Transport and mixing in the TTL
Convective sources

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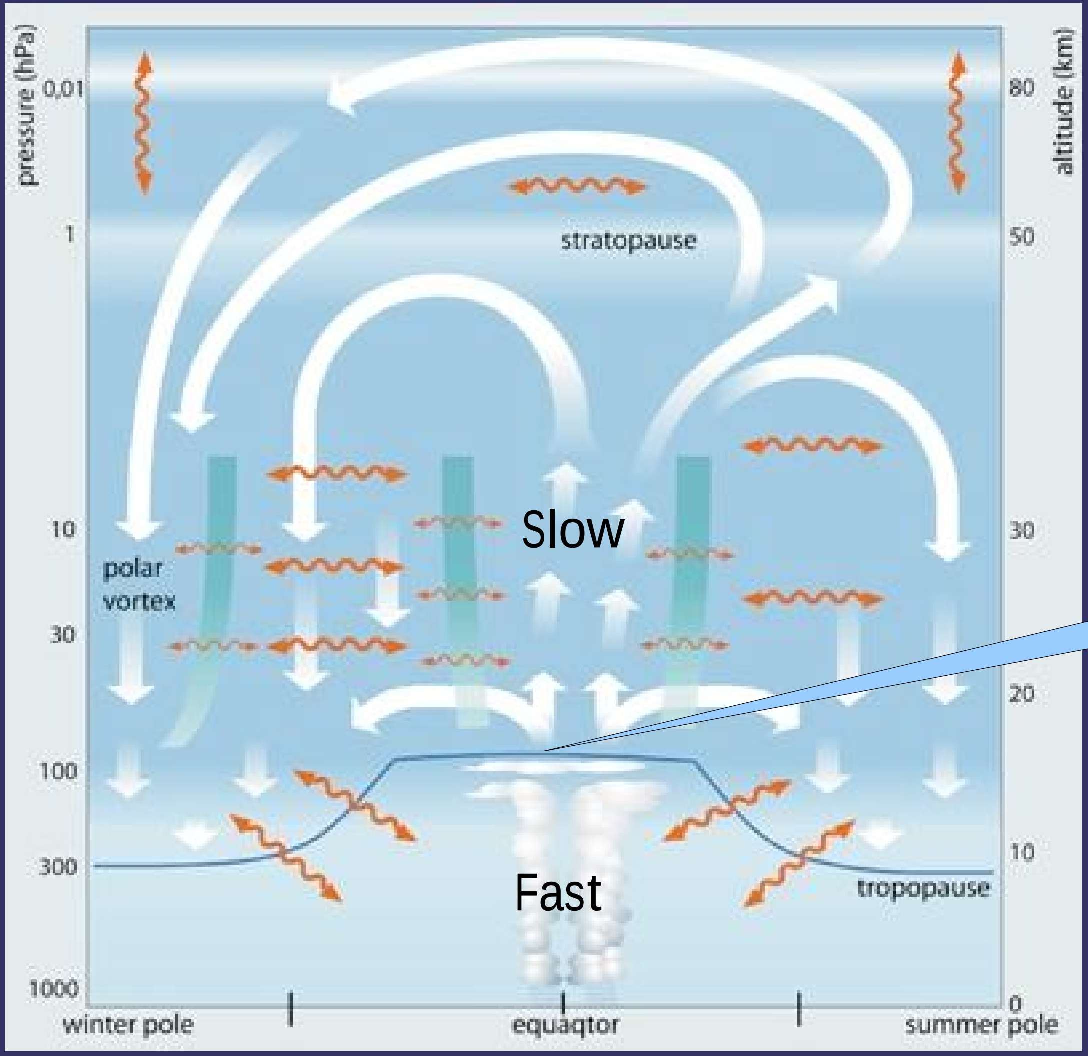
Outline

- The Tropical Tropopause Layer
- Convective sources
- Lagrangian trajectories between convective sources and the tropopause
- 1-D model of transport and mixing in the TTL
- Conclusions

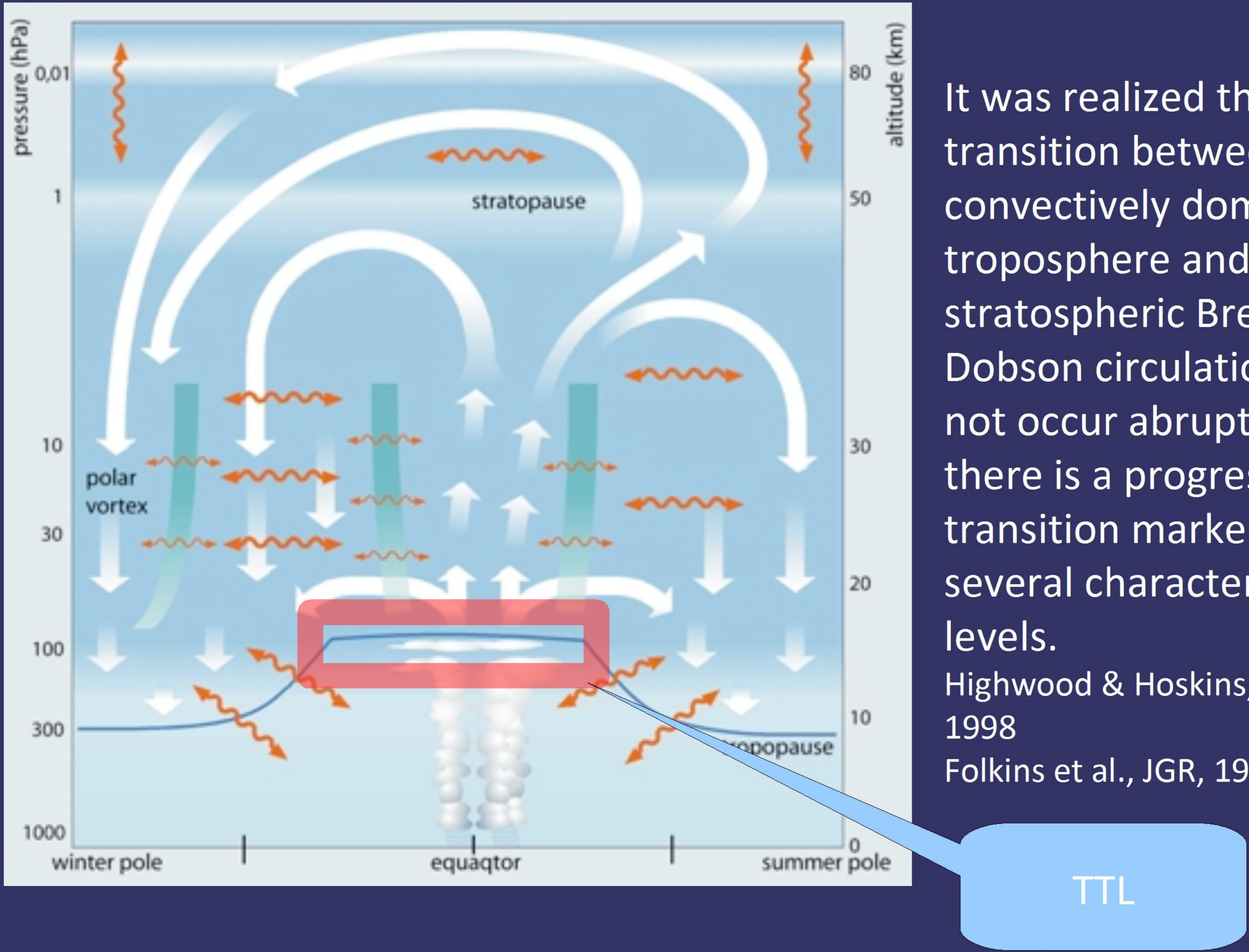
The Tropical Tropopause Layer

The tropical tropopause is the gate for air entering the Stratosphere and the Brewer-Dobson circulation



Tropical cold point
17.5 km, 195K

The tropical tropopause is the gate for air entering the Stratosphere and the Brewer-Dobson circulation



It was realized that the transition between the convectively dominated troposphere and the stratospheric Brewer-Dobson circulation does not occur abruptly but that there is a progressive transition marked by several characteristic levels.

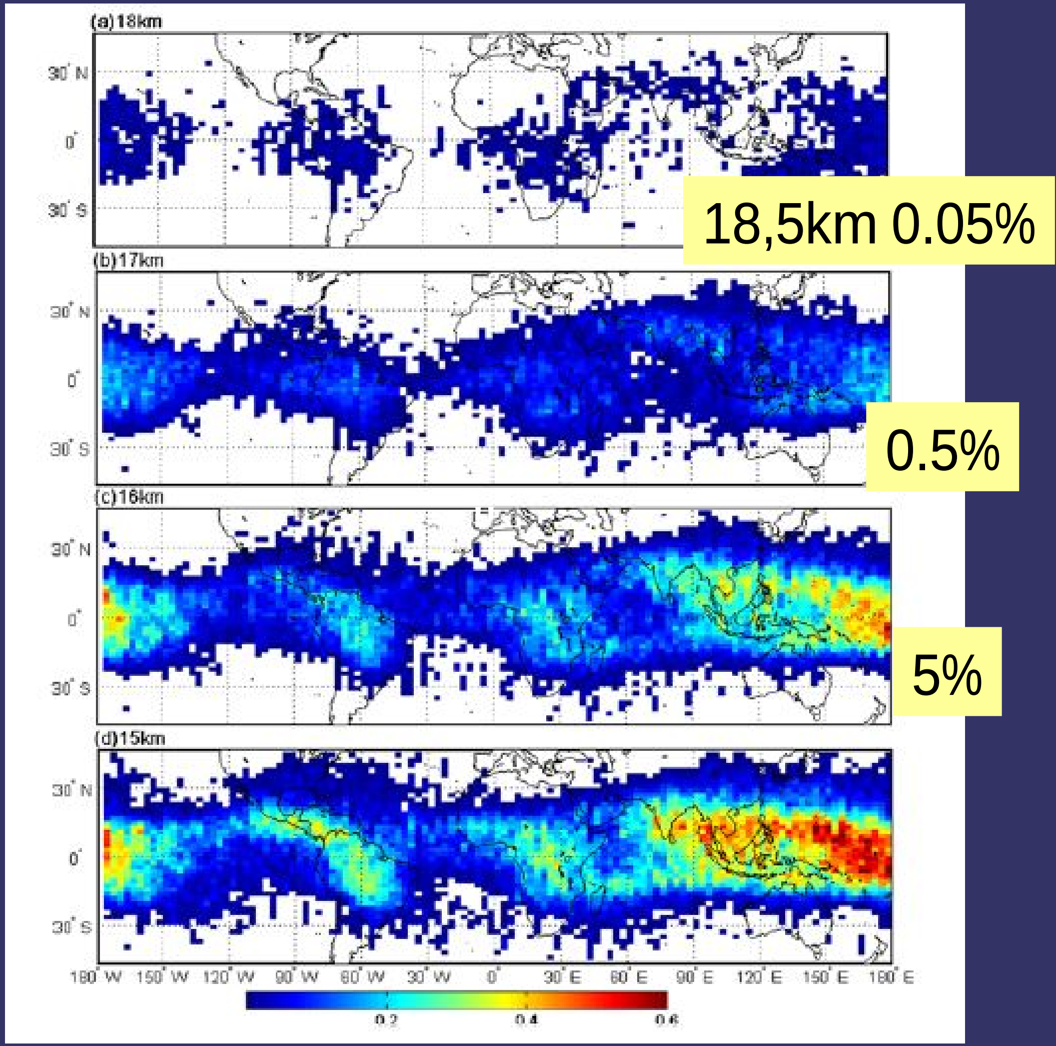
Highwood & Hoskins, QJRMS, 1998

Folkins et al., JGR, 1999

Convection hardly reaches the tropopause. Most clouds detrain below 15 km. Only a very small fraction (<0,5% in all seasons) is reaching the tropopause.

