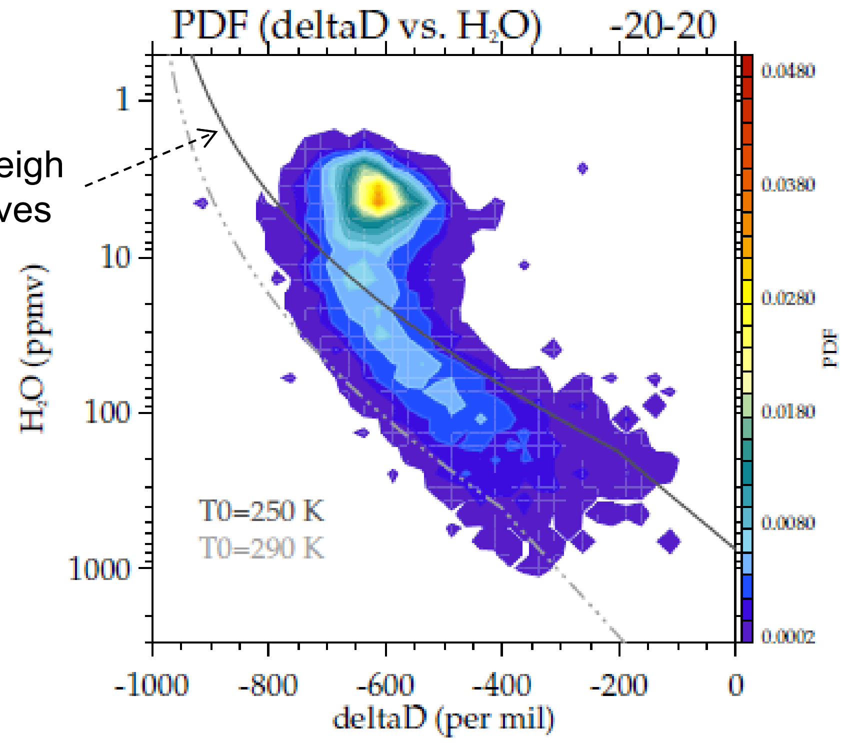
TTL minimum below tropopause

minimum in winter hemisphere



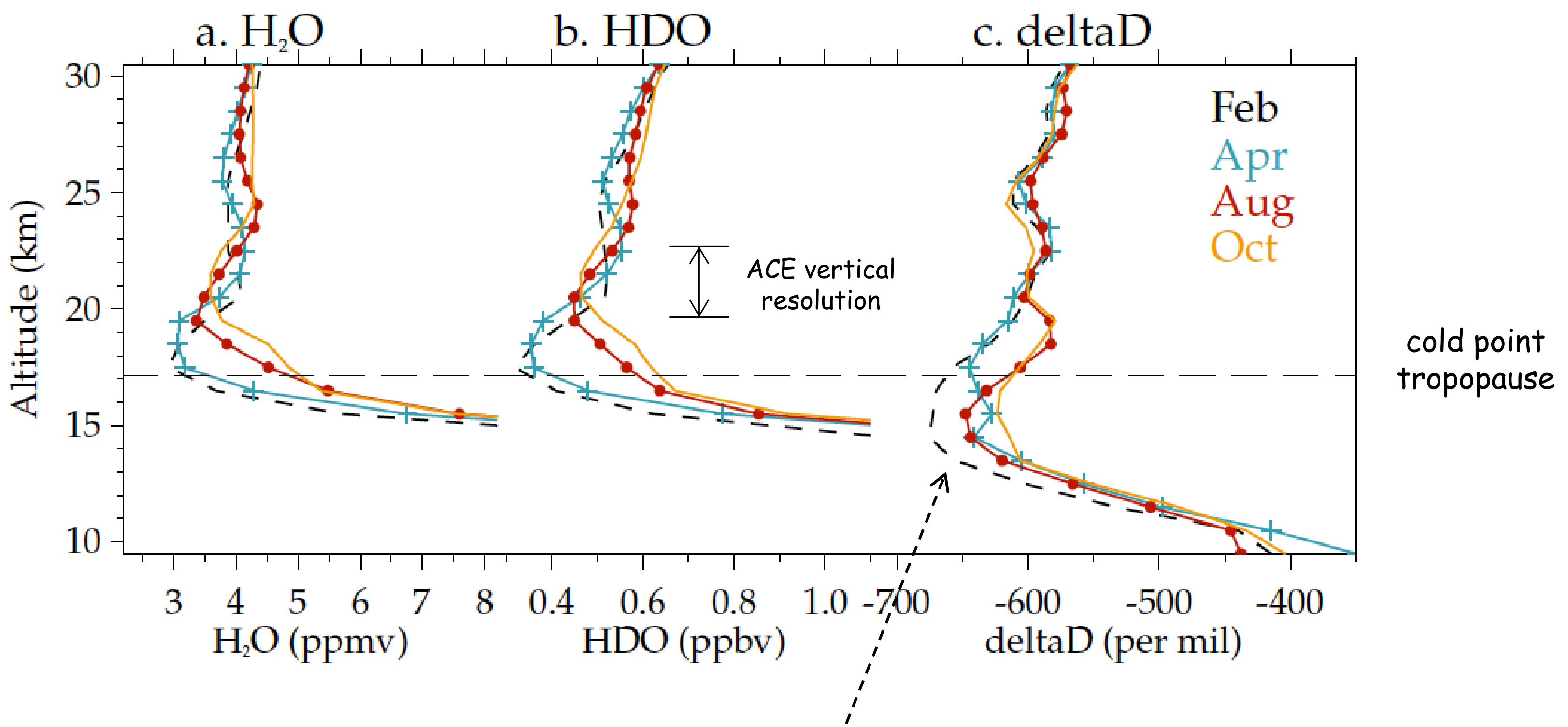
PDF of ACE-FTS in the tropics

Rayleigh curves



vertical coordinate is H_2O; similar behavior for altitude coordinate

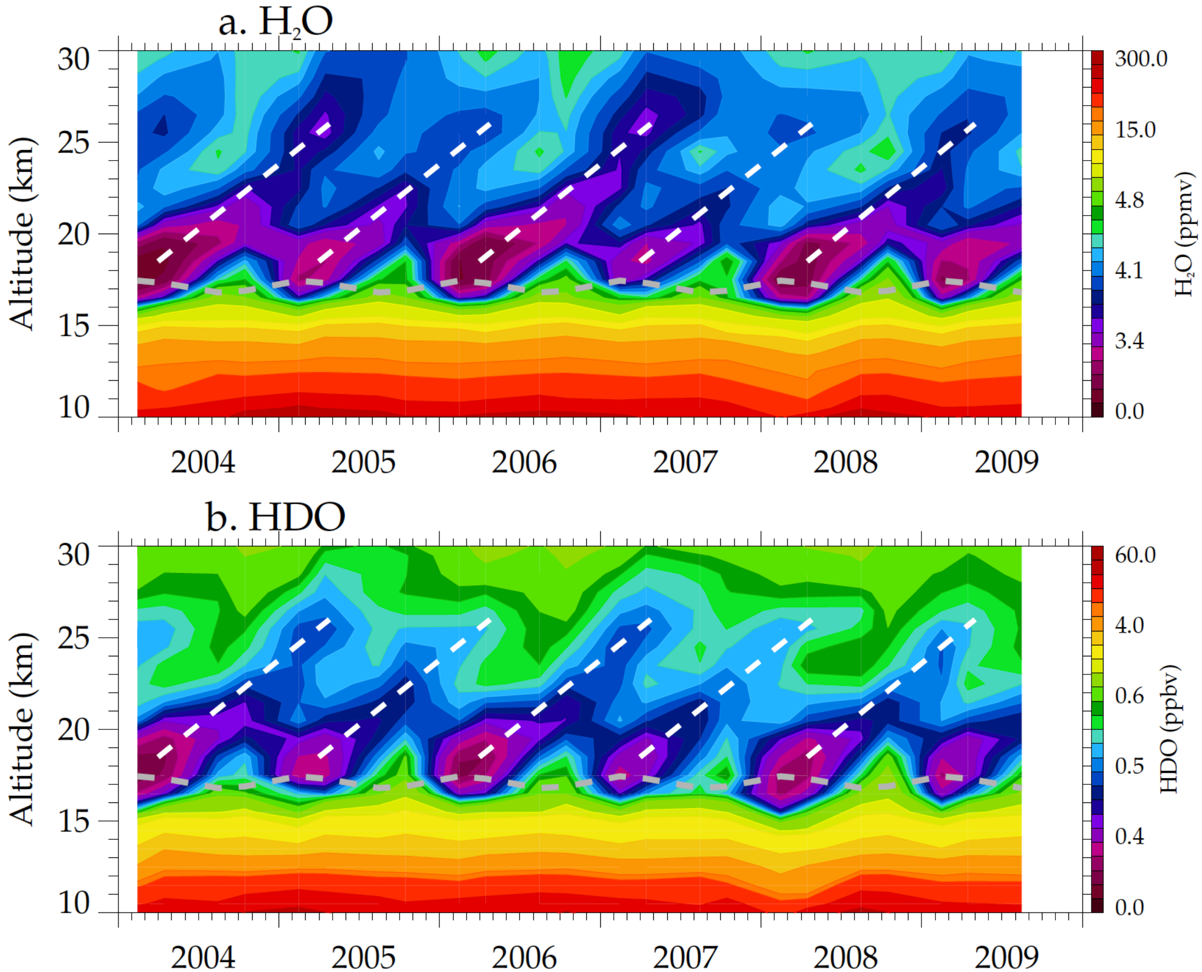
Tropical seasonal structure (15° N-S)



- minimum below tropopause
- strongest depletion in February

