Transport and mixing in the TTL
Convective sources

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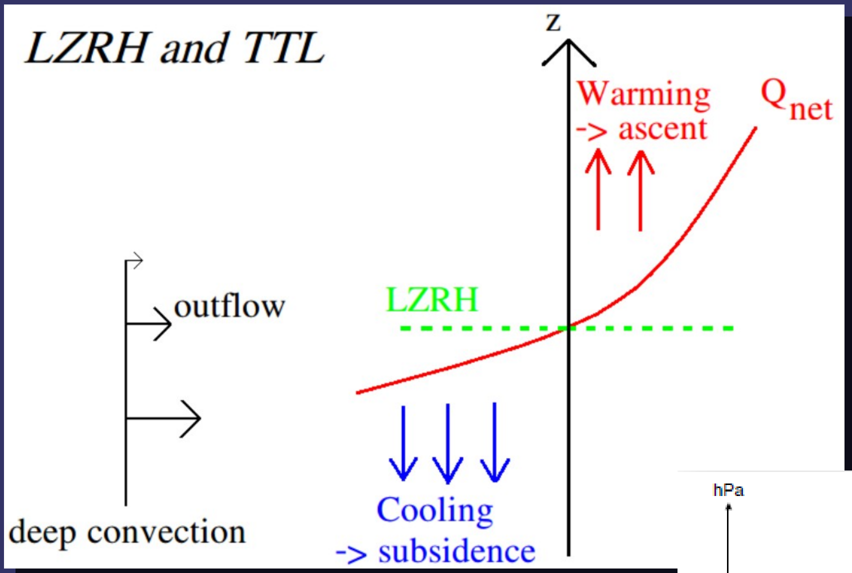
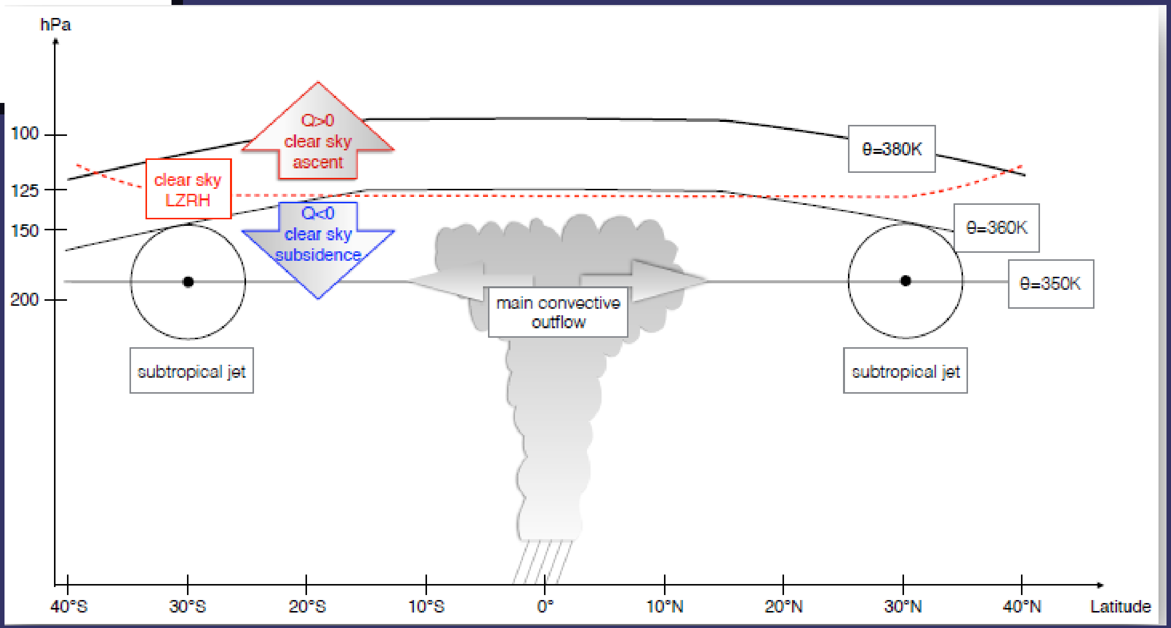
Convective sources

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



Schematic of troposphere-to-stratosphere transport pathway.