Liu and Zipser, JGR, 2005
Rosslow and Pearl, GRL, 2007
Fu et al, GRL, 2007
Yang et al., JGR, 2010

Cloud fraction according to CALIOP

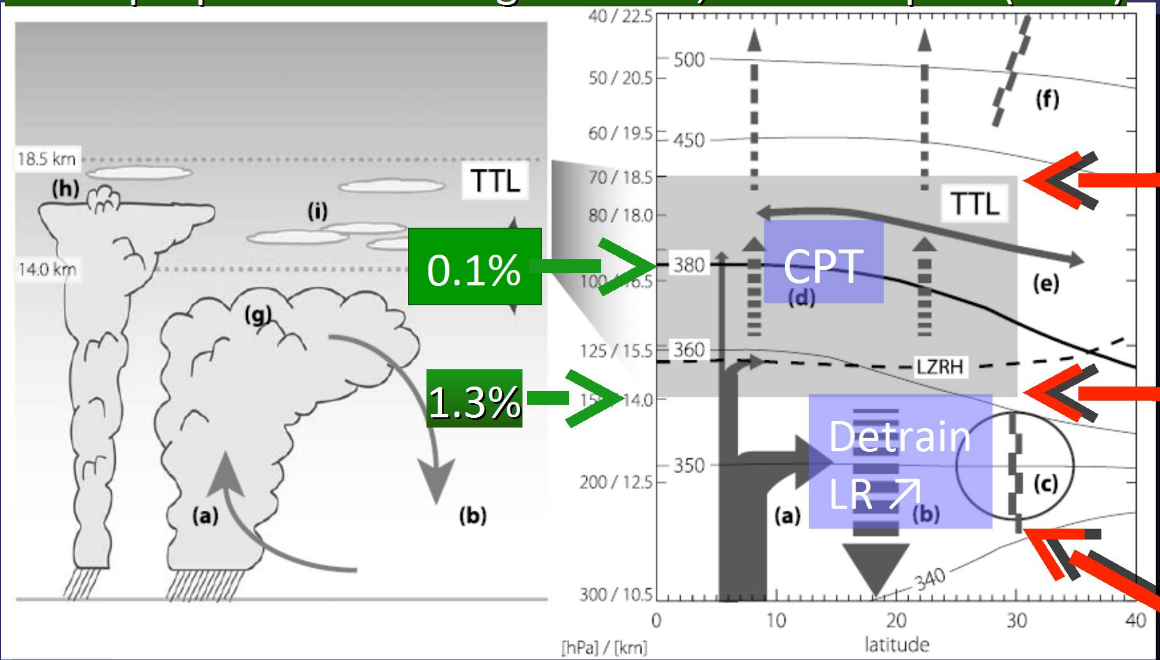


Fu et al, 2007

Definition of the TTL by Fueglistaler et al., RG, 2009

based on the large-scale dynamic and thermodynamic structure

Cloud proportion reaching the level, Liu and Zipser (2005)



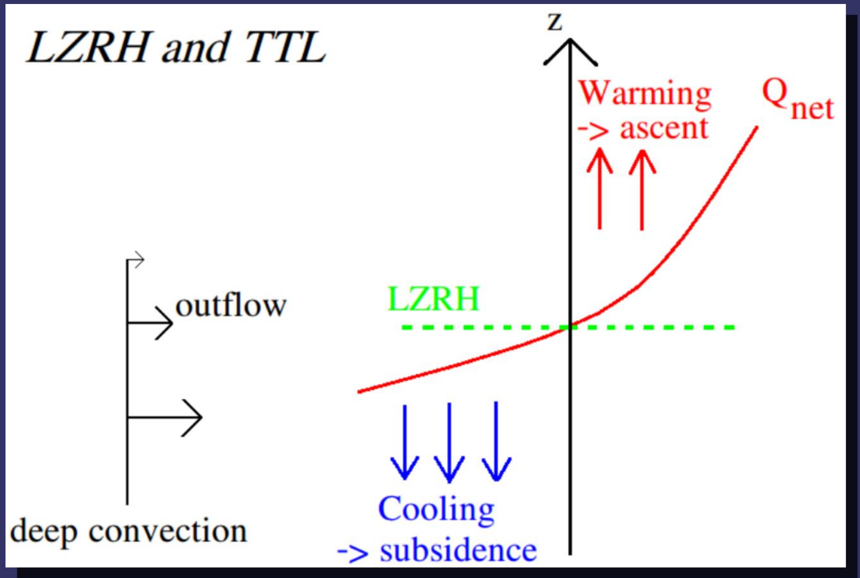
(adapted from Fueglistaler and al., 2009)

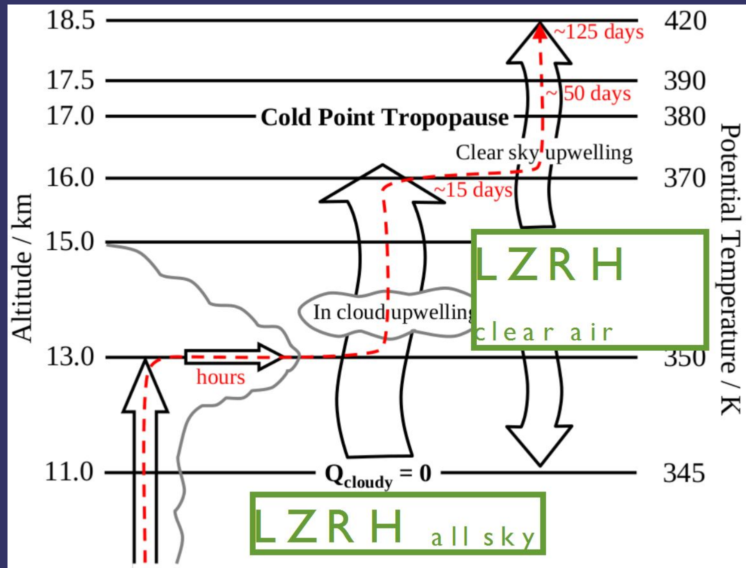
<u>70 hPa :</u>
Circulation no more influenced by geographical distribution of convection and the static stability is maximum.

<u>150 hPa :</u>
longitudinal temperature anomalies and radiative heating change sign : deep convection looses domination

<u>In latitude :</u>
zonal subtropical jets

Transition of radiative heating in the TTL from negative to positive values

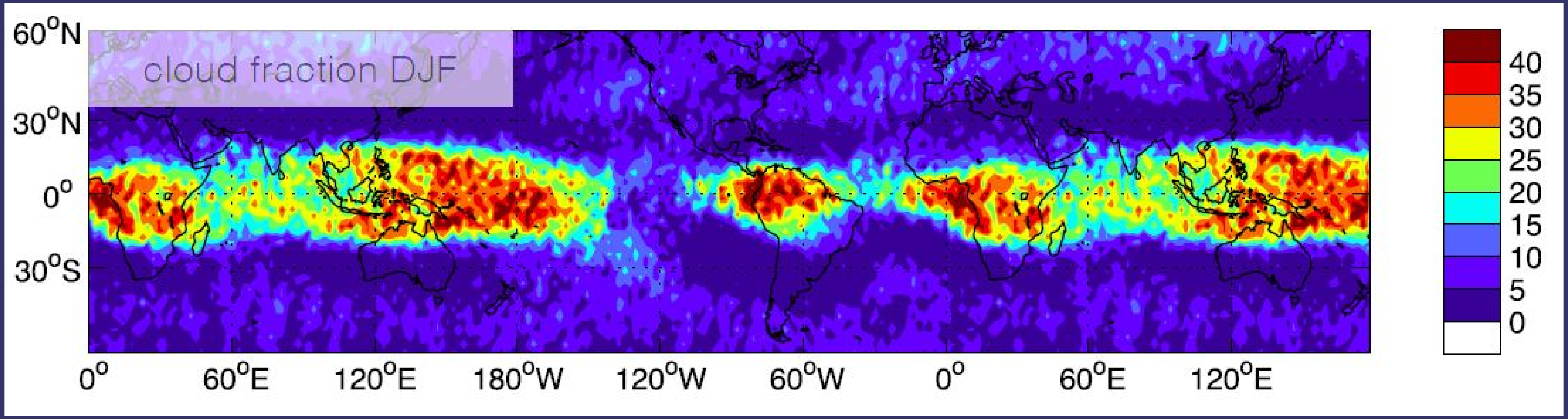




The Level of Zero Radiative Heating (LZRH) is above the mean level of convective outflow. It divides ascending (above) and descending (below) motion in clear air.

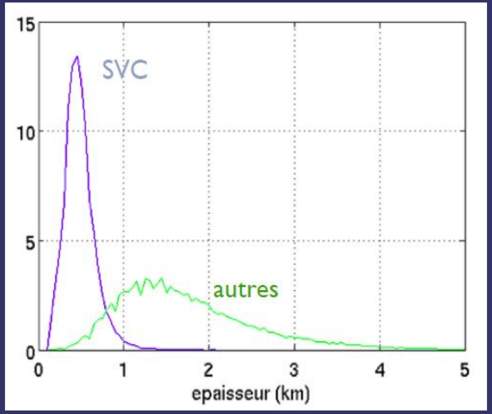
Schematic of troposphere-to-stratosphere transport pathway. Left : Deep convection of moderate strength up to about 350K. Center : In-cloud upwelling to 370K. Right : Upwelling in clear-sky or in optically thin cloud through the cold point tropopause into the lower stratosphere. [Corti and al., 2006]

Subvisible cirrus clouds (T<-74°C, 200K, optical depth < 0.03)
Average from CALIOP DJF

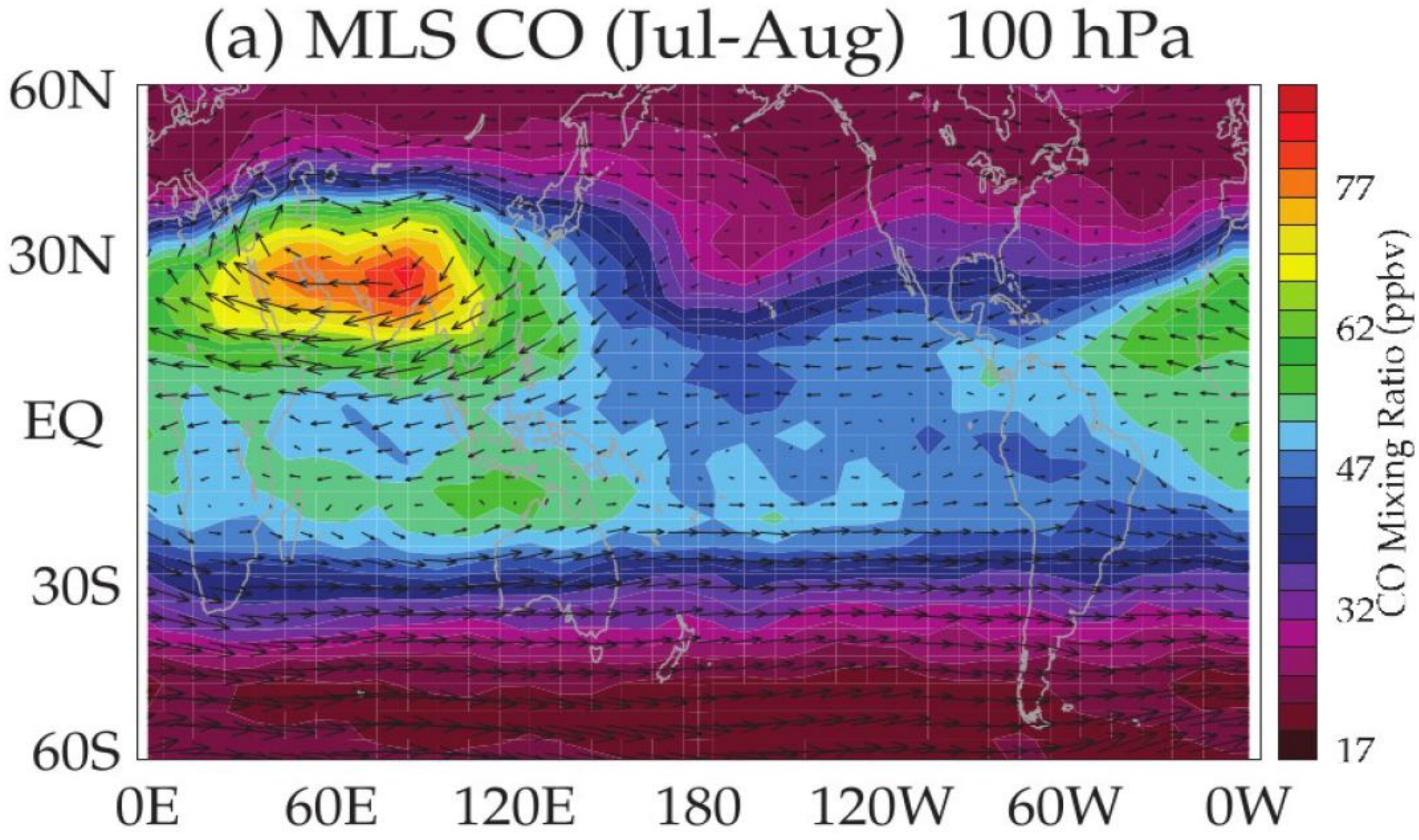


Thin cirrus extend over a large range in the tropics above and downstream of convective regions
Martins et al., JGR, 2011
Reverdy et al., ACP, 2012
They trace the dehydration of air entering the stratosphere.

Thickness is 30-50 % of other cirrus



During summer season a large upper layer anticyclonic circulation over Asia and Middle-East traps tropospheric compounds in the TTL and favors tropics – extratropics exchanges