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

Tape recorder and seasonal cycle in H_2O, HDO



H_2O

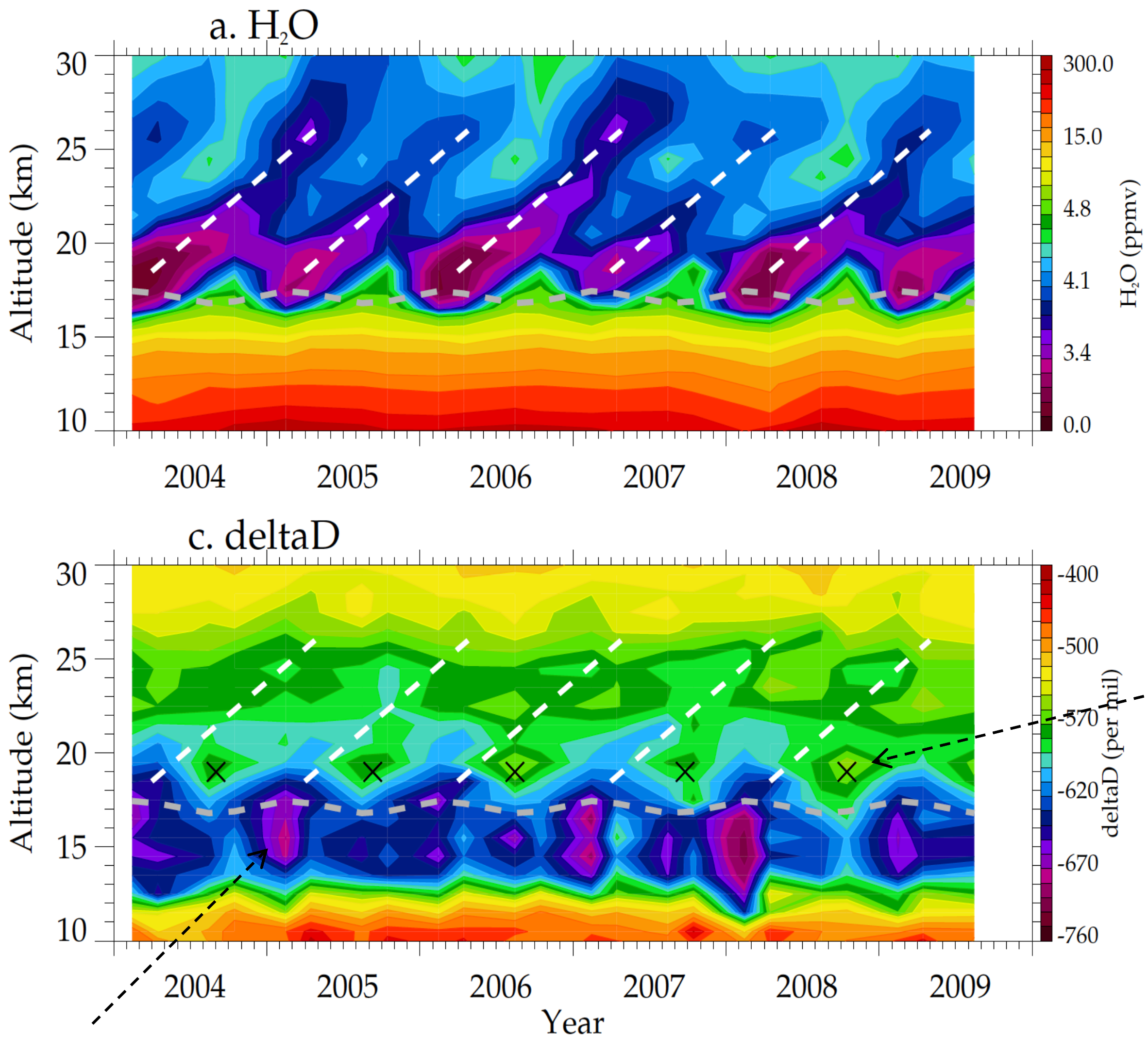
HDO

Note:
only 4 months
of data per year

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

H_2O

δD



monsoon signal

seasonal minimum below tropopause
(convection, not temperature)
Randel et al., 2012, J. Geophys. Sci.