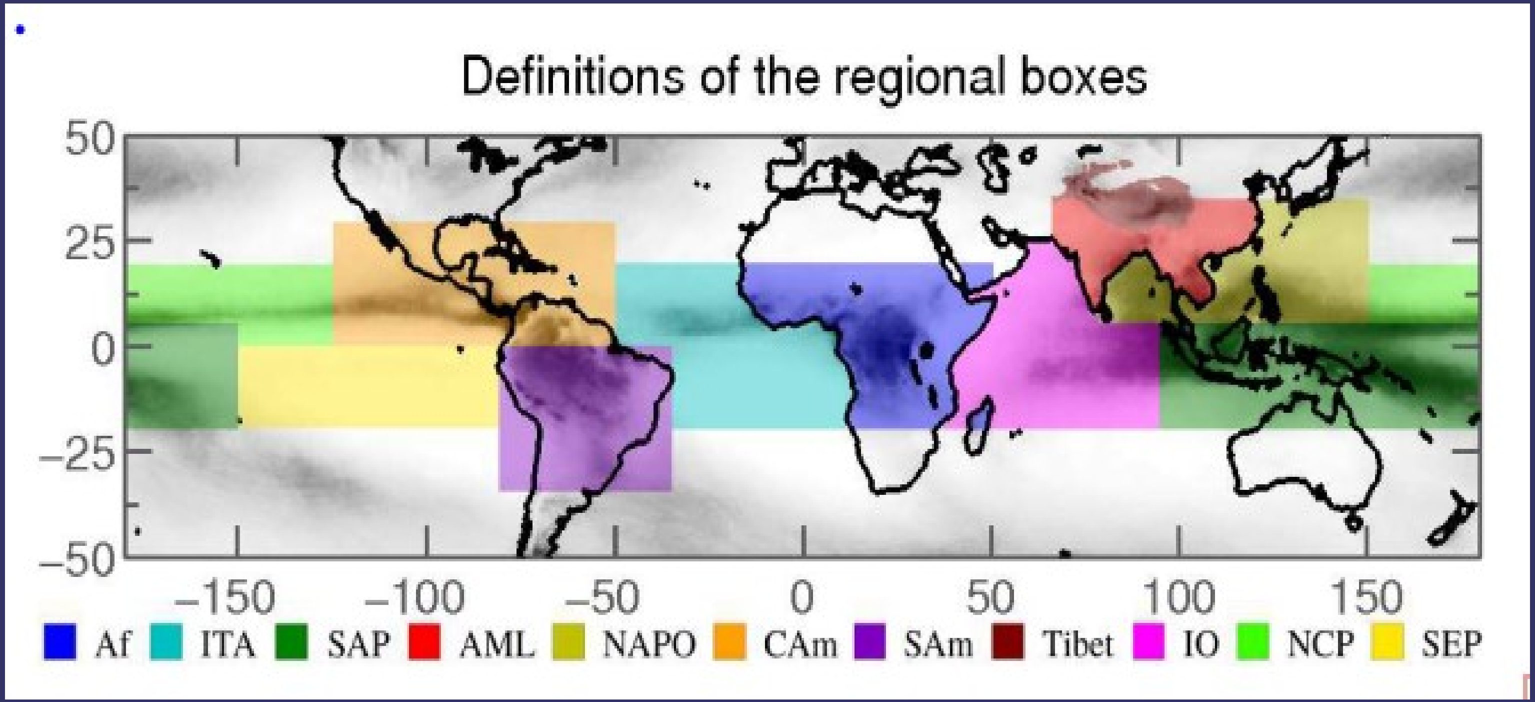


The Level of Zero Radiative Heating (LZRH) is above the mean level of convective outflow. It divides ascending (above) and descending (below) motion.
(Corti et al., 2006)

General questions

- How parcels detrained by convection are transported 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

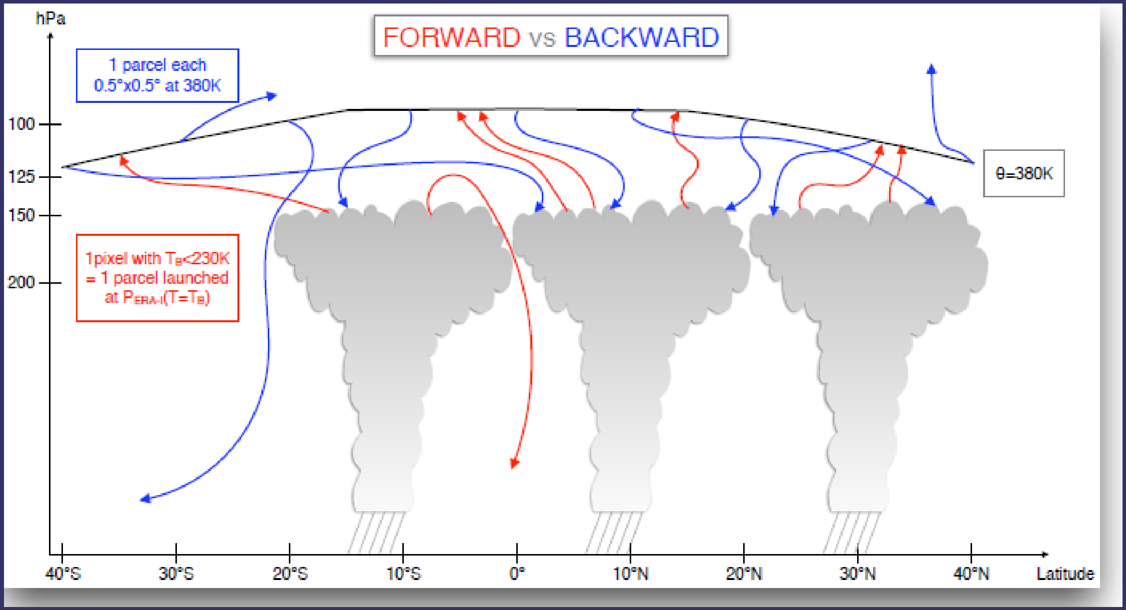
Sam : South America
Tibet : Tibetan plateau (orography > 3800m)
IO : Indian Ocean
NCP/ North Central Pacific
SEP : South East Pacific