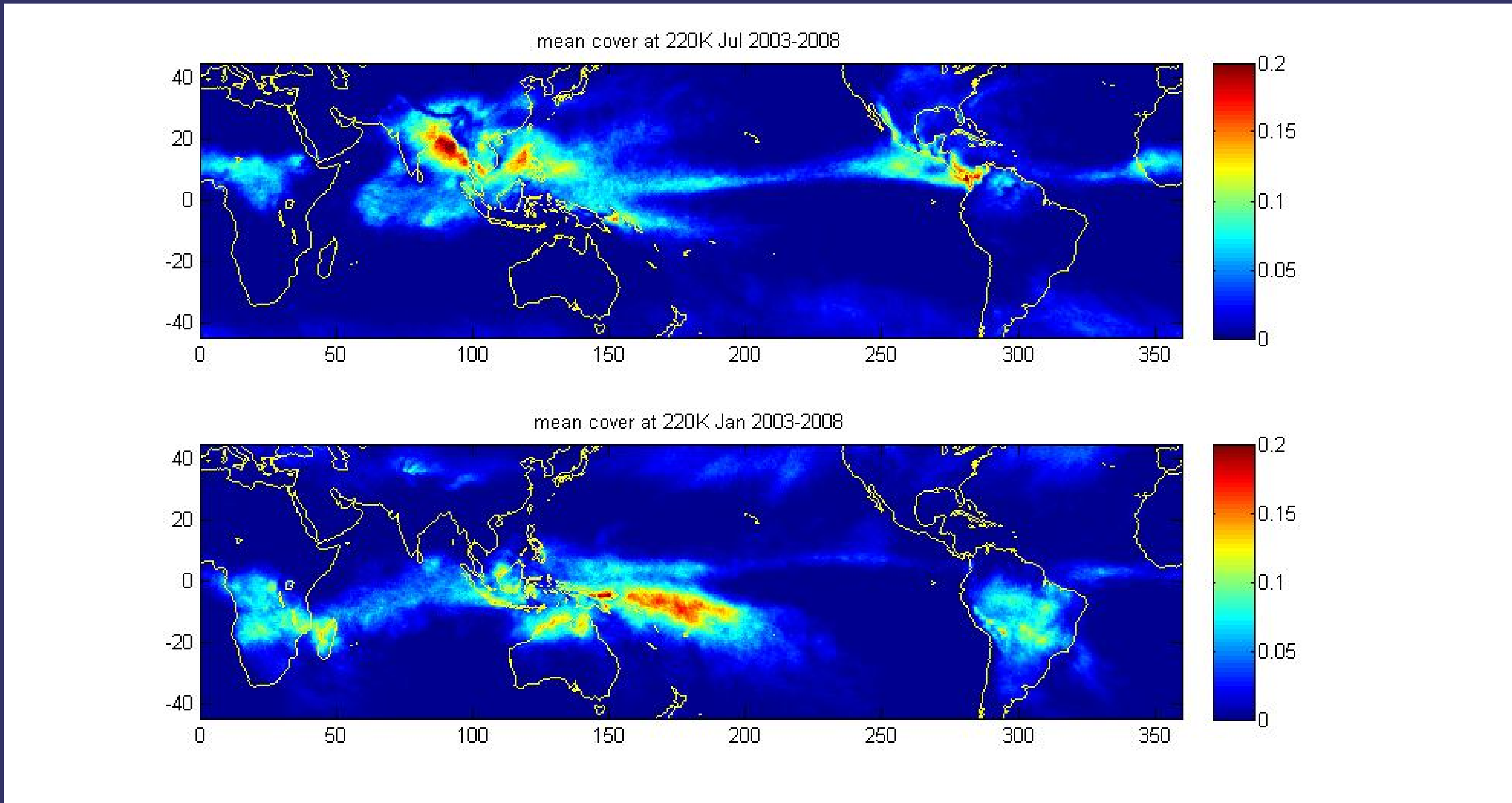


Park et al., JGR, 2007

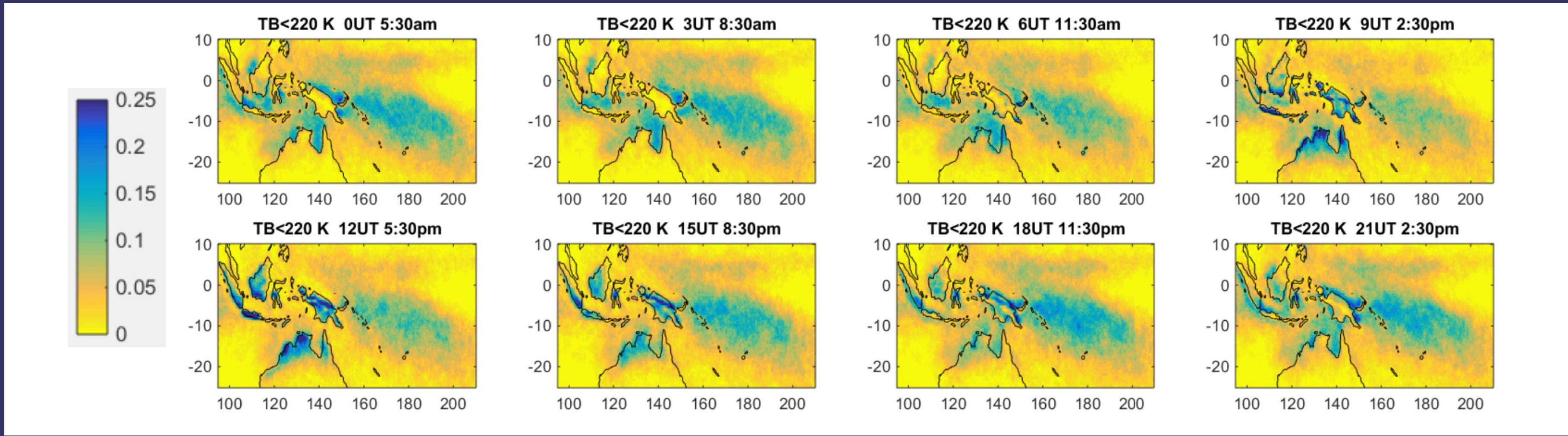
Convective sources

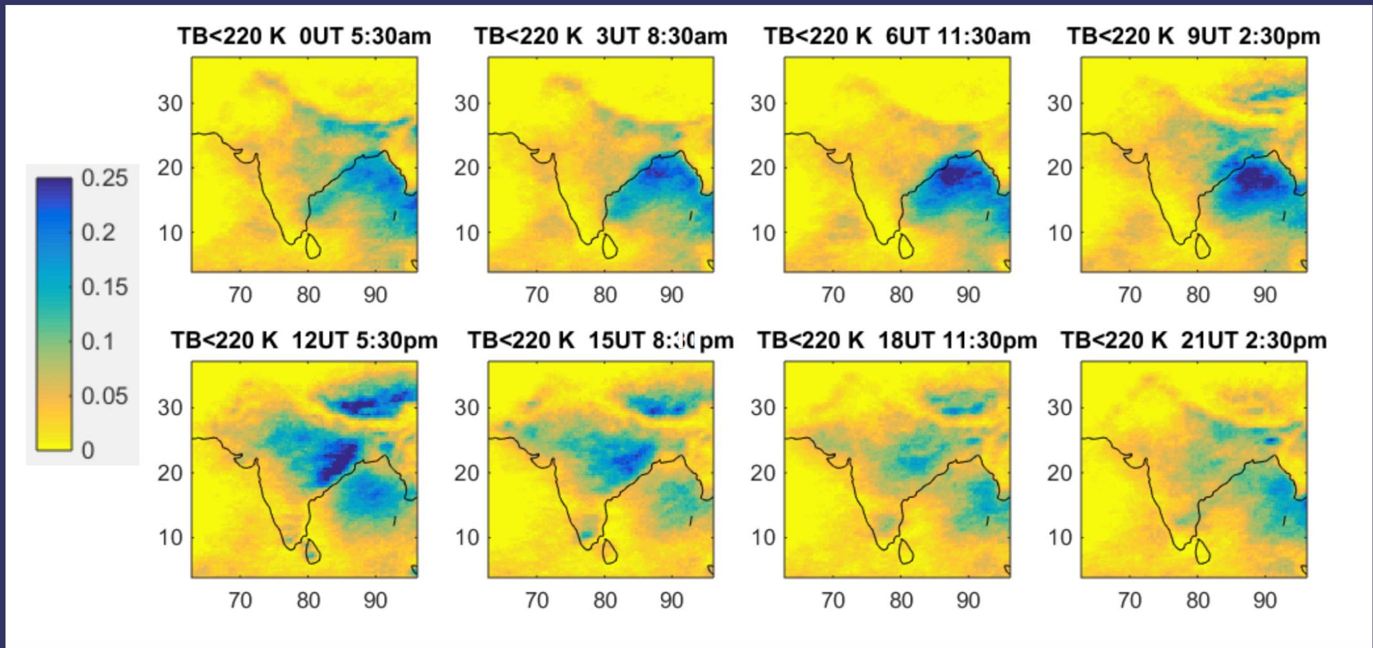
High cloud activity

Mean cloud cover with brightnes temperature < 220K
from CLAUS dataset



Daily cycle of high cloud activity over the warm pool during winter (JF) and over the Bay of Bengal, India and Tibet during summer (JA) 2003-2008

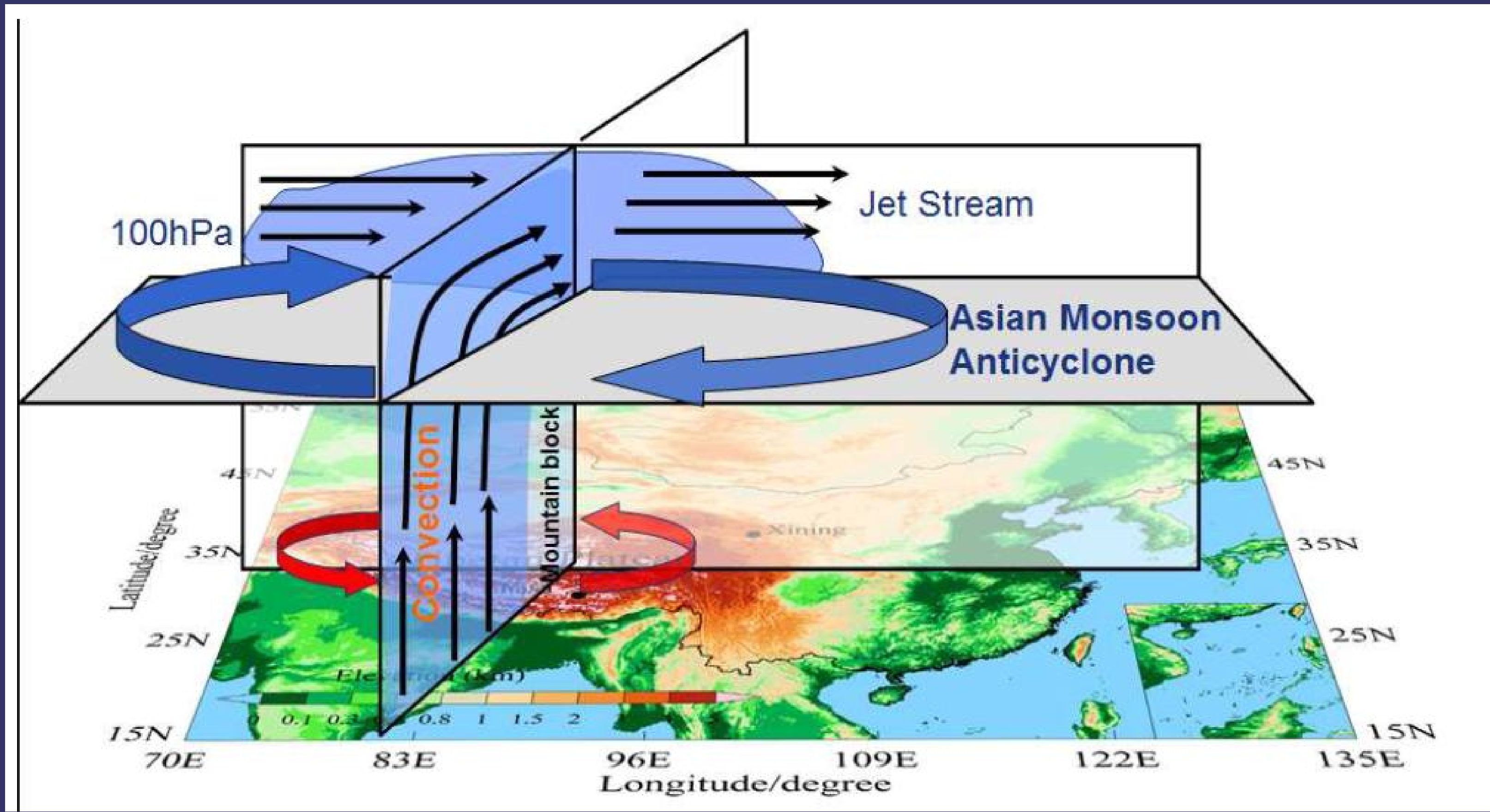




Cloud fraction

Convection occurs in the morning and early afternoon over the BoB and in the late afternoon and evening over land.

The upper level Asian monsoon anticyclone is ventilated by the convection beneath its easterly branch.

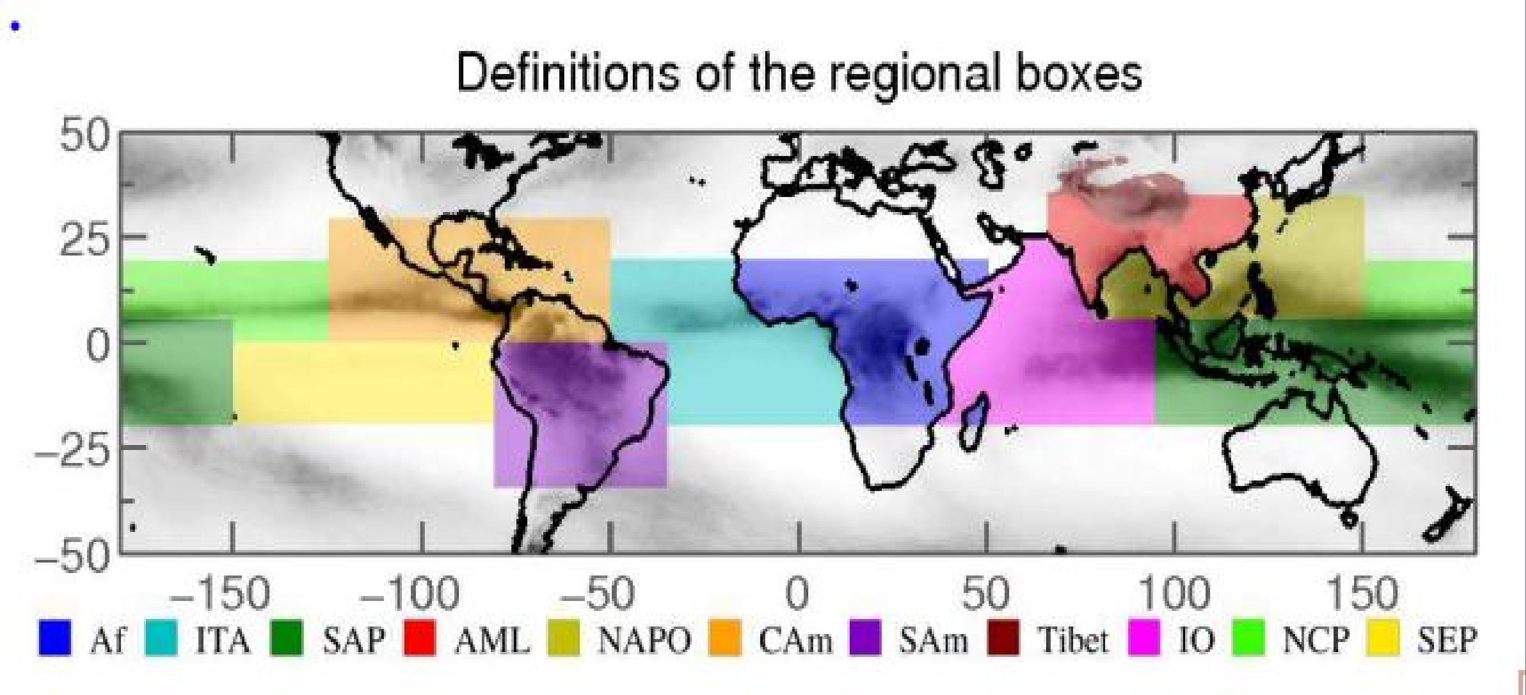


courtesy of Yong Wang

General questions

- How parcels detrained by convection are tranported in the TTL, across the level of zero heating ?
- What is the horizontal and vertical distribution of the convective sources ?
- What is the residence time of parcels within the TTL ?
- Seasonal and regional variability?