little evidence of tape recorder in δD

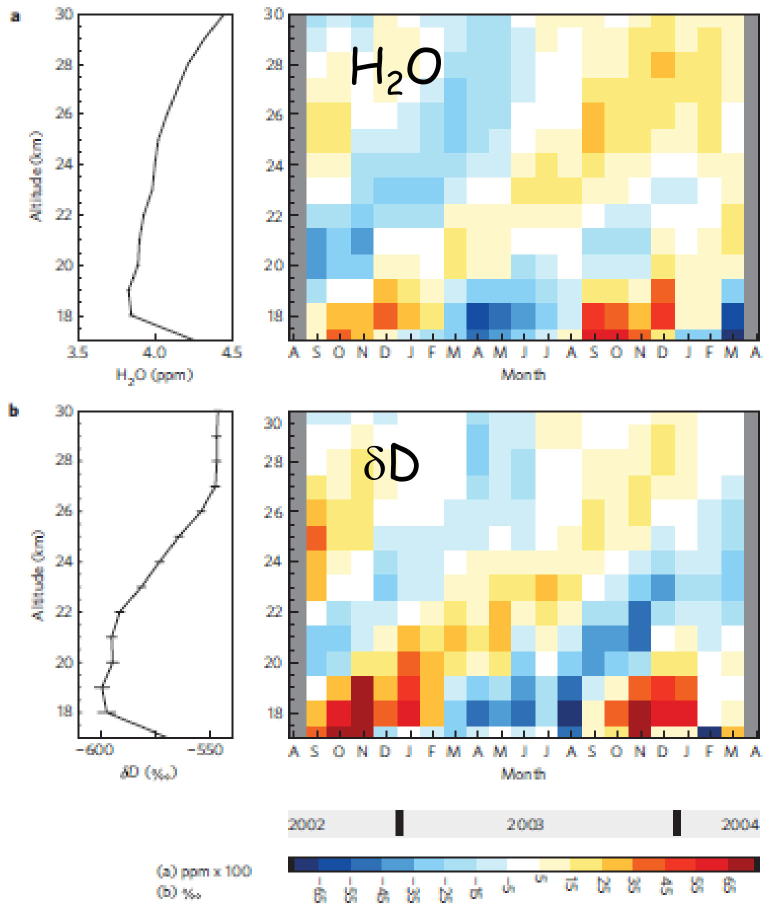
ARTICLES nature geoscience
PUBLISHED ONLINE: 28 MARCH 2010 | DOI: 10.1038/NGEO822

Tropical dehydration processes constrained by the seasonality of stratospheric deuterated water

Jörg Steinwagner[1], Stephan Fueglistaler[2]*, Gabriele Stiller[3], Thomas von Clarmann[3], Michael Kiefer[3], Peter-Paul Borsboom[1], Aarnout van Delden[1] and Thomas Röckmann[1]†

MIPAS satellite observations

this is very different from ACE-FTS results



Note these results are very different from Payne et al 2007 analysis of MIPAS data

vertical resolution 6-8 km ?

δD – corrections for methane oxidation

<u>Conservation of H:</u>

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

Observations + models:

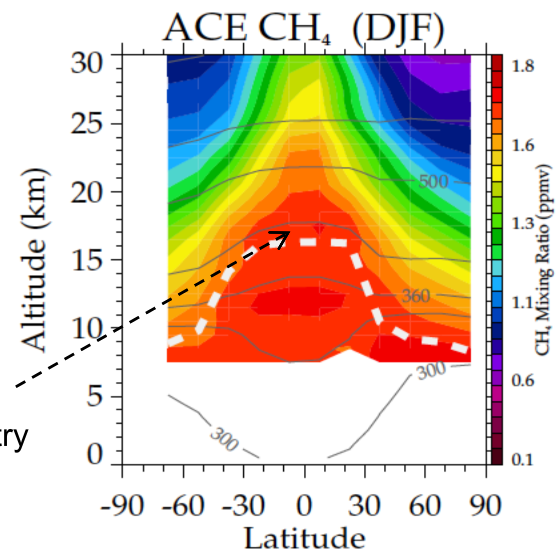
$\Delta\, H_2O \sim -\mathbf{2.0} * (CH_4 - CH_{4entry})$

<u>Conservation of D:</u>

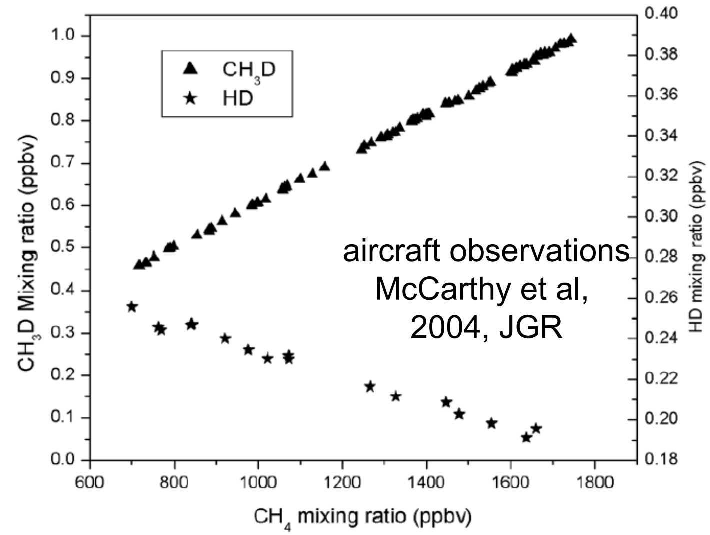
$(HD + HDO + CH_3D) = \text{const.}$

$$\Delta\, HDO = -\,\Delta\, HD - \Delta\, CH_3D$$
$$= -4.5 * 10^{-4}\,(CH_4 - CH_{4entry})$$