Lagrangian trajectories

Trajectory calculations with TRACZILLA

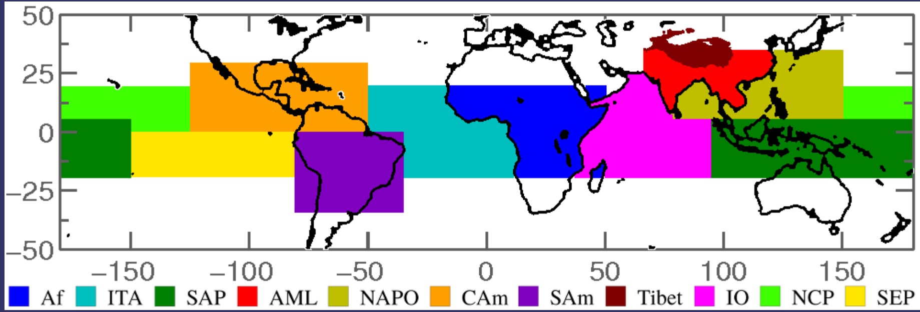
- TRACZILLA : modified version of FLEXPART ([Stohl and al, 2005], [Pisso and Legras,2008])
- Calculations of forward diabatic and backward diabatic trajectories.
- Trajectories are updated every 15 minutes.
- Horizontal part of the movement : calculated using wind fields of ERA-Interim.
- Vertical part of the movement : calculated using radiative heating rates of ERA-Interim.
- No latent heat.

Diabatic trajectories :
Horizontal motion due to horizontal wind
Vertical displacement by heating rates using potential temperature θ as coordinate.
3-hourly data for ERA-Interim, 6-hourly for JRA-55
Reference surface θ=380K
3-month trajectories



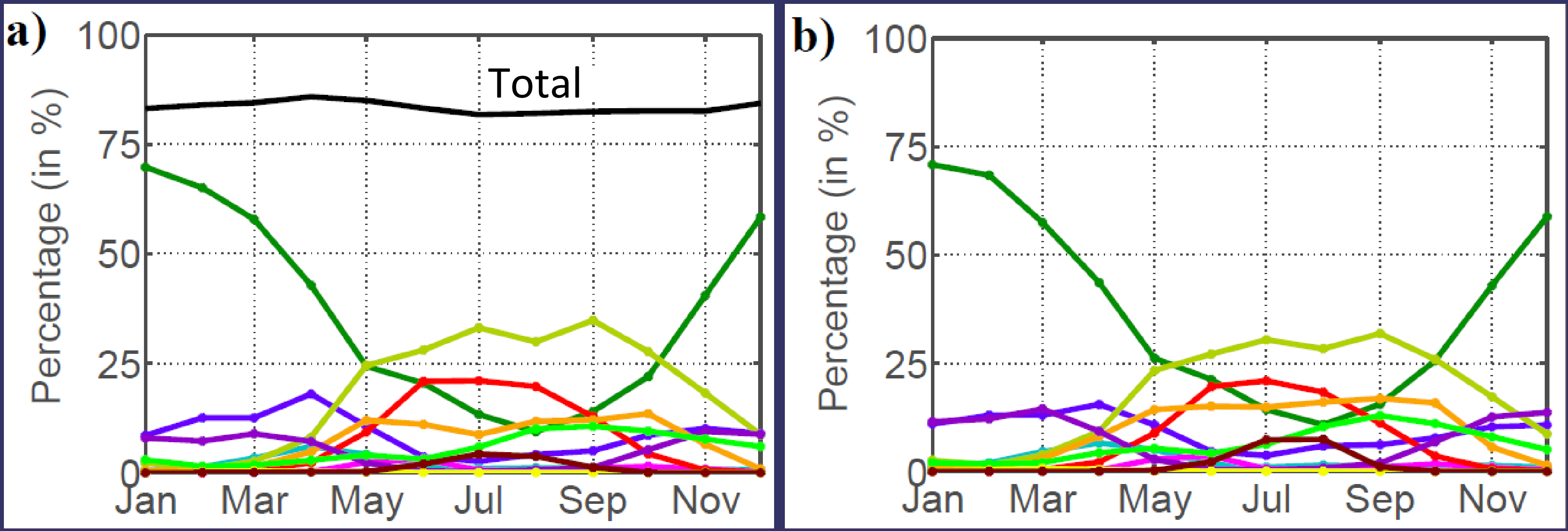
Backward launching : 1 parcel on 0.5°x0.5° grid on 40S-40N every two days, stopped at first encounter of cloud top + 1km
Forward launching : 1 parcel at cloud top +1km for each CLAUS pixel (3h and 30km resolution) at T<230K, stopped at first encounter of 380K surface

Source distribution among regions (2005-2008 ERA-Interim)



Backward

Forward



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

# of parcels which have reached 380K from a given region
/
Total # of parcels which have reached 380K from all regions

Domination of SAP during winter and of Asian sources (NAPO+AML) and Central America (CAm) during summer. Notice the African peak in April.
Excellent agreement between backward and forward indicates statistical robustness.

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

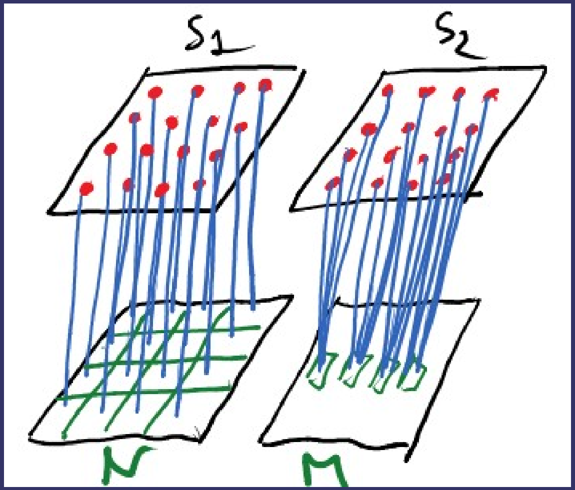
The Green function is also the probability to find in x at time t a parcel which was in y at time s.