Regional boxes are defined over the major contributing sources, separating continental from maritime convection

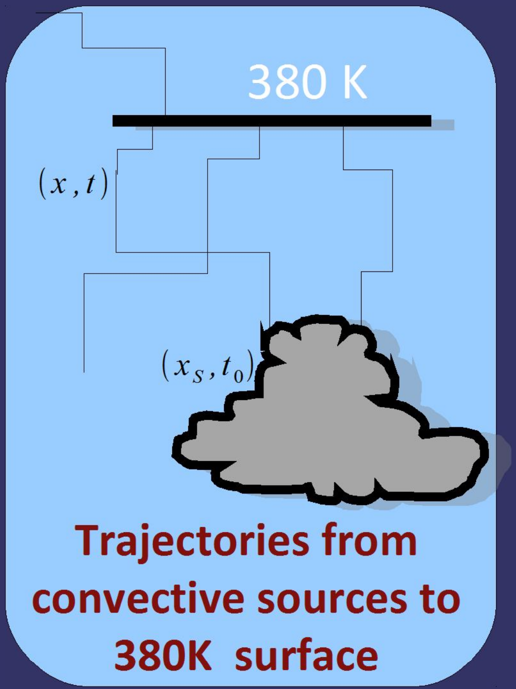


Af : Africa
ITA : Inter Tropical Atlantic
SAP ; South Asia – Pacific
AML : Asia Main Land
NAPO : North Asia – Pacific / Ocean
Cam : Central America

Sam : South America
Tibet : Tibetan plateau
IO : Indian Ocean
NCP/ North Central Pacific
SEP : South East Pacific

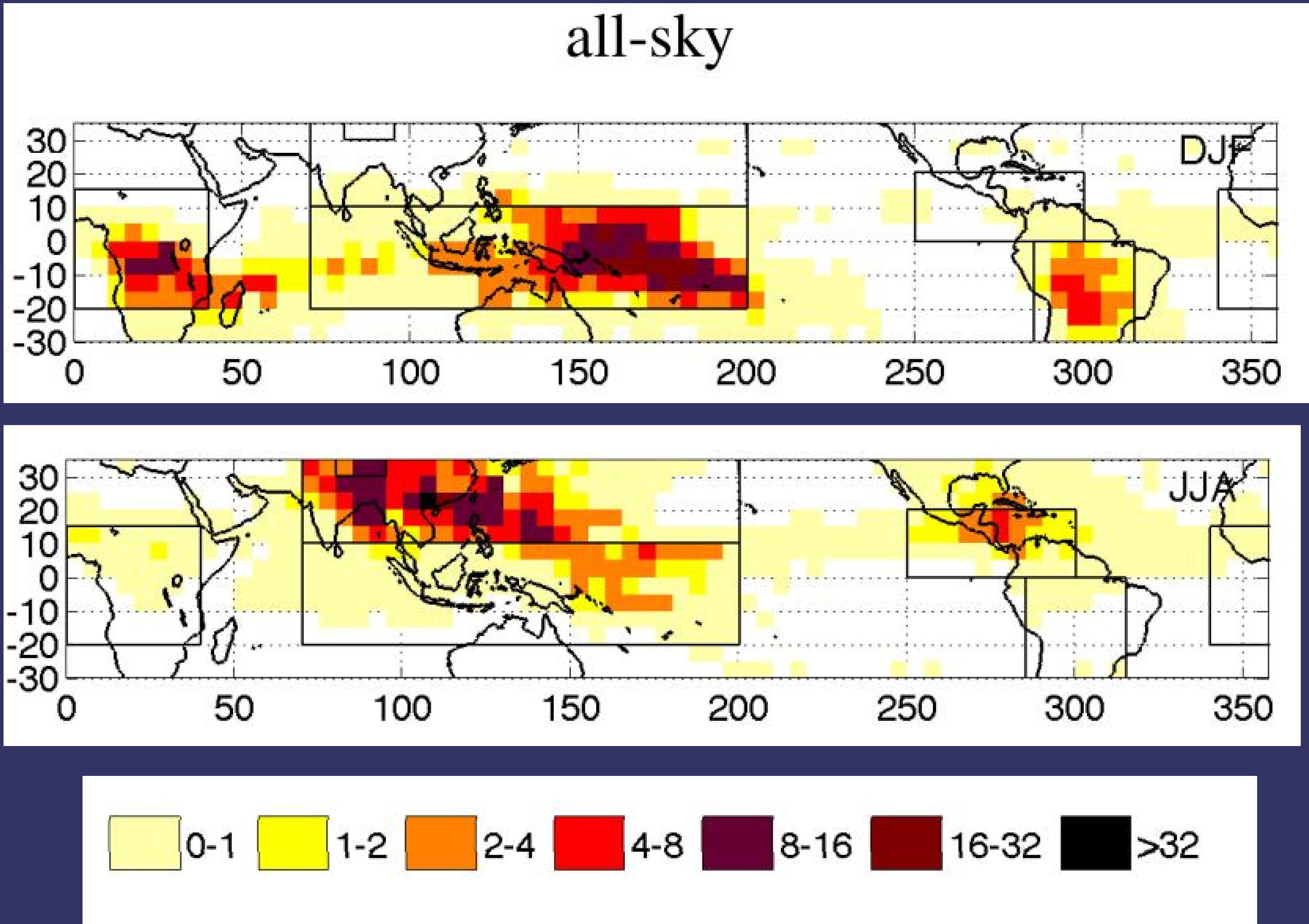
Lagrangian trajectories

- Lagrangian trajectry model TRACZILLA/FLEXPART ([Stohl and al, 2005], [Pisso and Legras,2008])
- Calculations of forward diabatic and backward diabatic trajectories..
- Horizontal part of the movement : calculated using wind fields of ERA-Interim.
- Vertical part of the movement : calculated using radiative heating rates of ERA-Interim.
- No latent heat

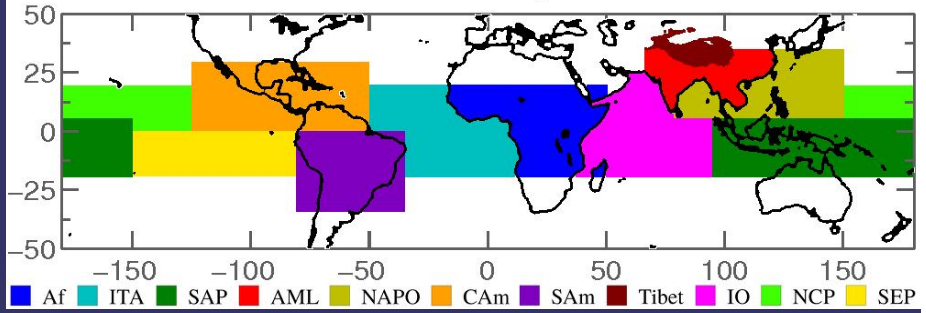


	Forward	Backward
Initialization	1 pixel T_B<230K of CLAUS between 20°S and 40°N = 1 parcel launched	1 parcel launched at 380K every 0.5°x0.5° every 2 days between 40°S and 40°N
End of the run : intersection	First intersection of the surface 380K between 40°S and 40°N	First intersection of a cloud : T_B<230K (cf. CLAUS) between 20°S and 40°N
Simulation time	3 months	
Simulations	Every month in 2005 until 2008	

Winter and summer distribution of sources

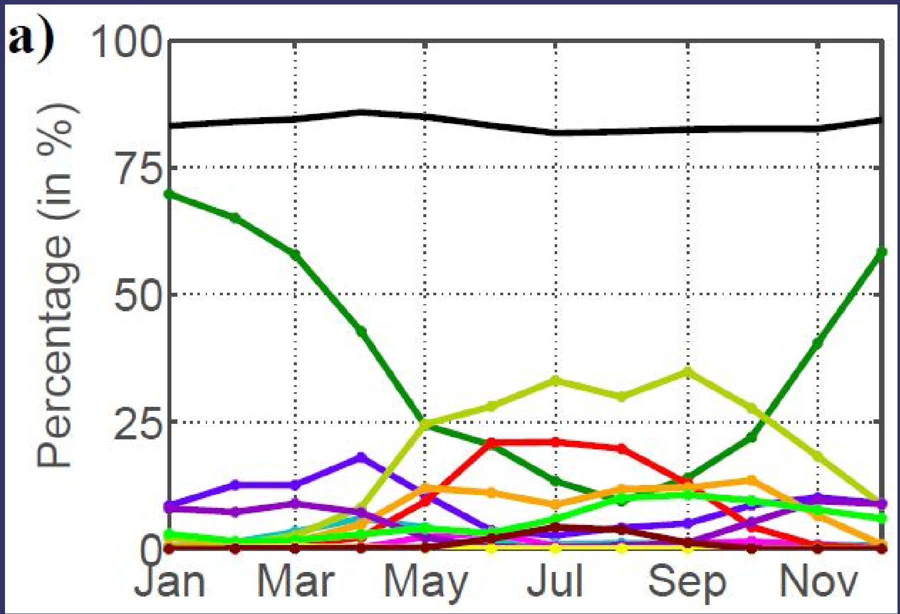


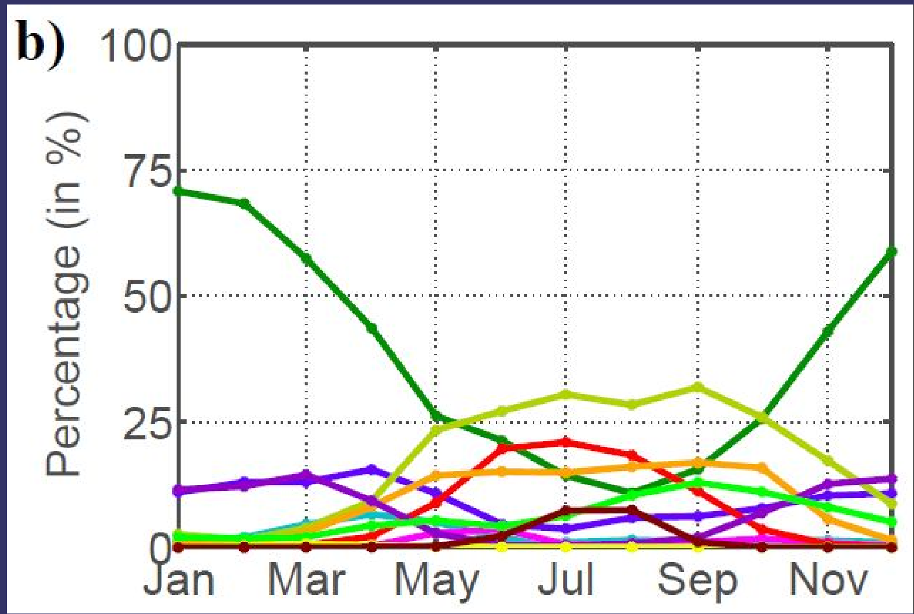
Source distribution among regions



Backward

Forward





$$\frac{\text{\# of parcels which have reached the top of a cloud in the region}}{\text{Total \# of parcels which have reached the top of a cloud}}$$

$$\frac{\text{\# of parcels which have reached 380K from a given region}}{\text{Total \# of parcels which have reached 380K from all regions}}$$

Tissier, Legras & Tzella, 2015, submitted

The advection - diffusion equation

$$\frac{\partial \chi}{\partial t} + u \nabla \chi = \frac{1}{\rho} \nabla \kappa \rho \nabla \chi$$

can be solved as

$$\chi(x,t) = \int \rho(y,s) G(x,t;y,s) \chi(y,s) d^3 y$$

where G is a Green function solution of

$$\frac{\partial G}{\partial t} + u(x,t) \nabla_x G = \frac{1}{\rho(x,t)} \nabla_x \rho(x,t) \kappa \nabla_x G \qquad (1)$$

or

$$- \frac{\partial G}{\partial s} - u(y,s) \nabla_y G = \frac{1}{\rho(y,s)} \nabla_y \rho(y,s) \kappa \nabla_y G \qquad (2)$$

with $\rho(y,s) G(x,s;y,s) = \delta(x-y)$

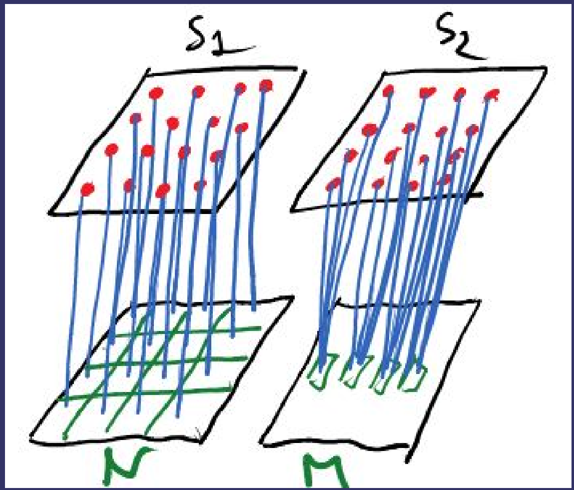
The Green function is also the probability to find in x at time t a parcel which was in y at time s.