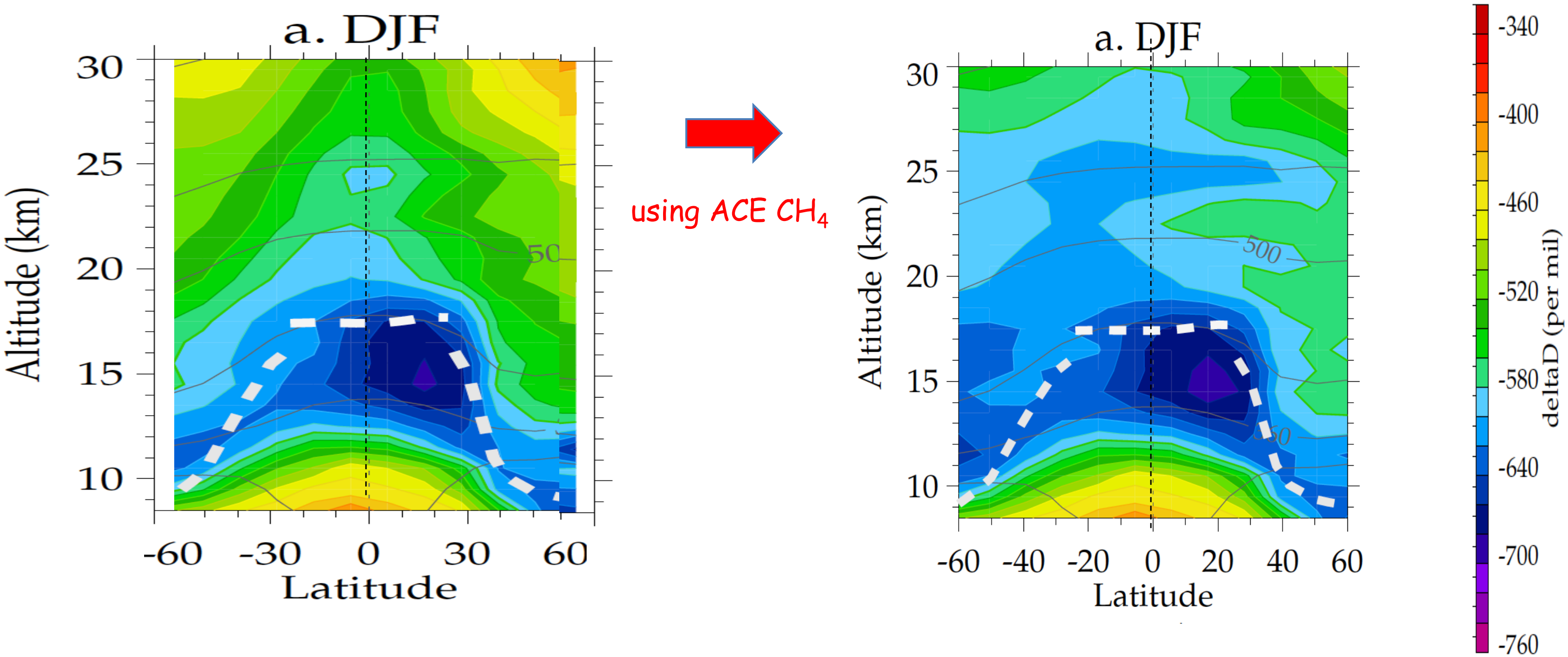
CH_4 from ACE



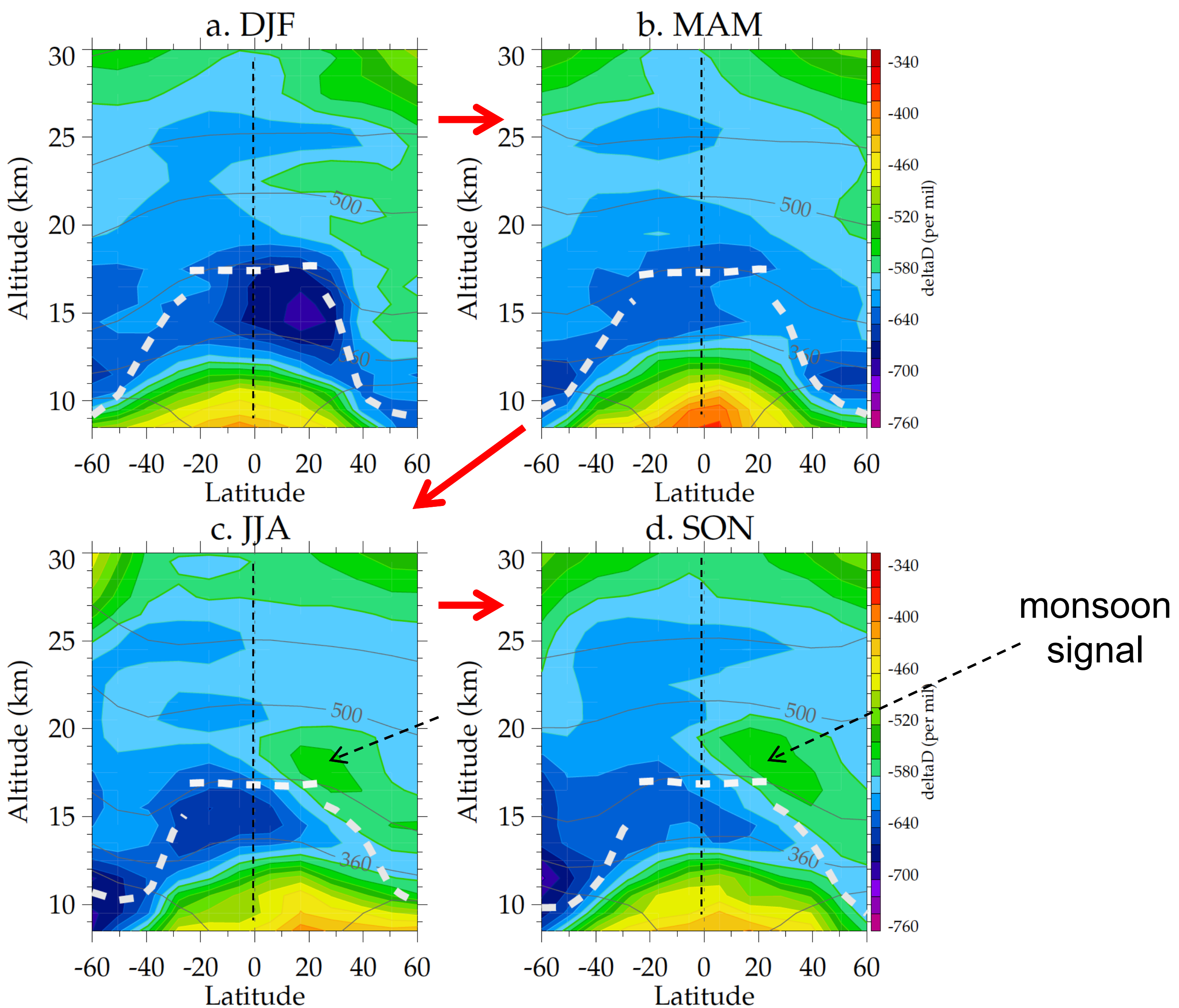
CH_{4entry}



δD – corrected for methane effects



Seasonal cycle of methane-corrected δD

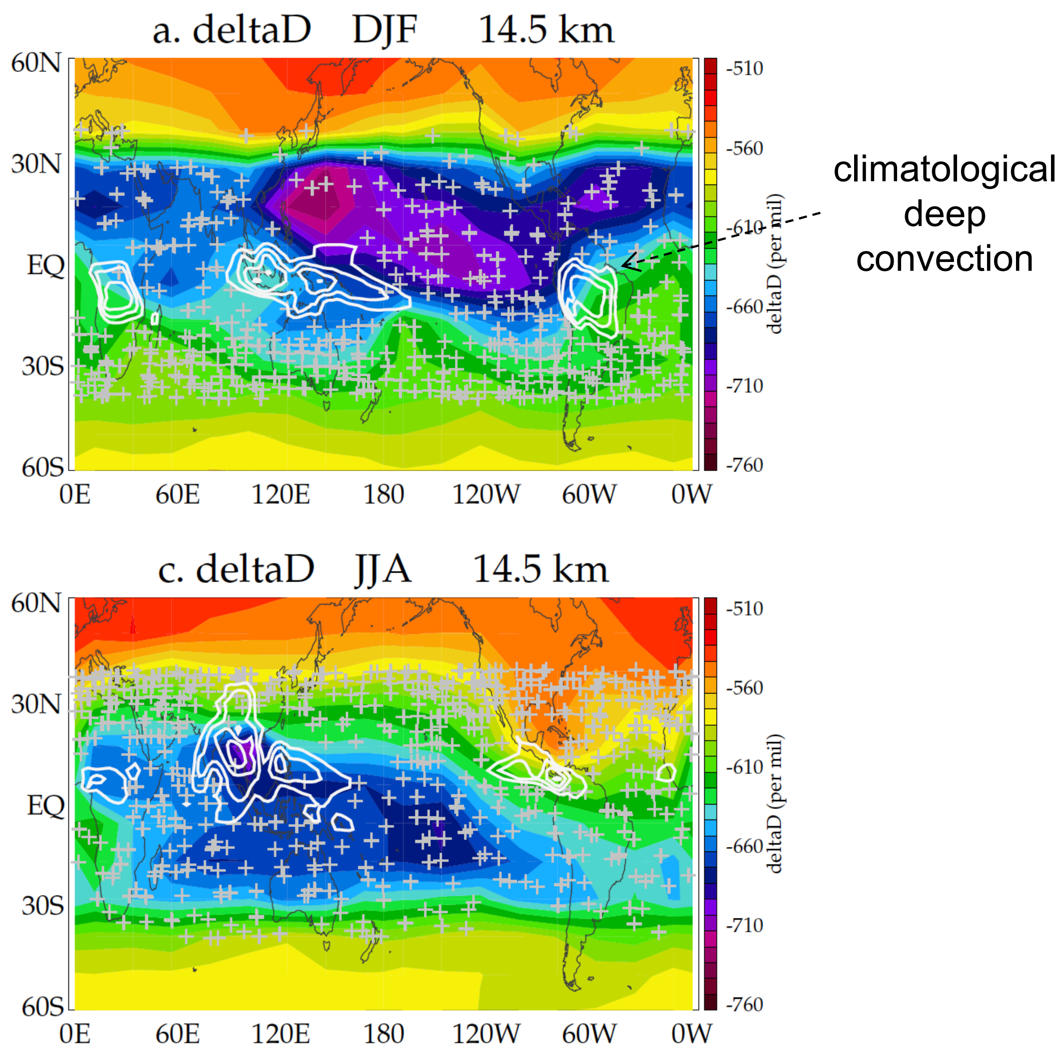


Longitudinal structure and ACE-FTS sampling

14.5 km

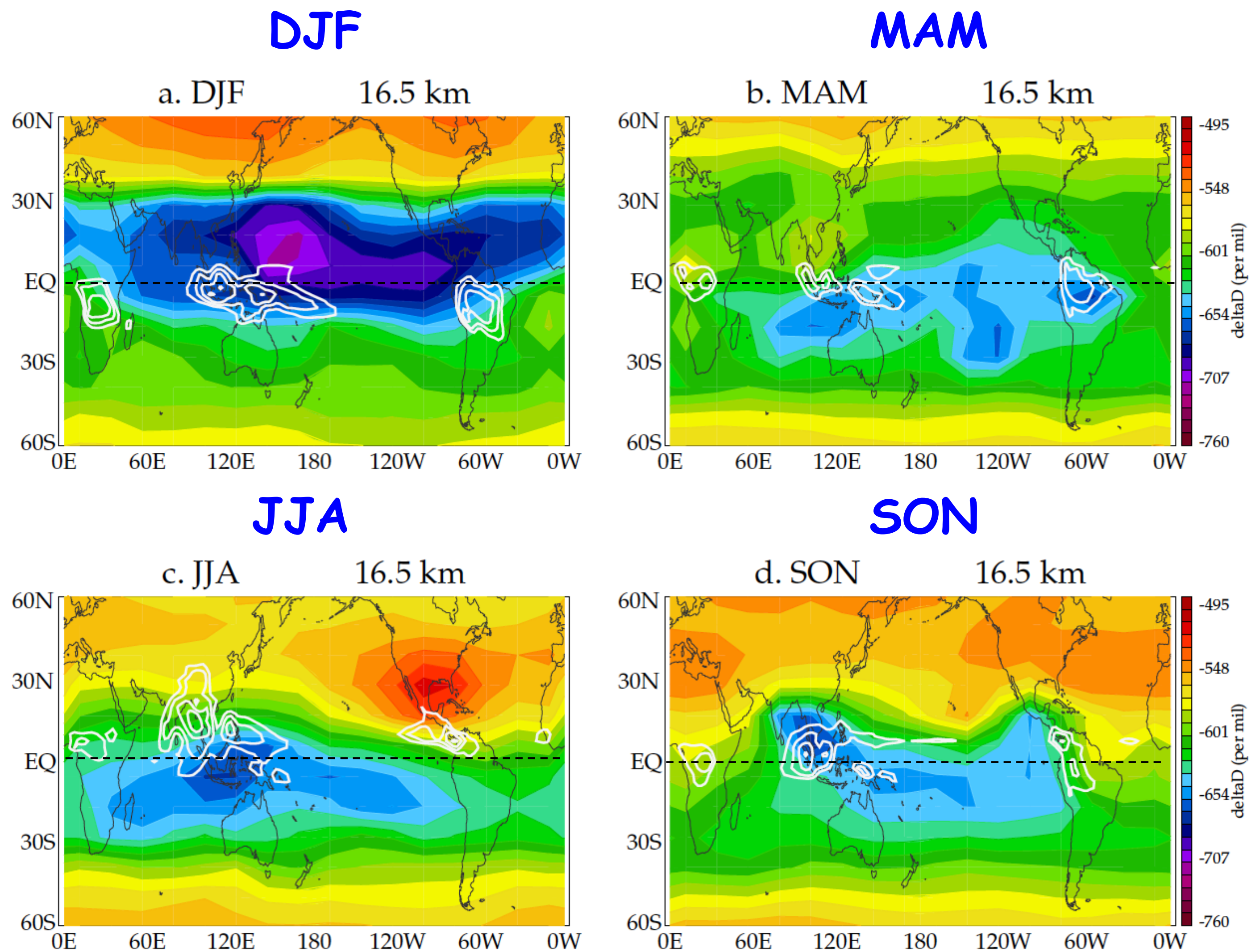