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.

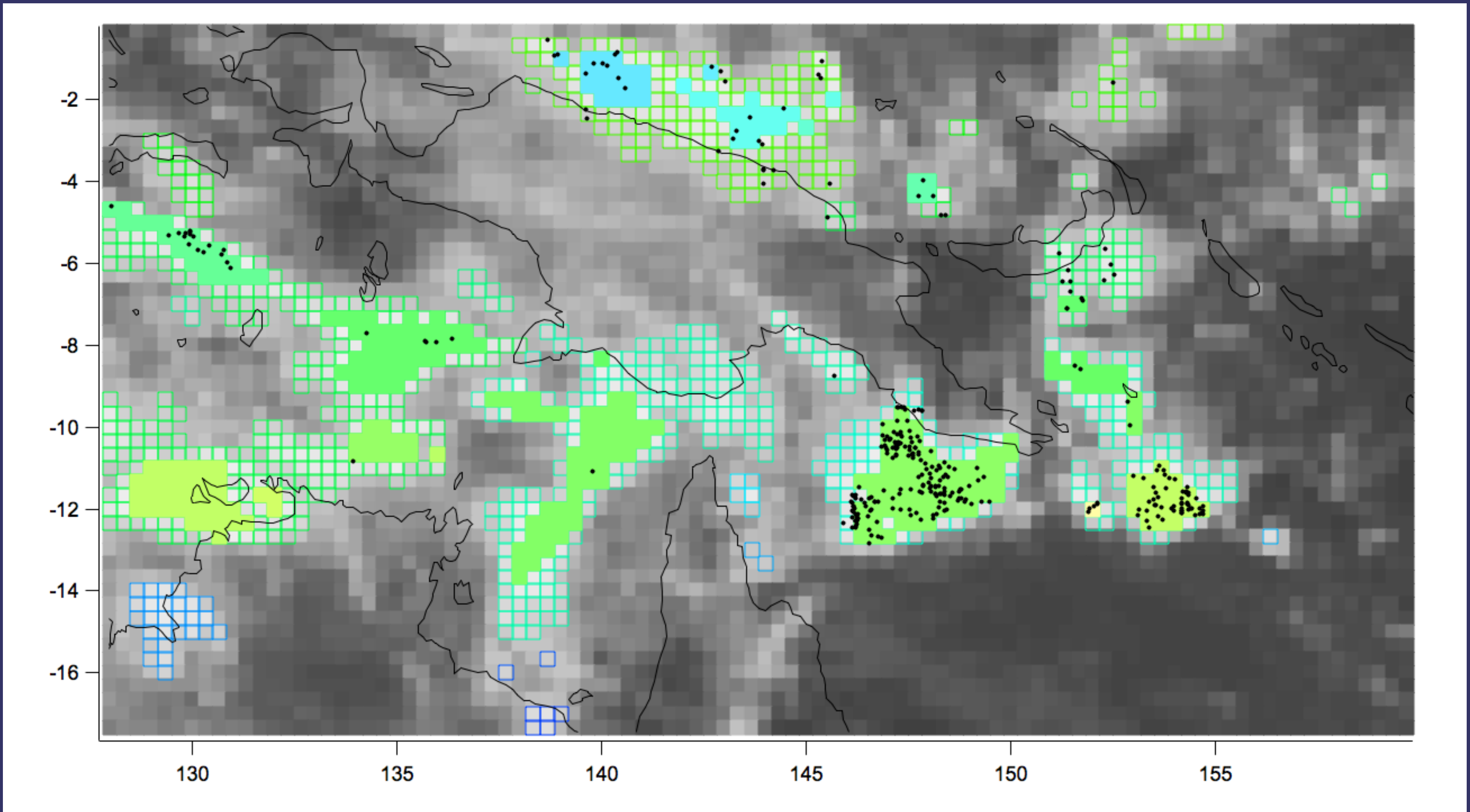
S2 is associated with M << N clouds, each one feeding a surface S2/M at the tropopause.

No other clouds and no lateral exchange

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

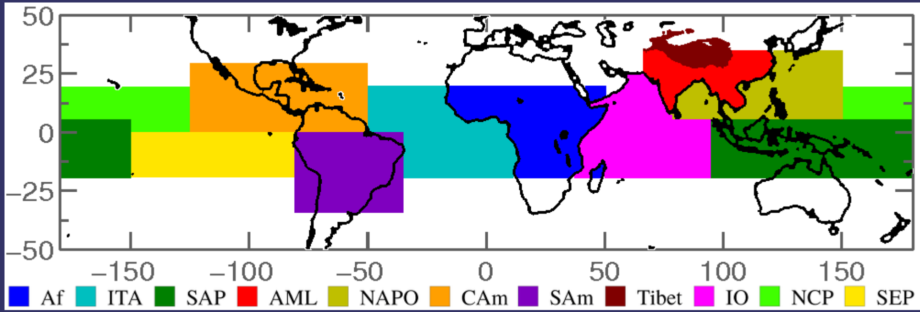
Forward calculations with one parcel over each cloud provides proportions N/(M+N) and M/(N+M) which are different.