It can be obtained either forward in time with (1) or backward in time with (2).

The calculation can be performed by Lagragian trajectories with noise.

However, subsampling of the initial or final space may break the reversibility due to the chaotic dispersion of trajectories.

Example of non reversibility of forward versus backward proportions.



Two regions of area S1 and S2

S1 is associated with a dense distribution of N convective sources, such that each cloud feeds a surface S1/N of same area at the tropopause.

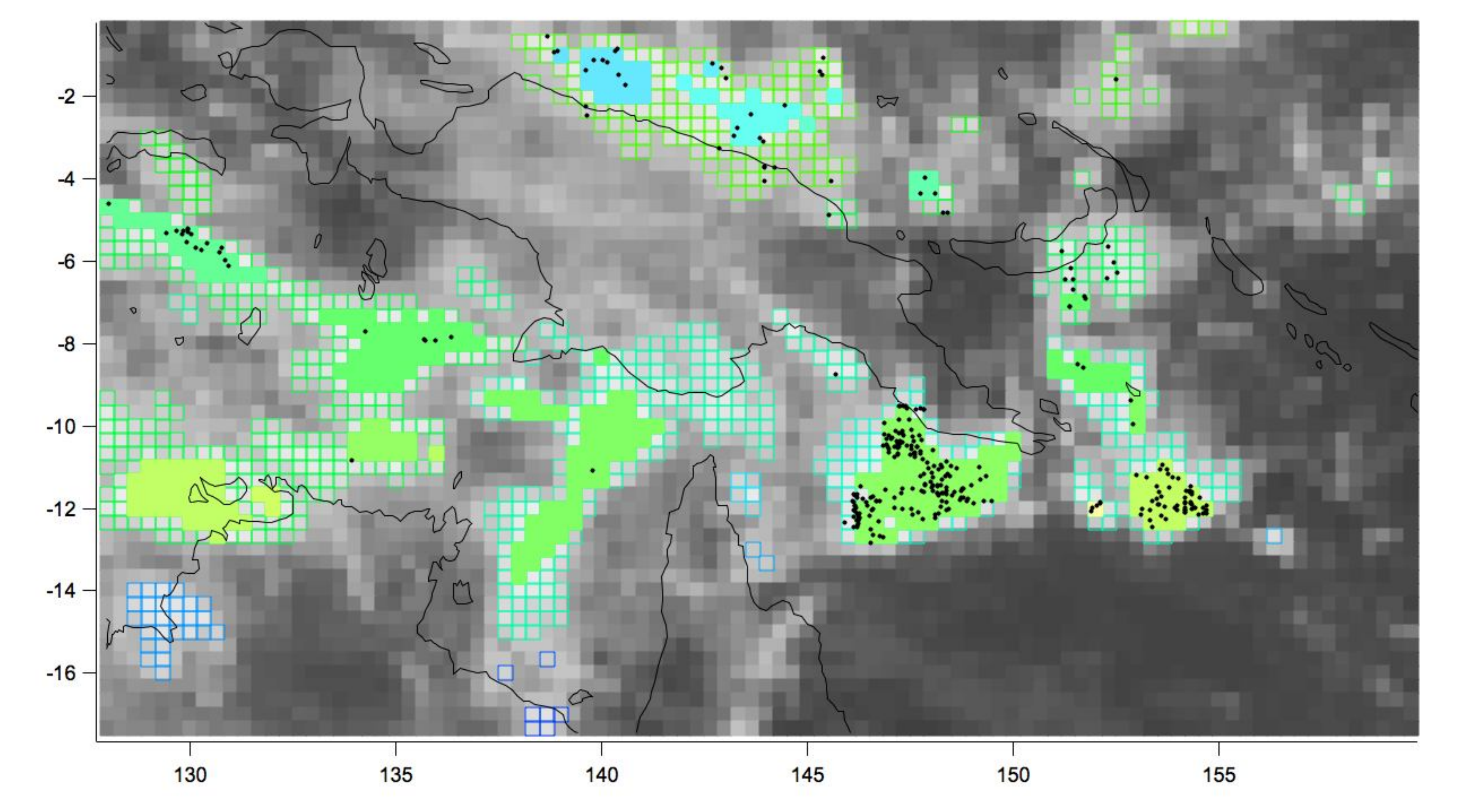
S2 is associated with M << N clouds, each one feeding a surface S2/M at the tropopause.

No other clouds and no lateral exchange

Backward calculations with regular sampling at the tropopause provides proportions S1/(S1+S2) and S2/(S1+S2)

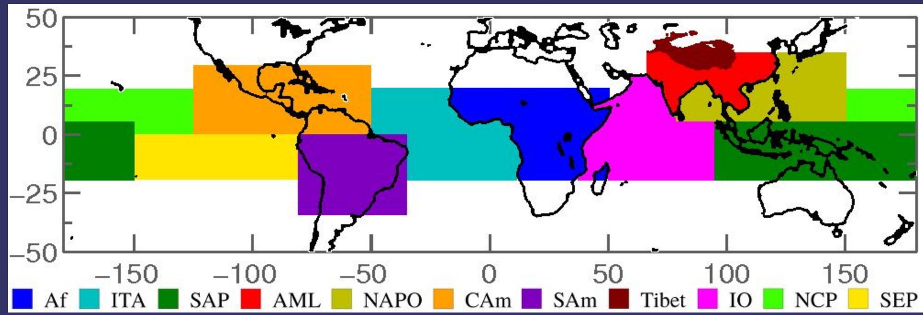
Forward calculations with one parcel over each cloud provides proportions N/(M+N) and M/(N+M) which are different.

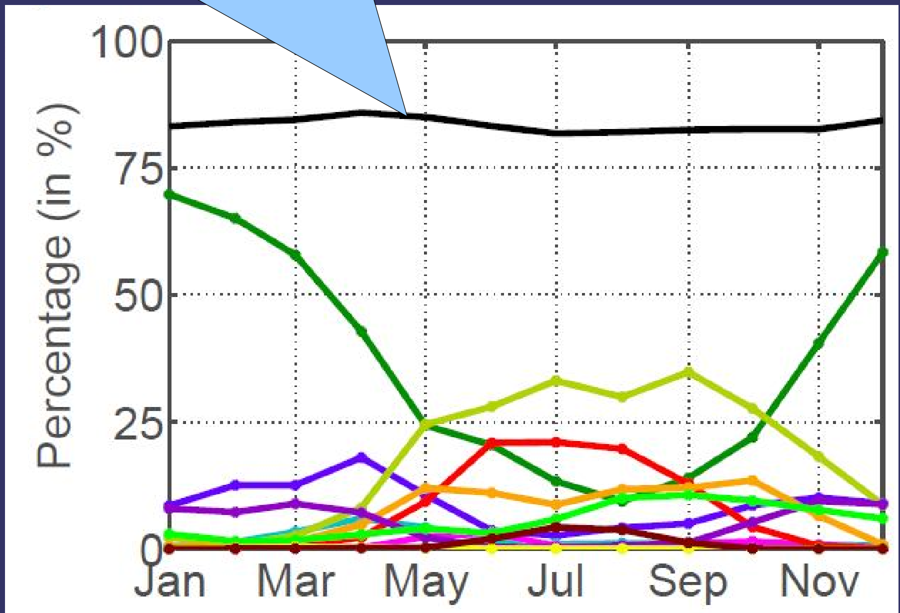
Localisation of sources on a given day over the Bay of Carpentaria

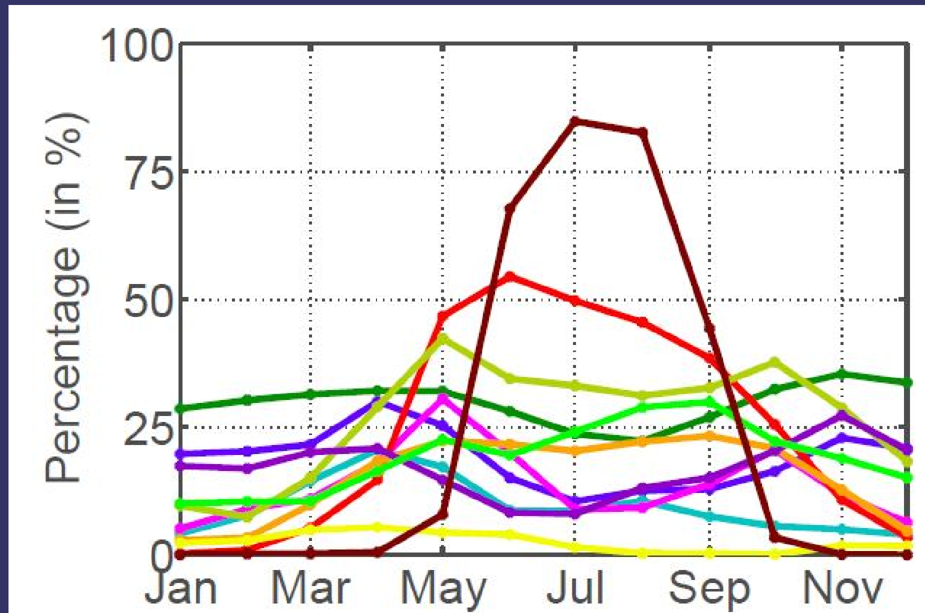


Backward trajectories hit preferentially some clouds and ignore other ones.
Pixel size : 30km

Proportion of parcels launched at 380K, reaching a cloud within 3 months ~ 82 %







# of parcels which have reached the top of a cloud in the box
Total # of parcels which have reached the top of a cloud

# of parcels which have reached 380K
# of parcels launched from the box

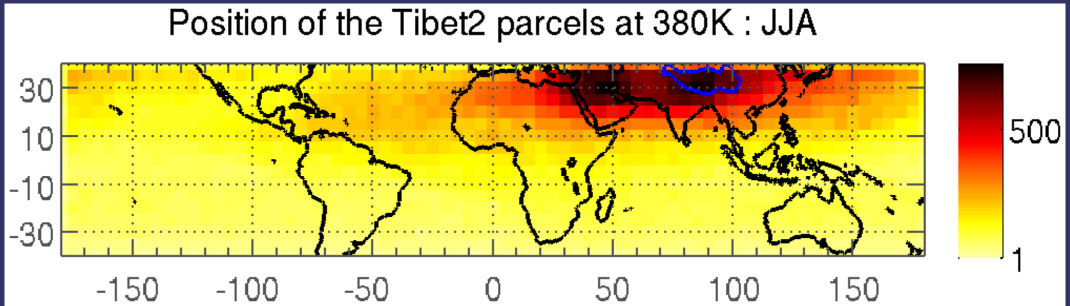
Weight of the source regions

Efficiency of the source regions

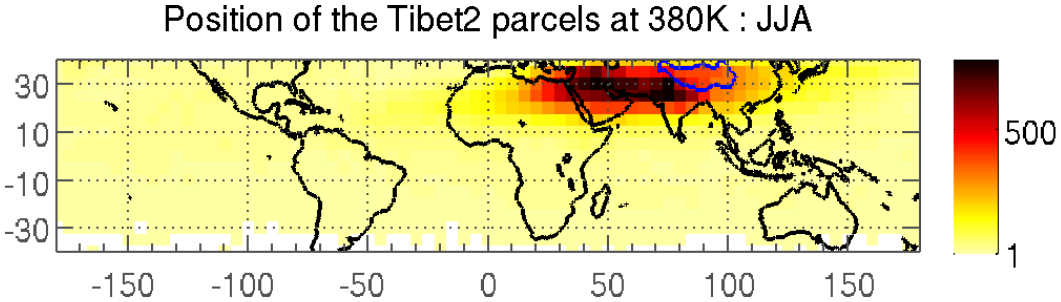
Tissier, Legras & Tzella, 2015, submitted

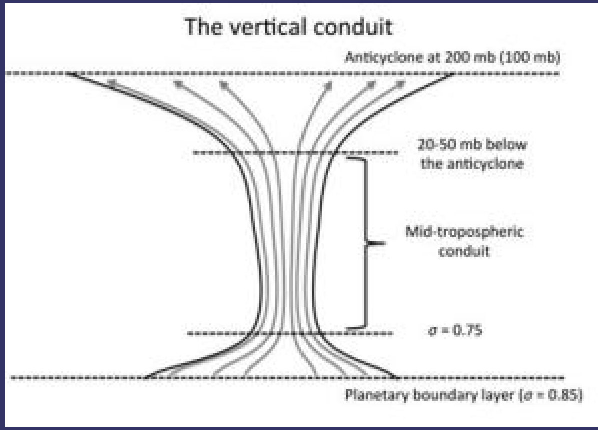
During summer, the Tibetan plateau;in spite of its small total contribution is the most efficient region in transporting air parcels from cloud top to 380K.