DJF

JJA

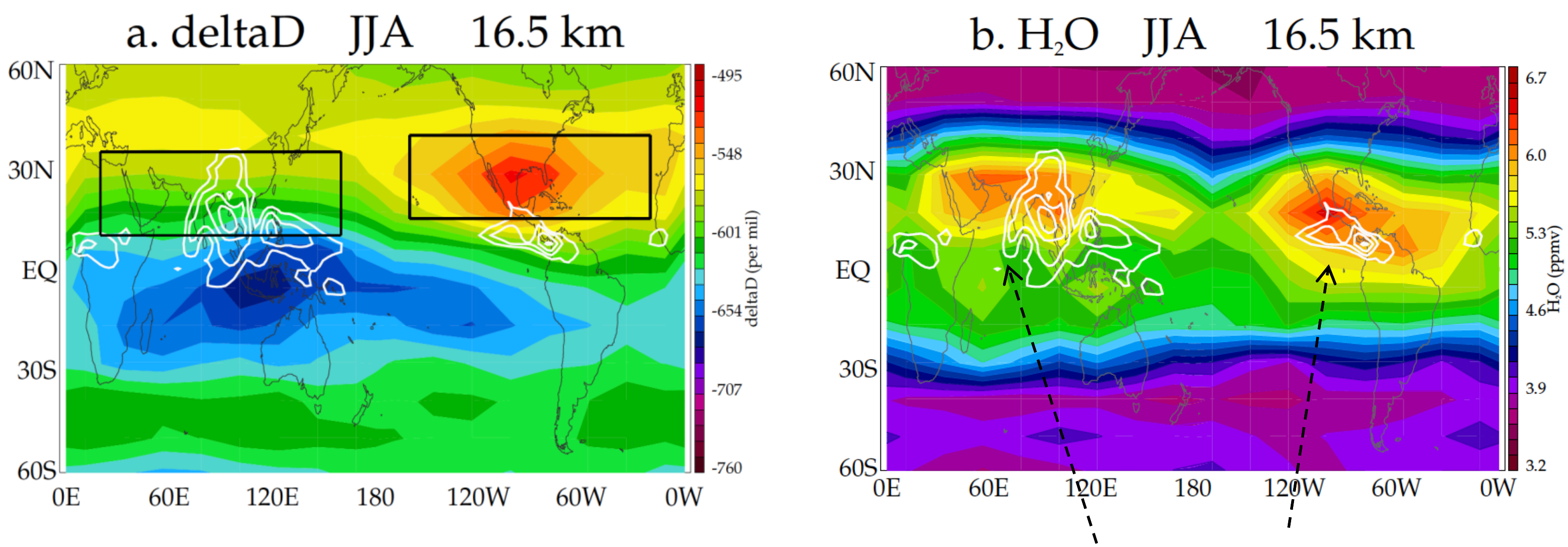


δD at 16.5 km

isotopically depleted air close to deep convection

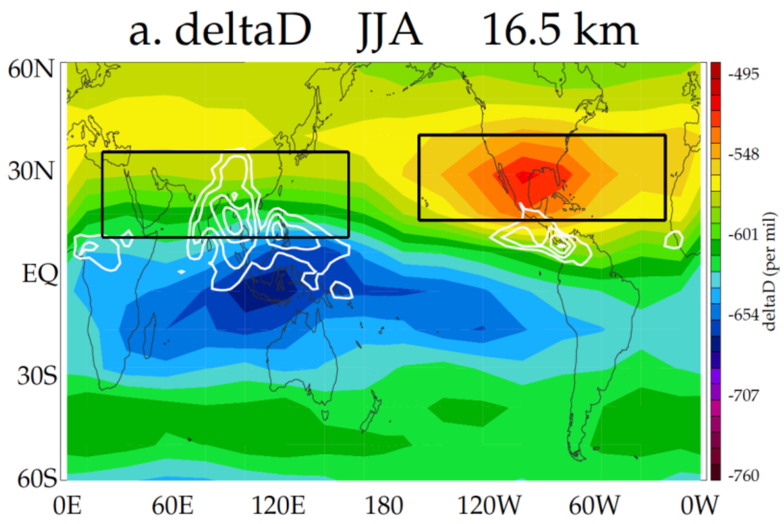


Distinct behavior of Asian, NA summer monsoon regions

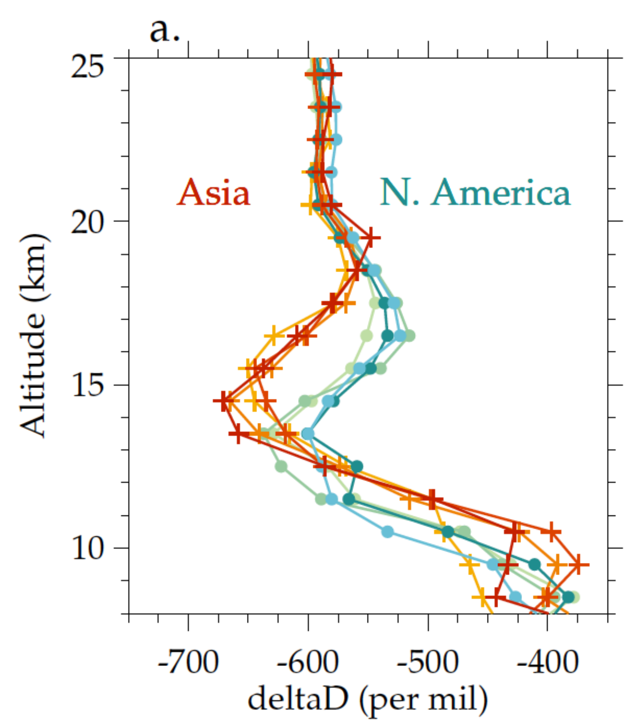


Very different δD

Similar H_2O patterns over Asian, NA monsoons