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

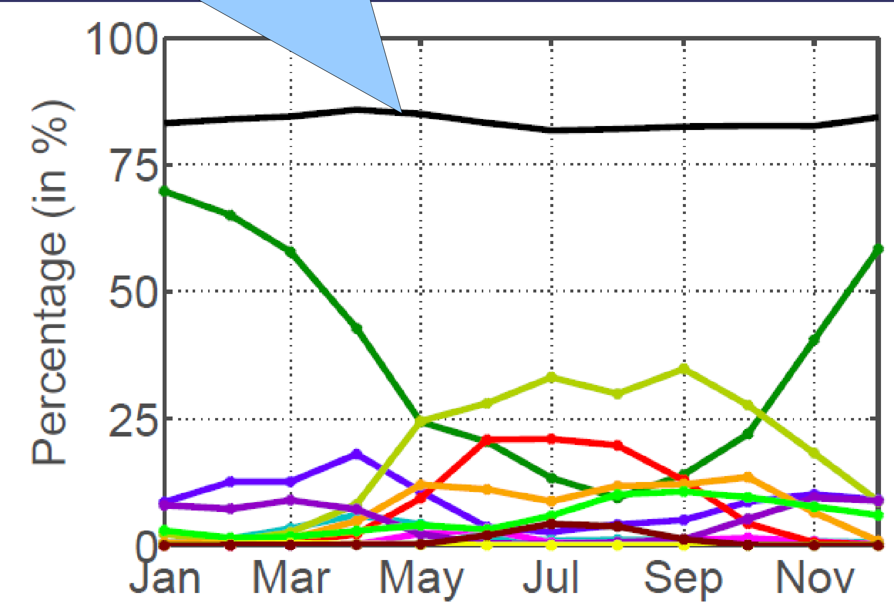


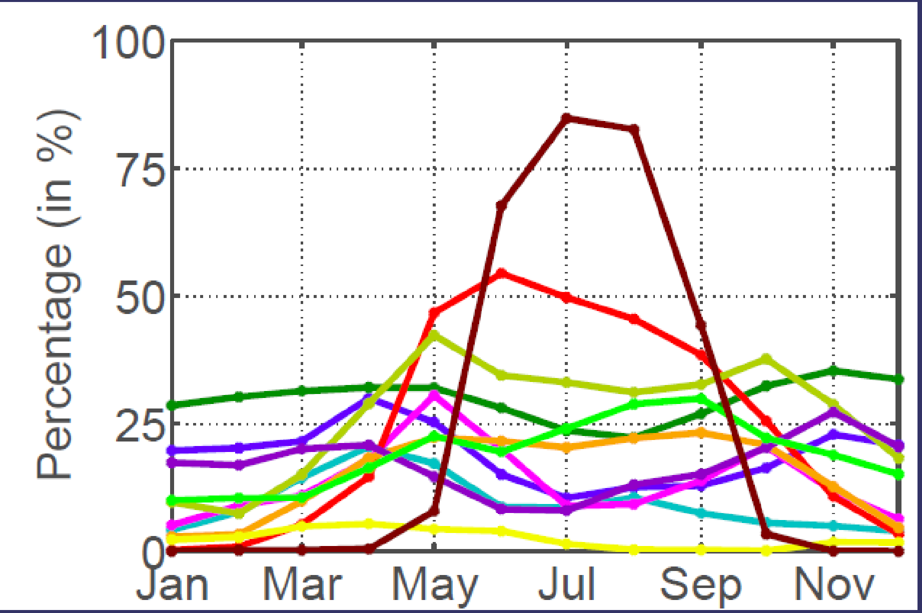
Backward trajectories hit preferentially some clouds and ignore other ones.
Pixel size : 30km

2005-2008 ERA-Interim



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

Weight of the source regions

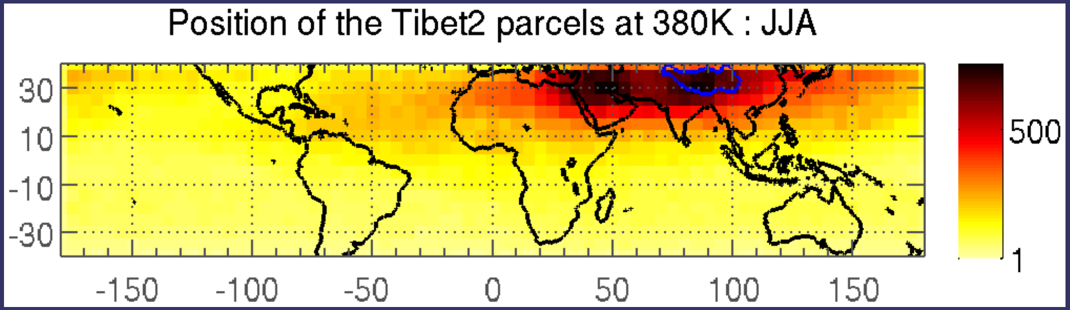
# of parcels which have reached 380K / # of parcels launched from the box