Backward



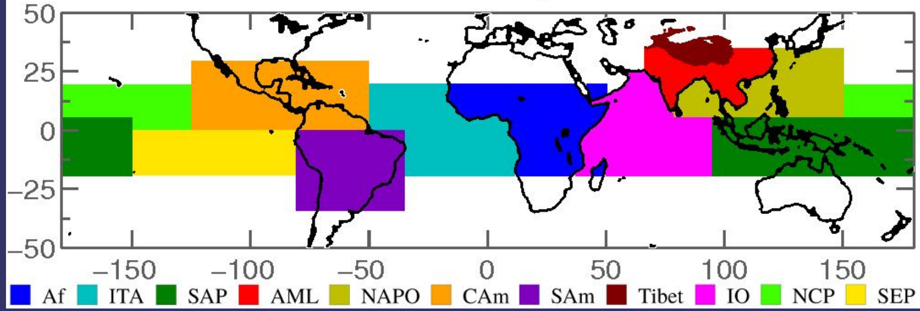
Forward

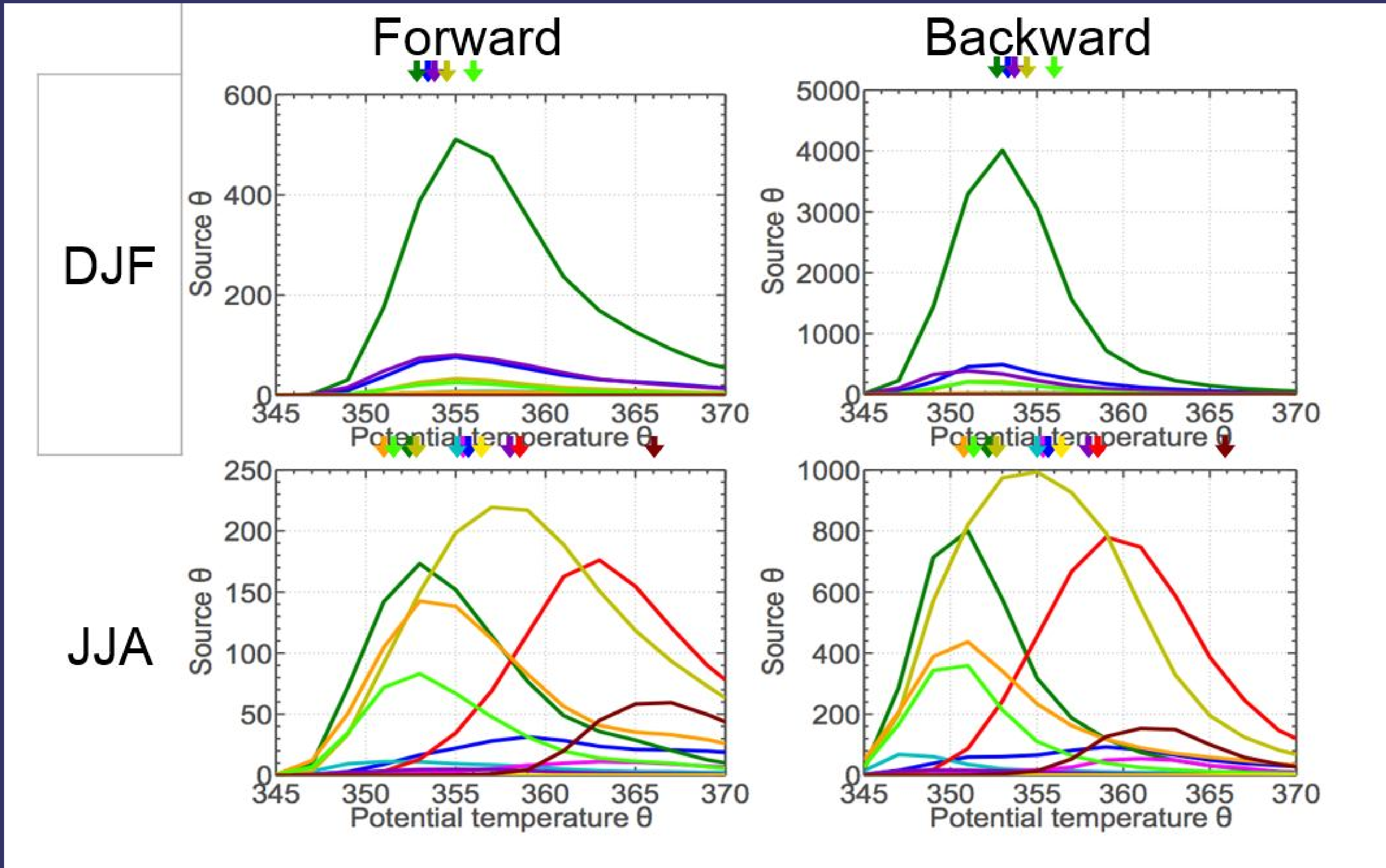




Bergman et al., ACP 2013

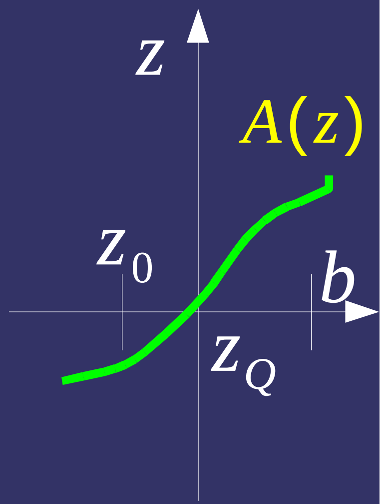
Vertical distribution of sources





A 1D model of TTL transport and mixing

A simple model of transport from LZRH to the tropopause



Mean heating rate

Motion: mean heating rate + noise $\delta z = A\,\delta t + B^{1/2}\,\delta w$

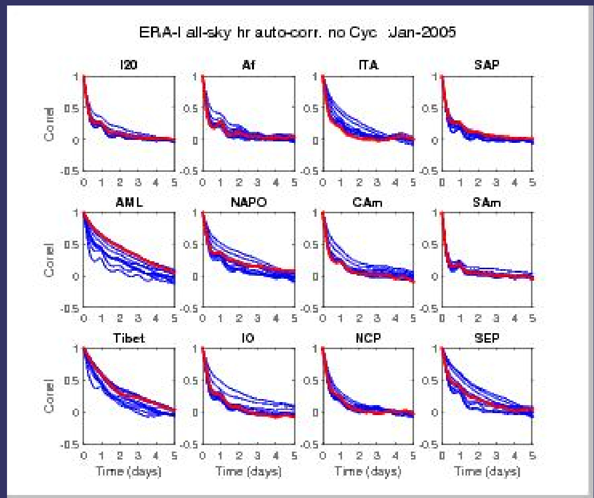
LZRH : $A(z_Q)=0$

Equation for the probability $p(z,t\,|\,z_0,0)$ of transit from z_0 at time 0 to z at time t

$$\partial_t\, p = -\,\partial_z A\,p + \frac{1}{2}\,\partial^2_{z^2} B\,p$$

B is the product between the heating rate variance and the life-time τ of the heating rate

The decorrelation curves of the heating rate show that $\tau=1$ day is a good choice over convective regions.



Equation for the probability $p(z,t\,|\,z_0,0)$ of transit from z_0 at time 0 to z at time t

$$\partial_t p = -\partial_z A p + \frac{1}{2}\partial_{z^2}^2 B p$$

This problem can be solved analytically for many interesting quantities (Gardiner, 2009)

For example, the probability to cross b (the tropopause) while starting in z_0 is $\Pi_b(z_0) = \frac{\int_{-\infty}^{z_0} \psi^{-1}(y)\,dy}{\int_{-\infty}^{b} \psi^{-1}(y)\,dy}$ with $\psi(y) = \exp \int^{y} \frac{2A(x)}{B(x)}\,dx$

Then the probability of crossing can be multiplied by the probability distribution of cloud tops to obtain the distribution of sources.

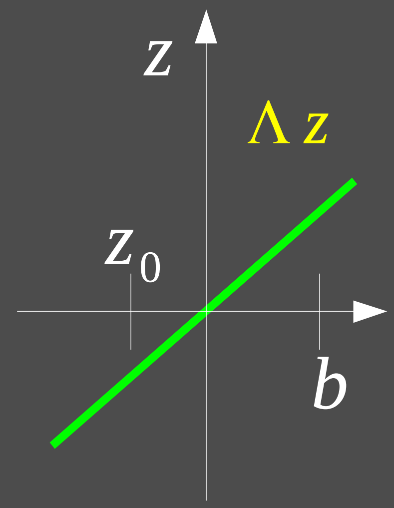
The mean transit time between z_0 and the tropopause can also be calculated (Gardiner, 2009):

$$T_b(z_0) = \frac{\int_{z_0}^{b} K_b(x)}{\psi(x)} dx - \frac{1-\Pi_b}{\Pi_b} \frac{\int_{-\infty}^{z_0} K_b(x)}{\psi(x)} dx$$

with $K_b(x) = 2\int_{LZRH}^{z_0} \frac{\Pi_b(y)\psi(y)}{B(y)} dy$

In the simplest case, when $A(z)=\Lambda z$ and $B=2\kappa$ the Fokker-Planck equation for the transit probability $p(z,t|z_0,0)$ is

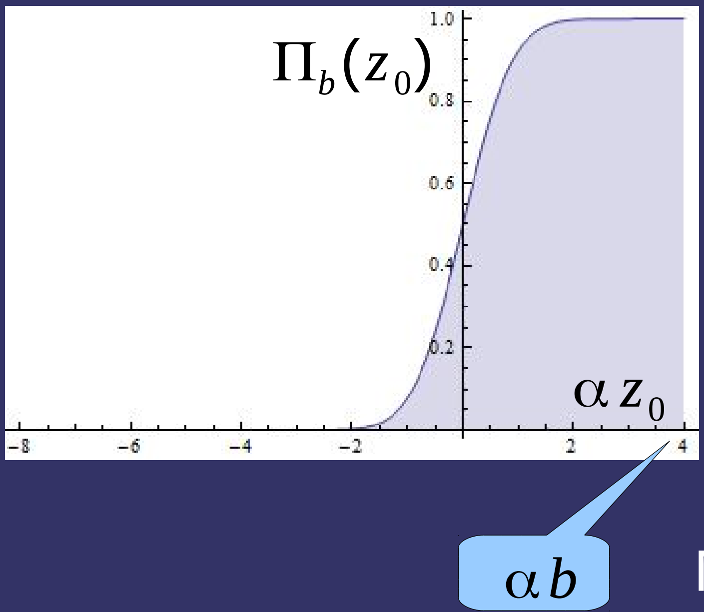
$$\partial_t p = -\partial_z \Lambda z p + \kappa \partial^2_{z^2} p$$



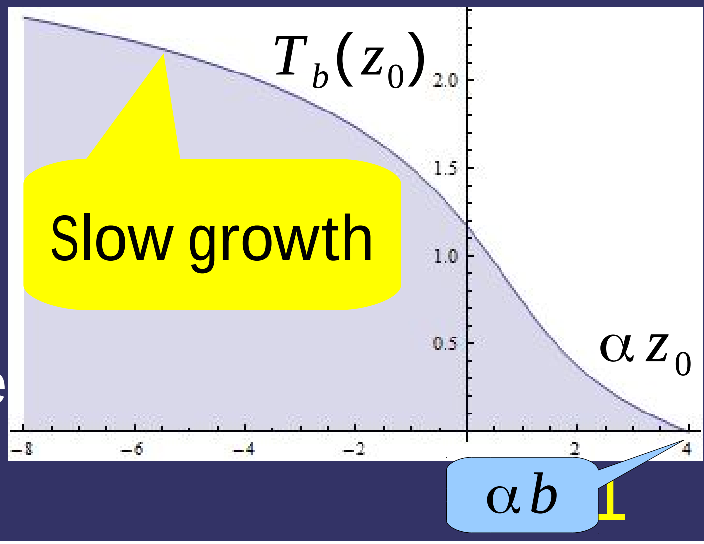
Mean heating rate

Probability to exit from b while starting in z_0:

$$\Pi_b(z_0) = \frac{1+erf(\alpha z_0)}{1+erf(\alpha b)} \qquad \text{with} \qquad \alpha = \sqrt{\frac{\Lambda}{2\kappa}}$$



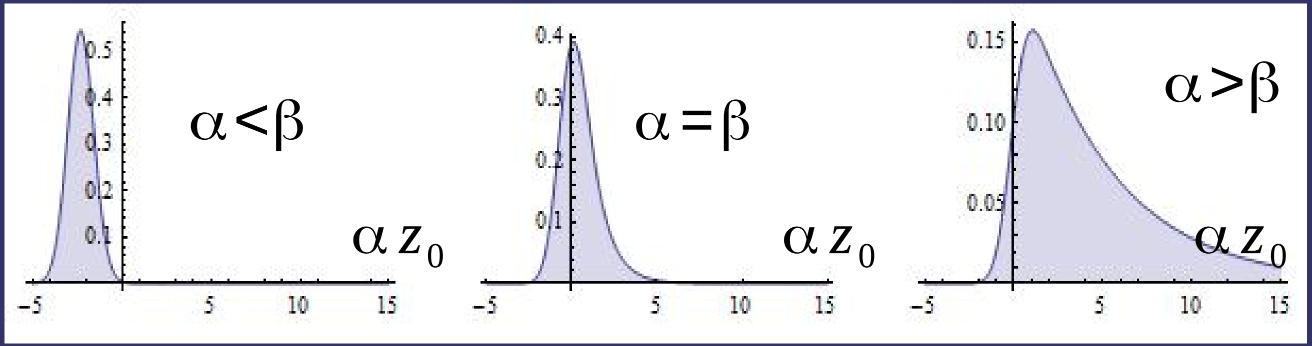
Mean transit time from z_0 to b



Detrainment level of clouds

Assuming an exponential distribution of convective detrainment ~ $e^{-\beta z}$,
the probability that a convective parcel reaching level b
has been detrained at level z_0 is

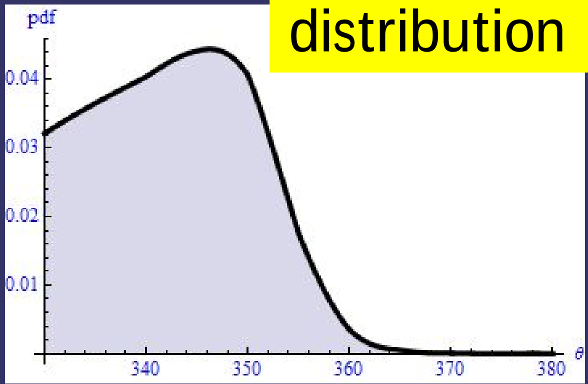
$$P(b, z_0) = N^{-1} e^{-\beta z} (1 + erf(\alpha x))$$