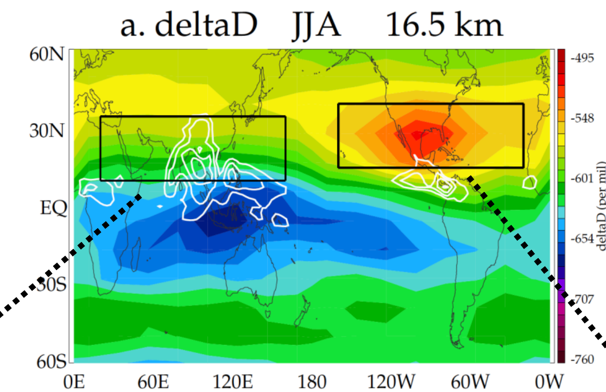


Persistent behavior: vertical profiles over Asian, NA monsoons for different years

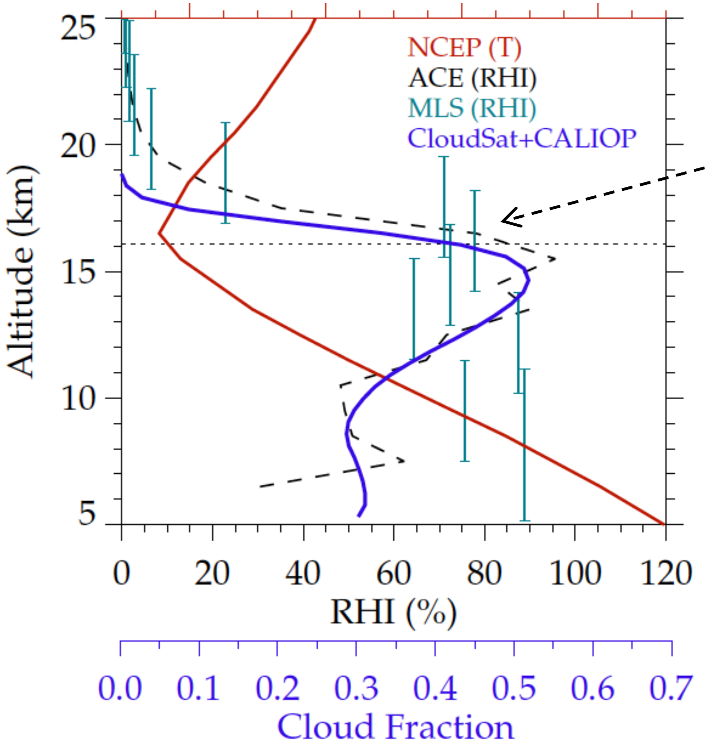


Relevant physics: depth of overshooting convection, into unsaturated stratosphere (e.g. Dessler and Sherwood, 2004)

Clouds and thermodynamic profiles over monsoons