Efficiency of the source regions

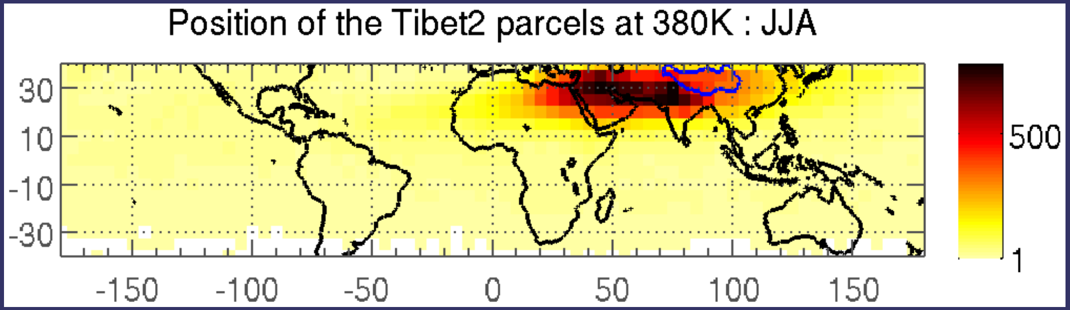
Tissier & Legras, 2015

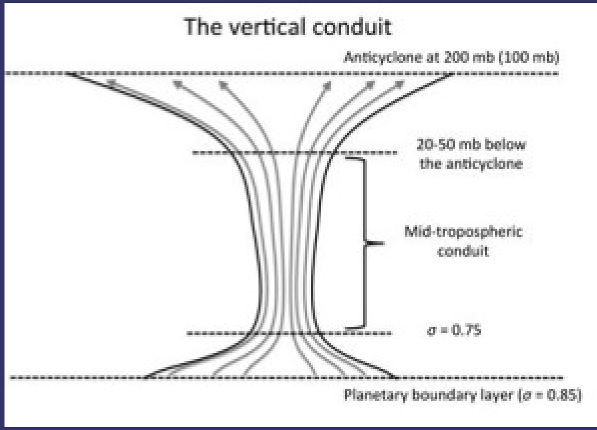
During summer, the Tibetan plateau, in spite of its small total contribution, is the most efficient region in transporting air parcels from cloud top to 380K.