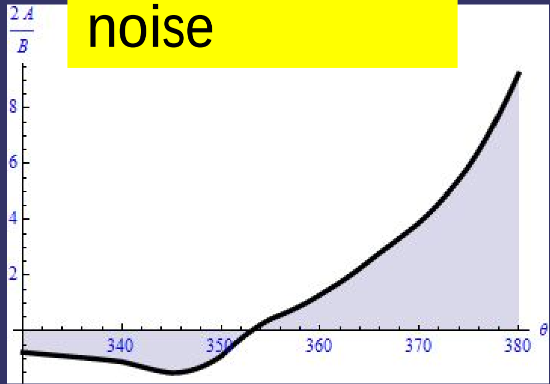
According to the ratio β/α, convective sources are below $(\beta/\alpha > 1)$ or above $(\beta/\alpha < 1)$ the LZRH

South-Asian Pacific region (warmpool) winter 2005

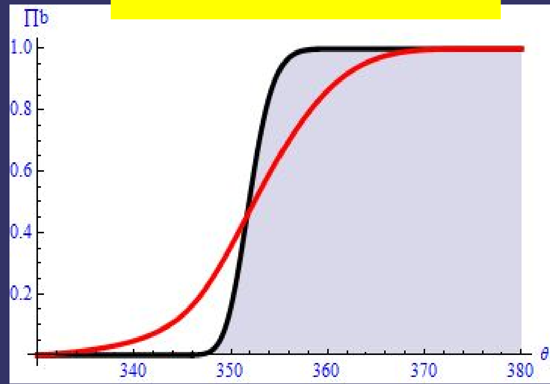
Brightness temperature distribution



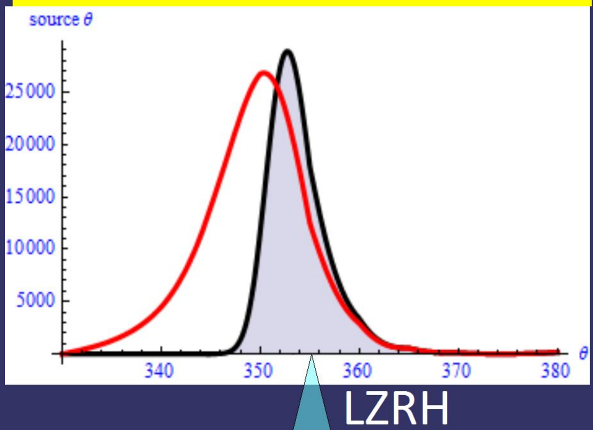
Mean heating / noise



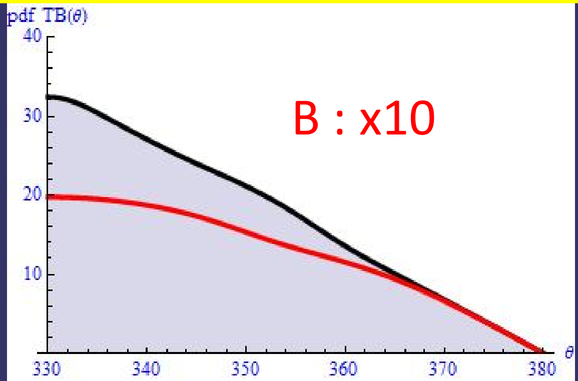
Transit probability



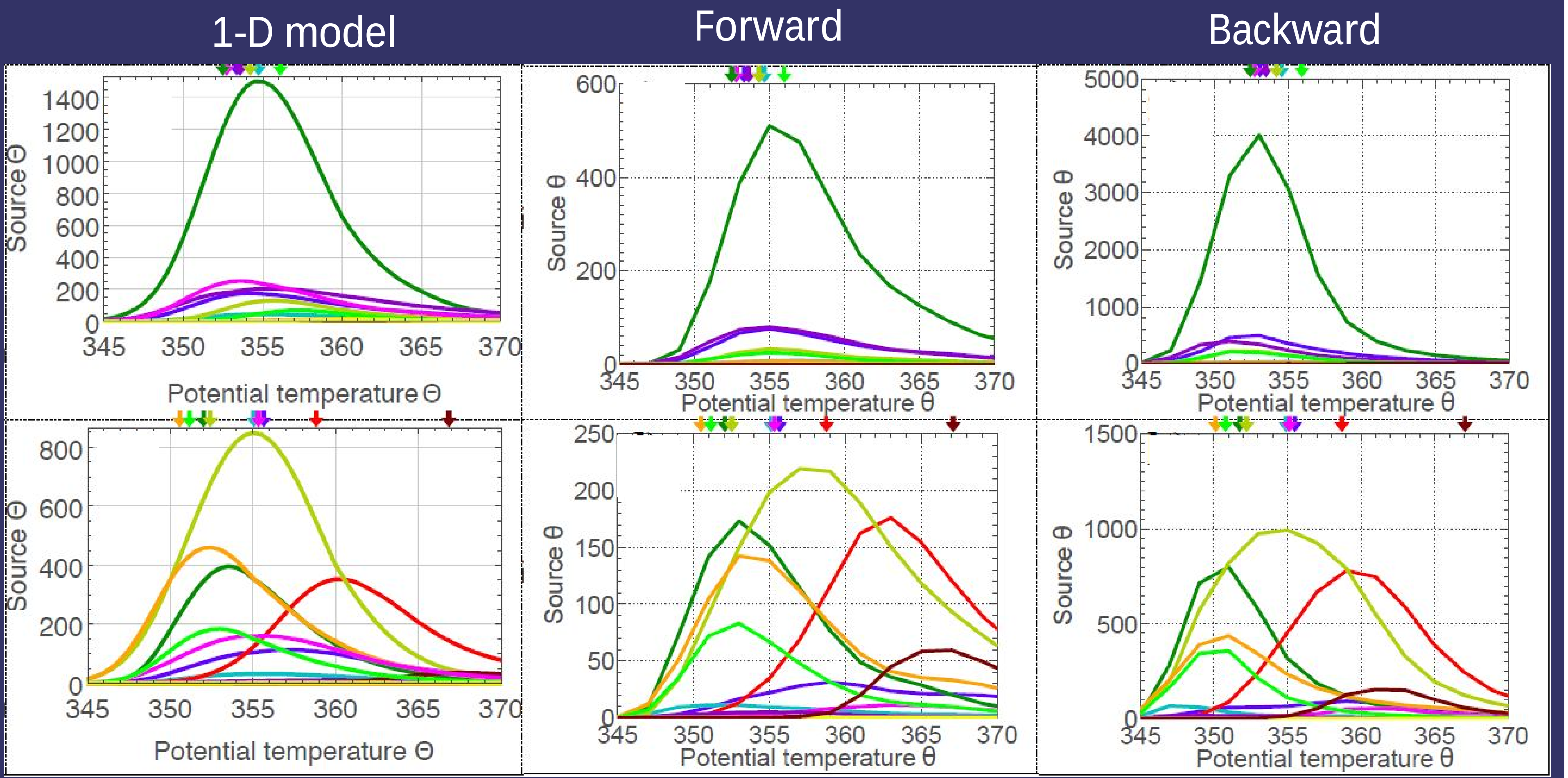
Convective source distribution of Θ



Mean transit time as a function of Θ



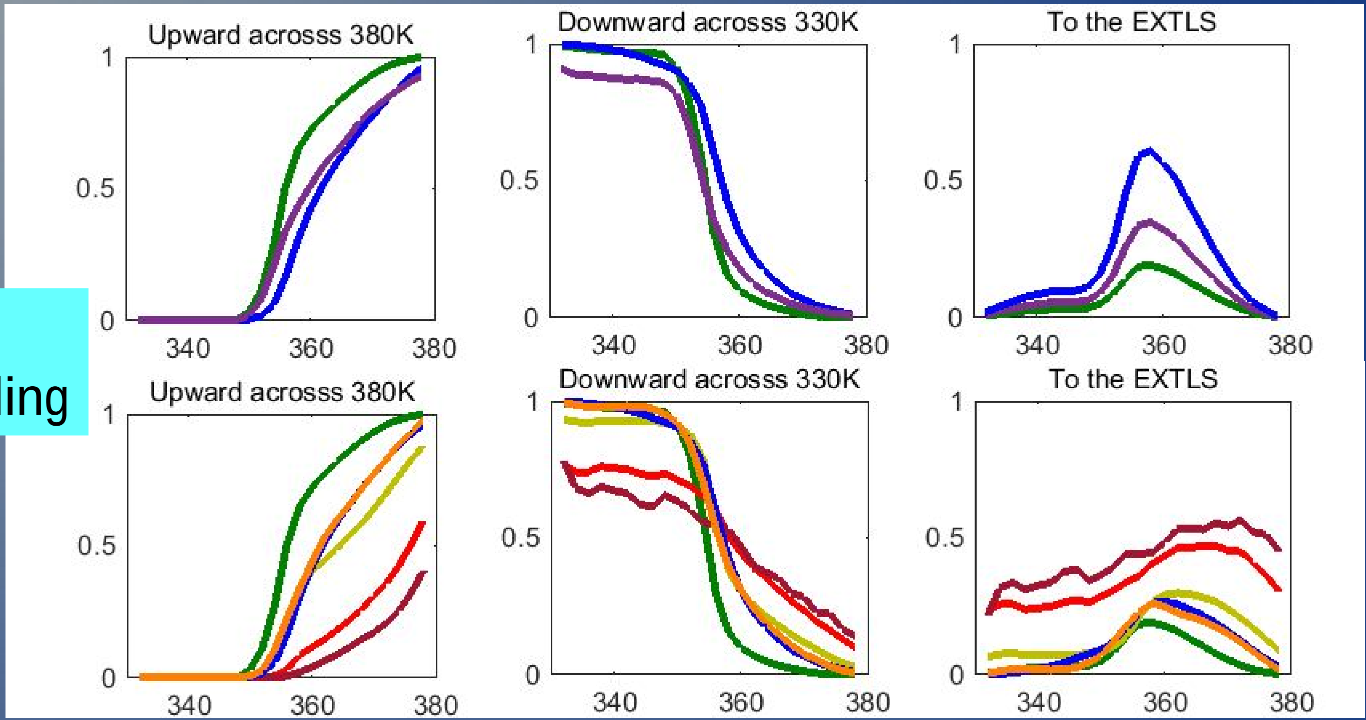
Sources in the 1D model compared to forward and backward 3D calculations



Differences in magnitude between 1D and forward are due to horizontal motion and parcels leaking to the extra-tropics.
Tissier, Legras & Tzella, 2015, submitetd