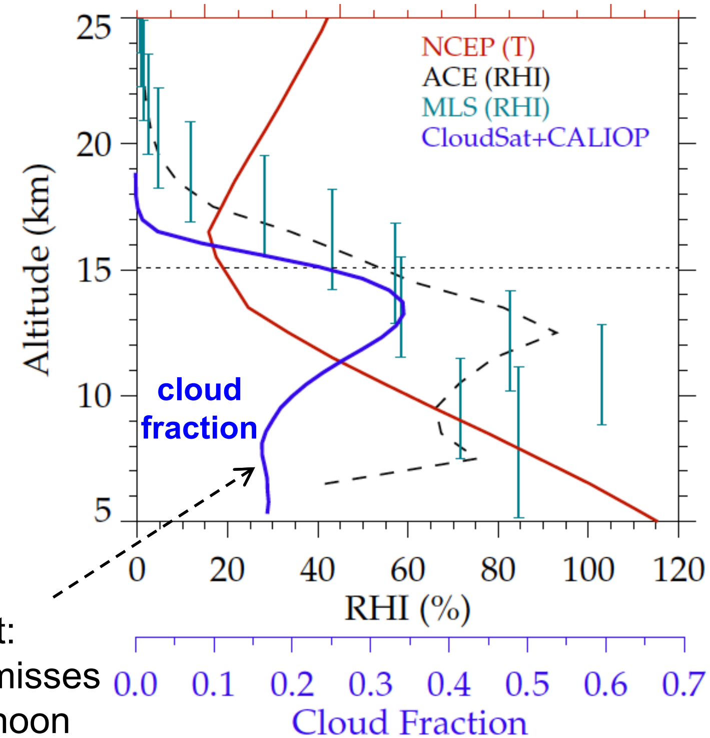


Asia monsoon



higher saturation over Asian monsoon

N. America monsoon

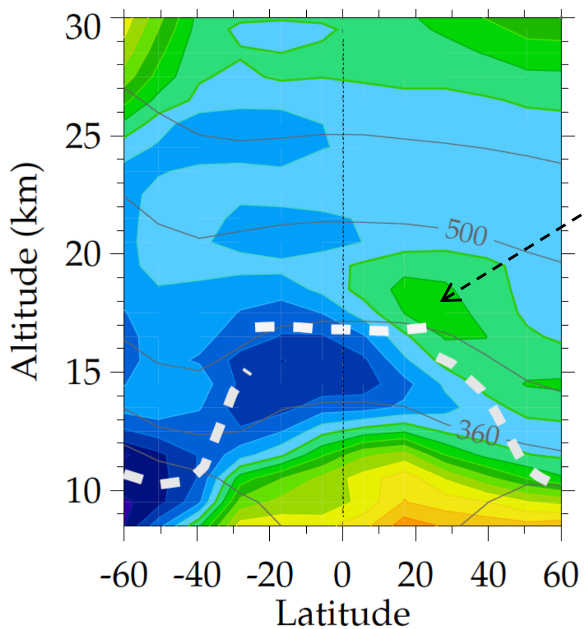


Caveat: CALIPSO misses late afternoon deep convection

monsoon signal in δD

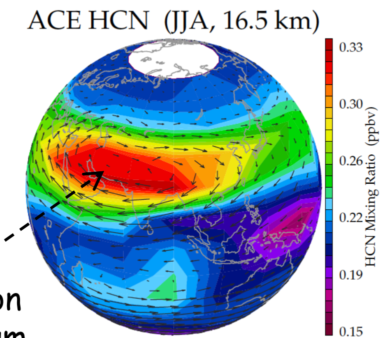
(comes mainly from N America)