Backward



Forward

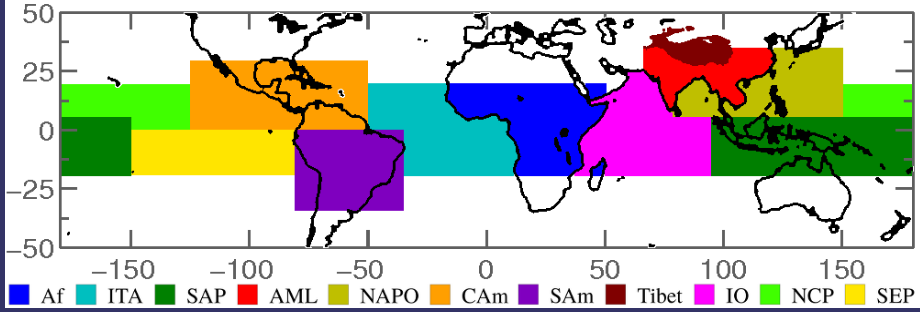


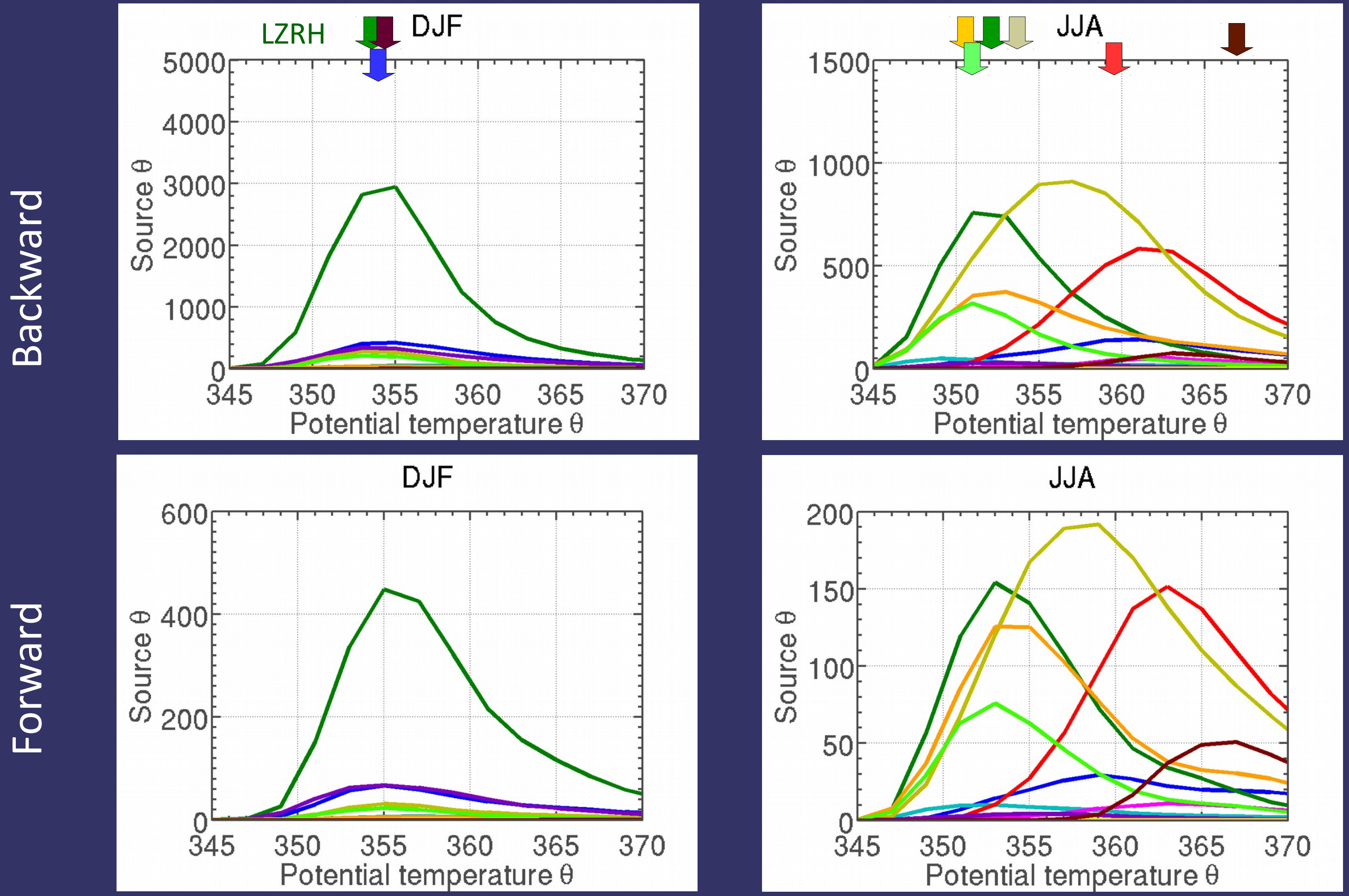


Bergman et al., ACP 2013

Vertical distribution of sources (2005-2008 ERA-Interim)

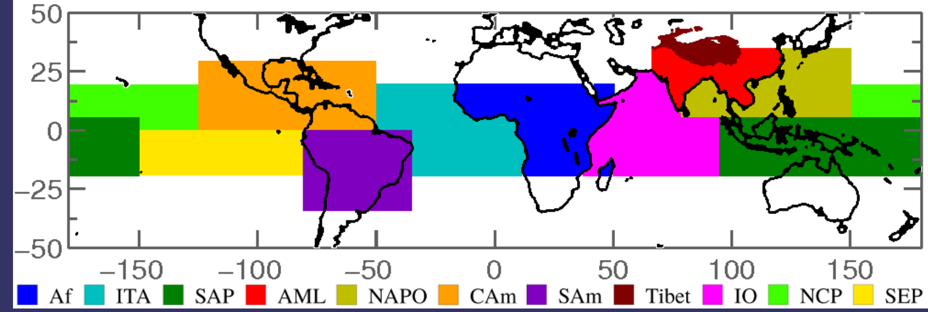
Asian monsoon sources, especially continental, at higher levels than Pacific maritime sources and above all sky LZRH (but for Tibet).





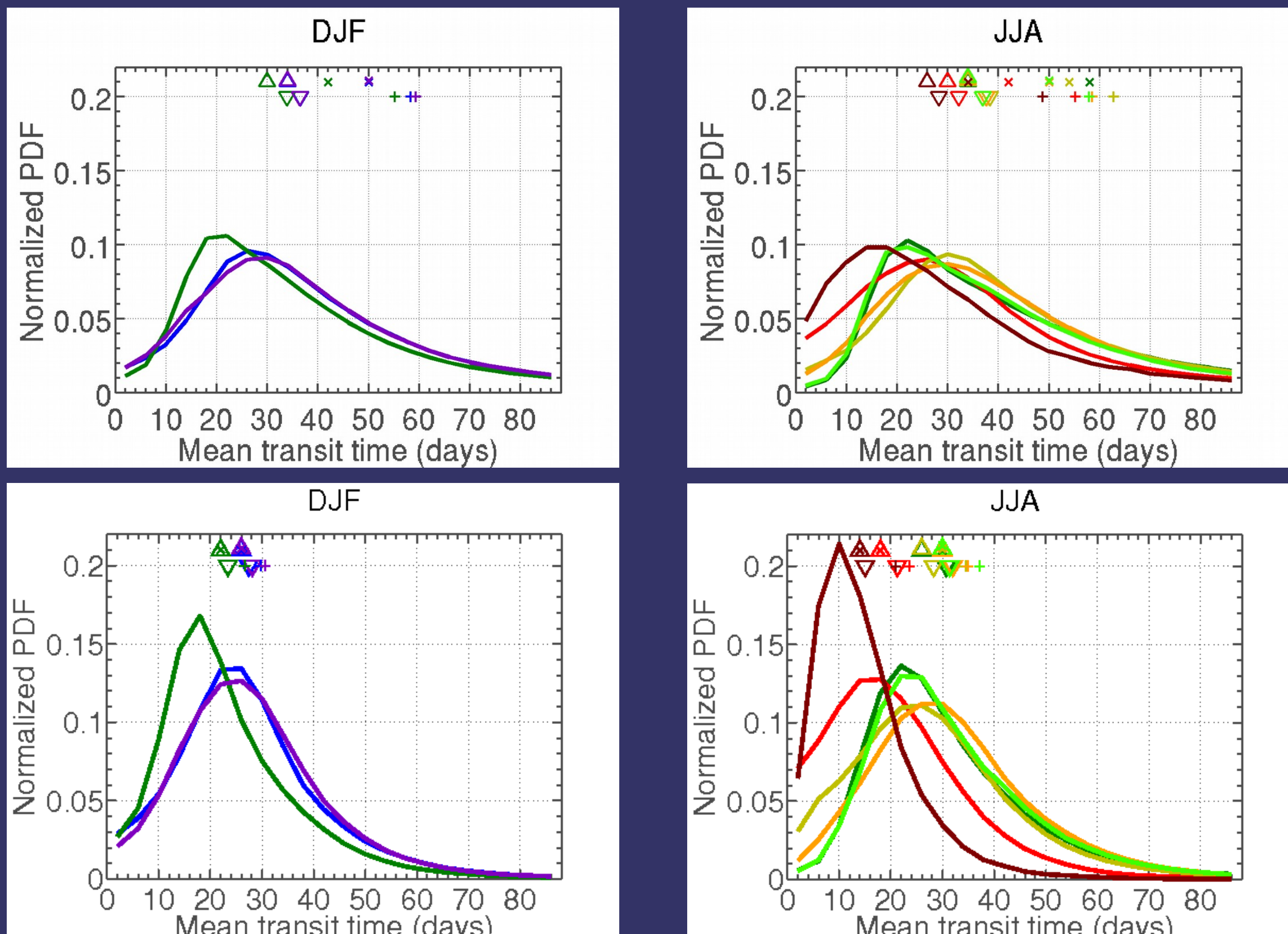
Distribution of transit times (2005-2008 ERA-Interim)