Probability of exit to the 380 K surface and to the lower troposphere

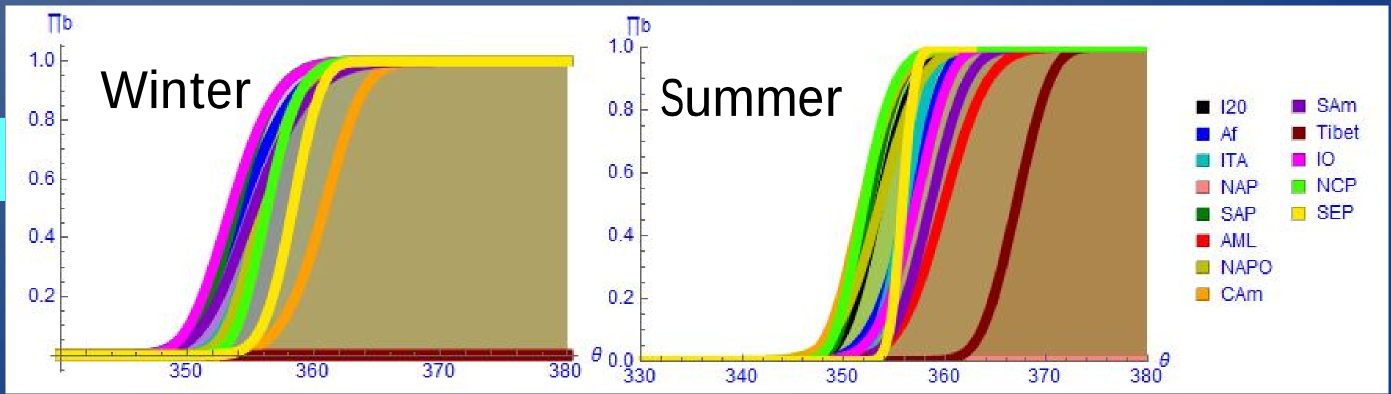
Forward Space filling



Winter

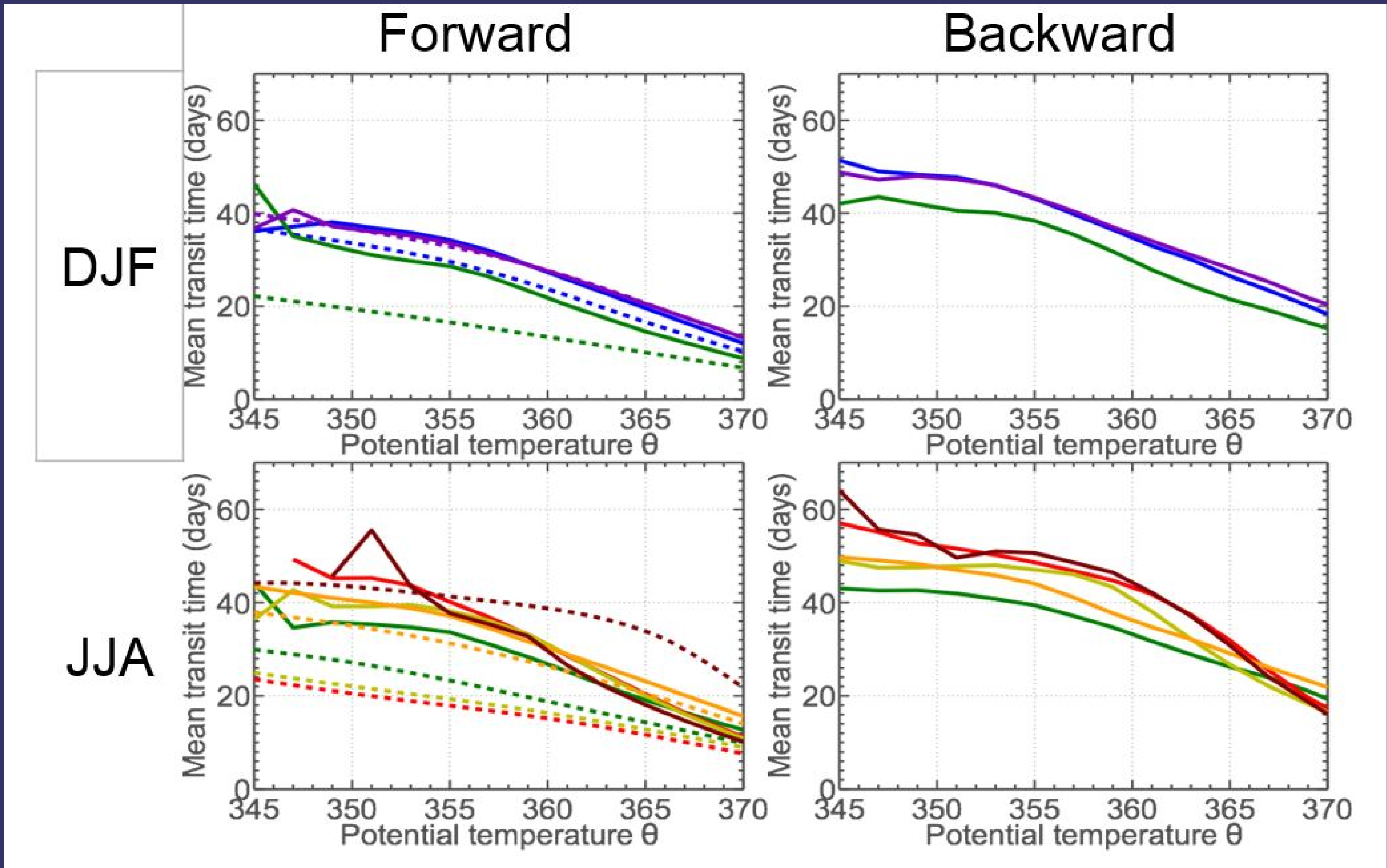
Summer

1-D model

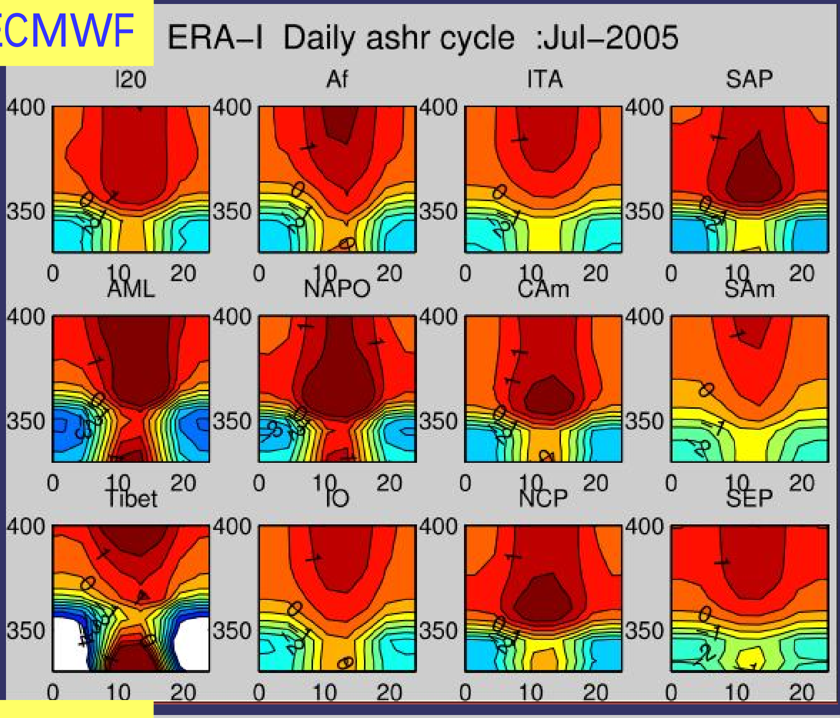


Mean transit times

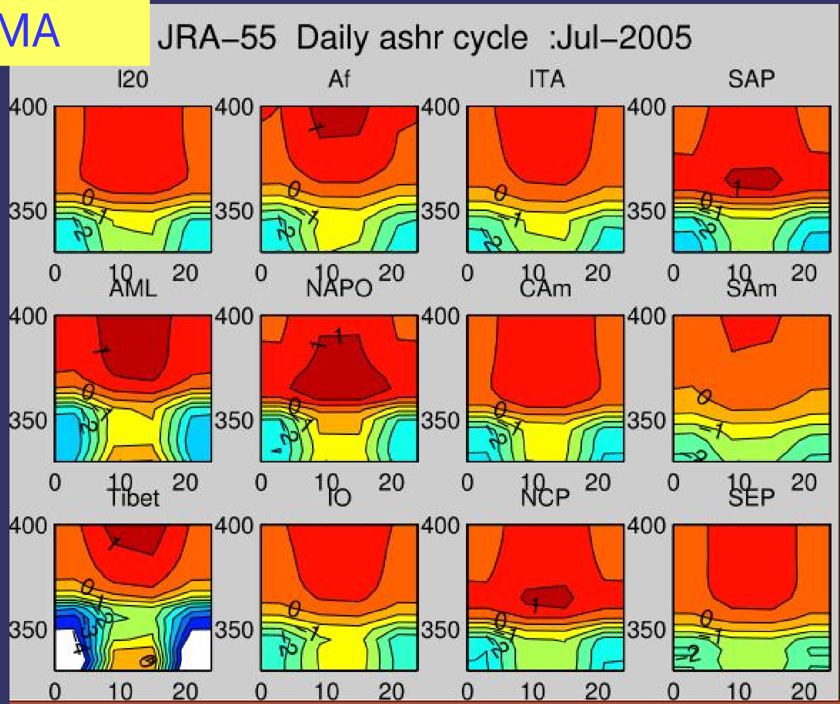
Dotted : 1D model



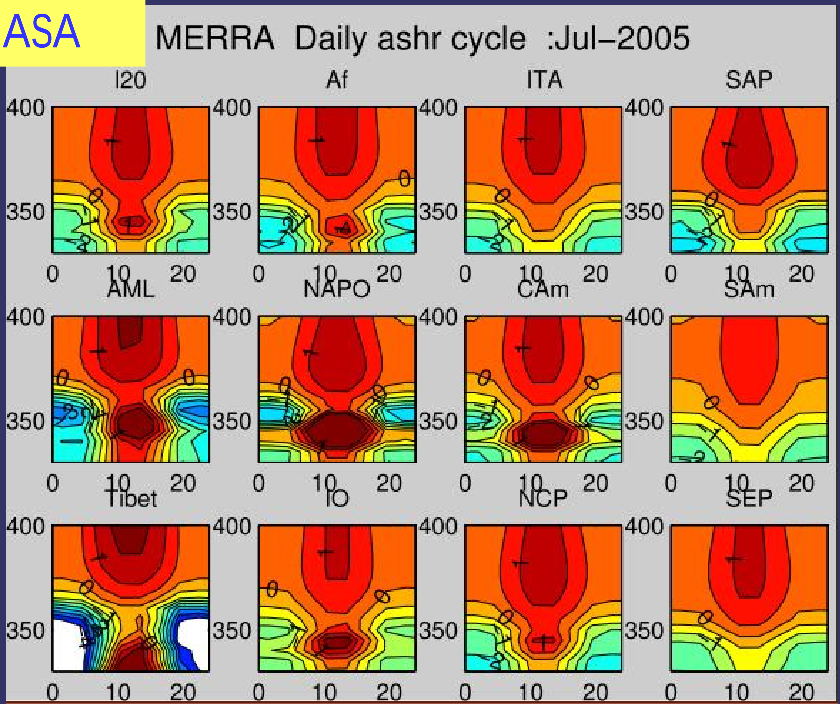
ECMWF



JMA

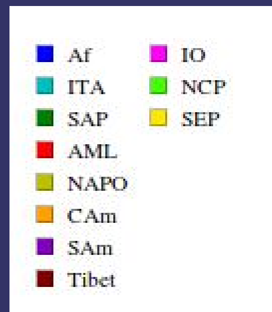


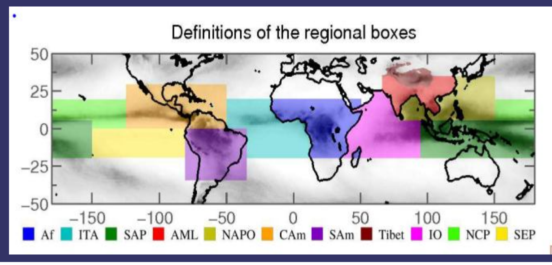
NASA



All sky heating rate cycle (averaged in local time)

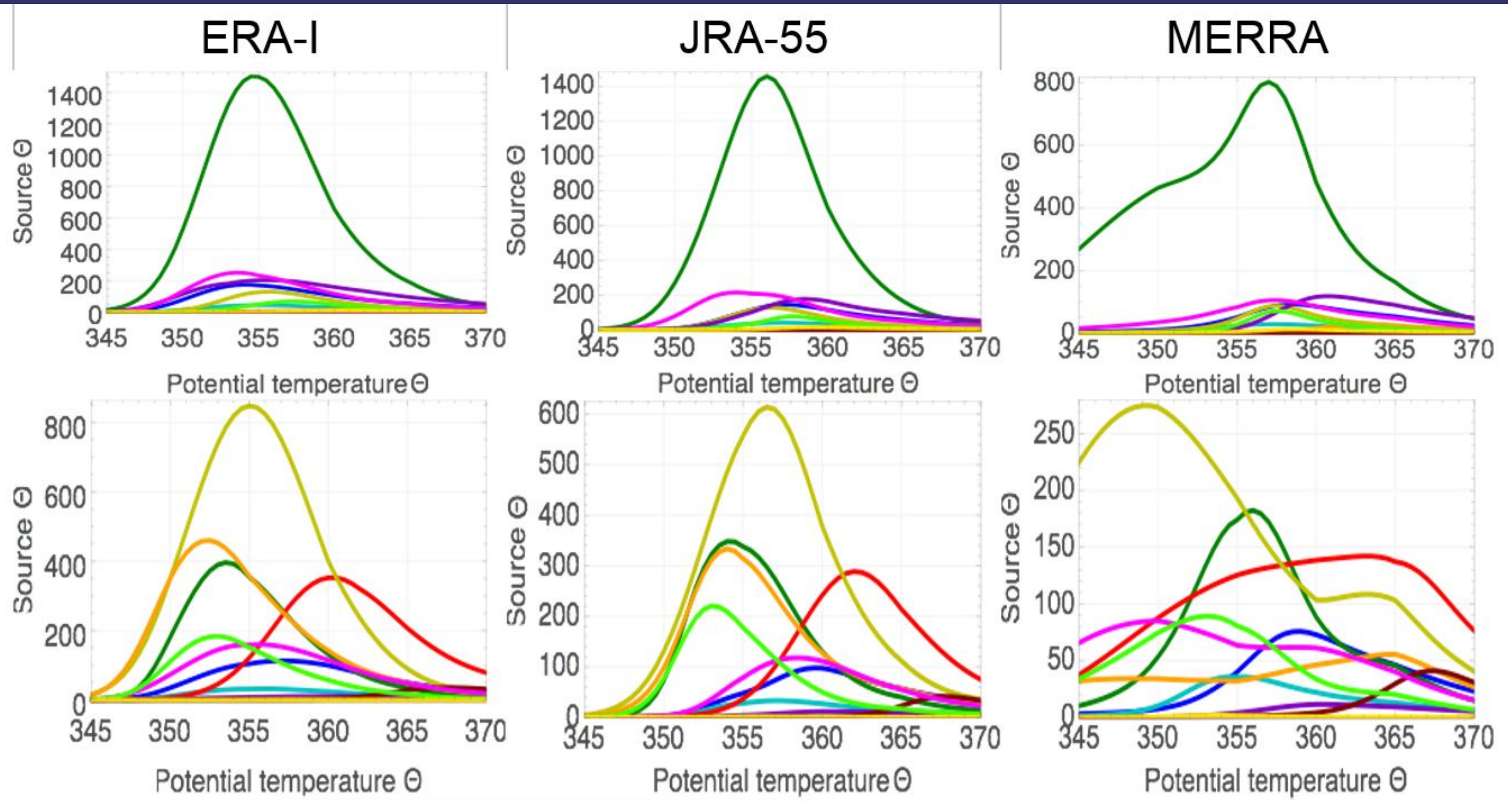
July 2005





Source distraibution among modern reanalysis

ECMWF Japan Met Agency NASA GMAO



Average 2003-2008

Good agreement between ERA-Interim and JRA-55. MERRA at odd.

Tissier, Legras & Tzella, submitted

Conclusion

The sources are vertically distributed over 10-15 K surrounding the all sky level of zero radiative heating (LZRH) , that is well above the mean level of convective outflow. The LZRH and sources are higher over continental convection.

The South Asia Pacific region (warmpool) is the main contributor during winter season (actually half of the year) while Asian Land and Asian Ocean regions are the largest contributors during summer and the Asian monsoon.

Long transit times are produced by parcels wandering near the LZRH.

Trapping within the Asian Monsoon Anticyclone is most effective for parcels released by convection over the Tibetan plateau.

The source distribution is well reproduced by a 1-D stochastic model due to its concentration near the LZRH.

Among modern reanalysis, MERRA is at odd with ERA-Interim and JRA-55 (NCEP CSFR not yet tested).

Caveats and remaining questions

Validity of reanalysed winds and heating rates
Subgrid-scale high frequency motion (increased diffusivity?).
Mass fluxes and detrainment