ACE δD JJA



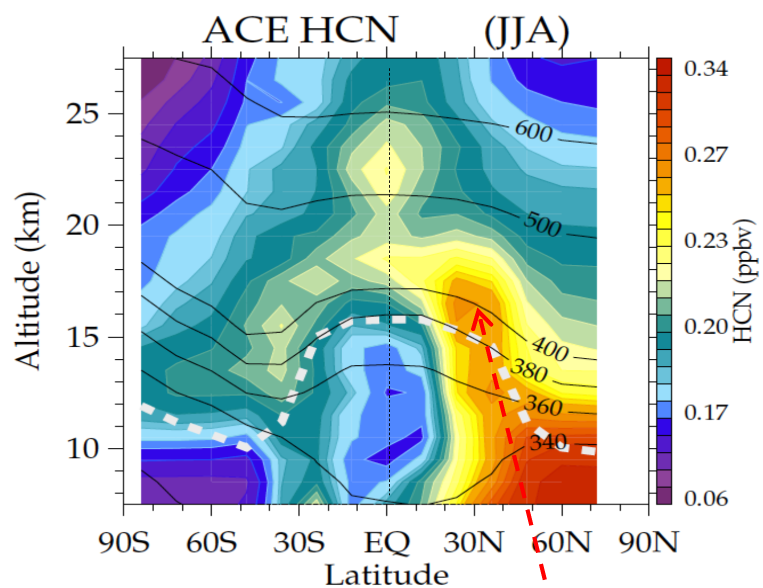
isotope signal mainly from N. America

Asian monsoon signal in HCN



Asian monsoon maximum

Randel and Park, 2006, J. Geophys. Res.



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:

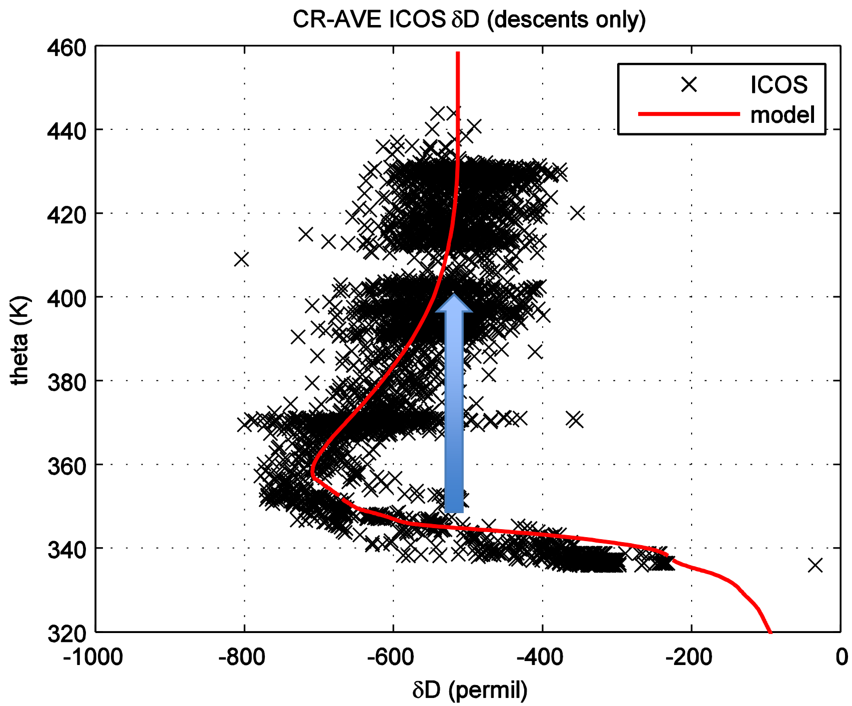
- What causes the seasonal variation in tropical δD?
  (max. depletion during NH winter)

- 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’)?

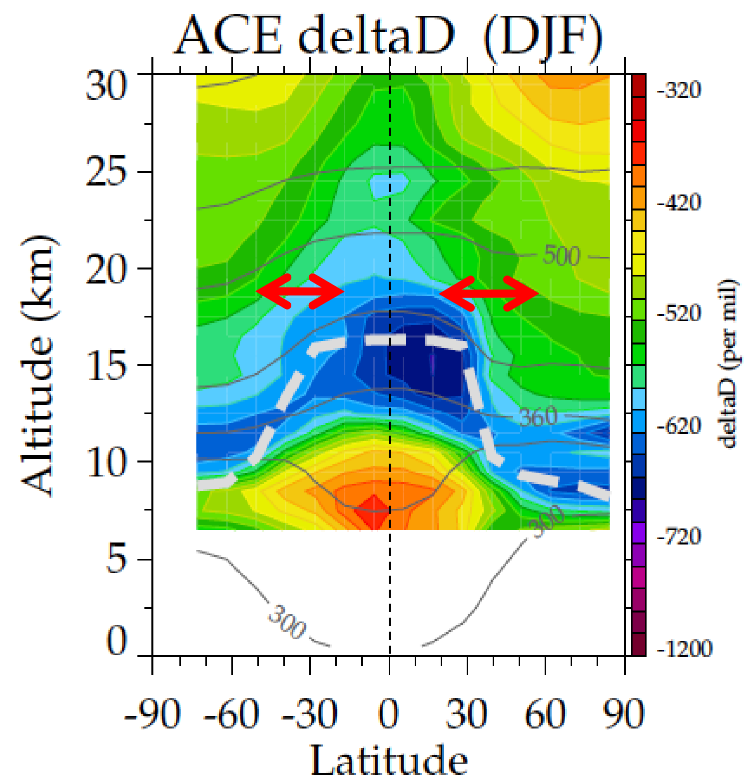
Mechanisms for the increase of δD above tropopause:

1) Convective ice lofting



Simulation by Max Bolot, LMD

2) Mixing from extratropics



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