Backward transit times are shifted to large values with respect to forward times due to the intermittency of cloud encounter and recirculations, especially over Asia.



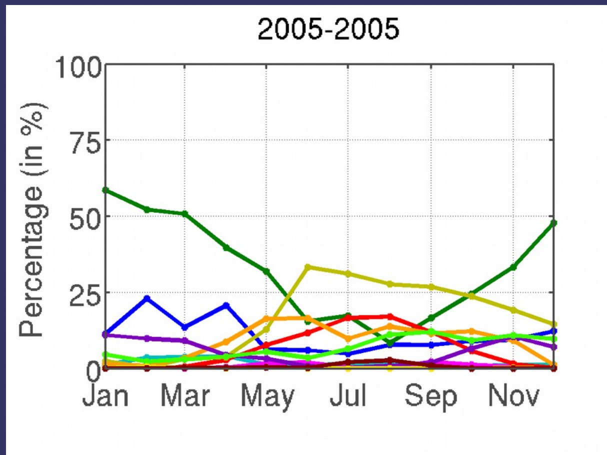
Backward

Forward

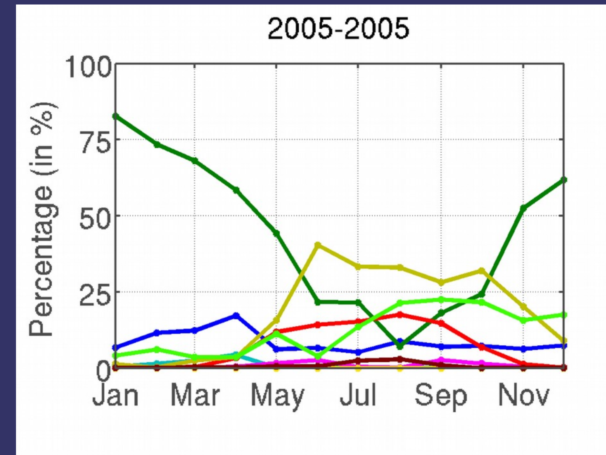


Comparison ERA-Interim versus JRA-55 (based on backward and 2005 only)

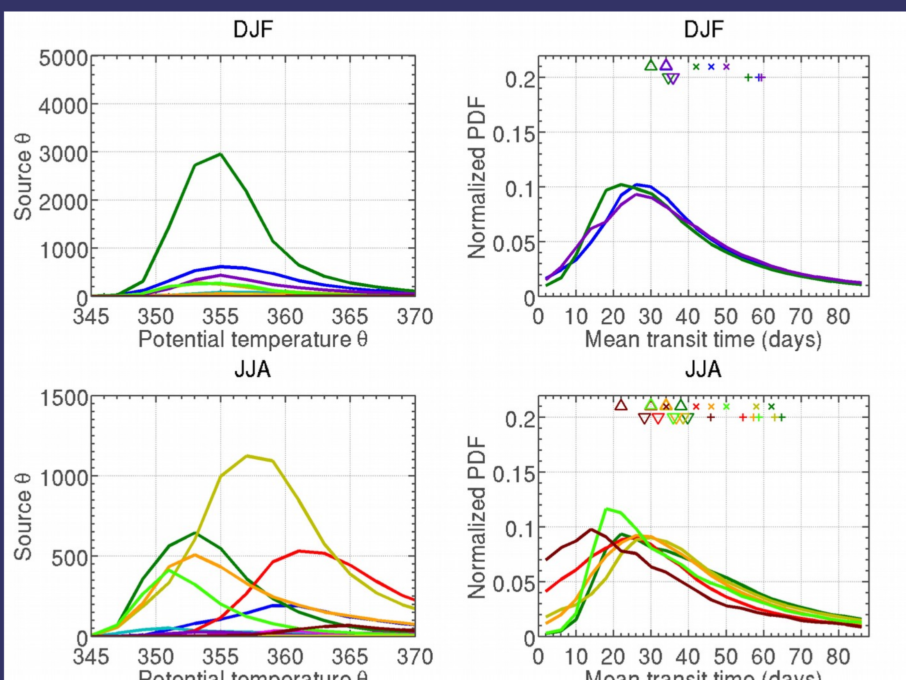
ERA-Interim

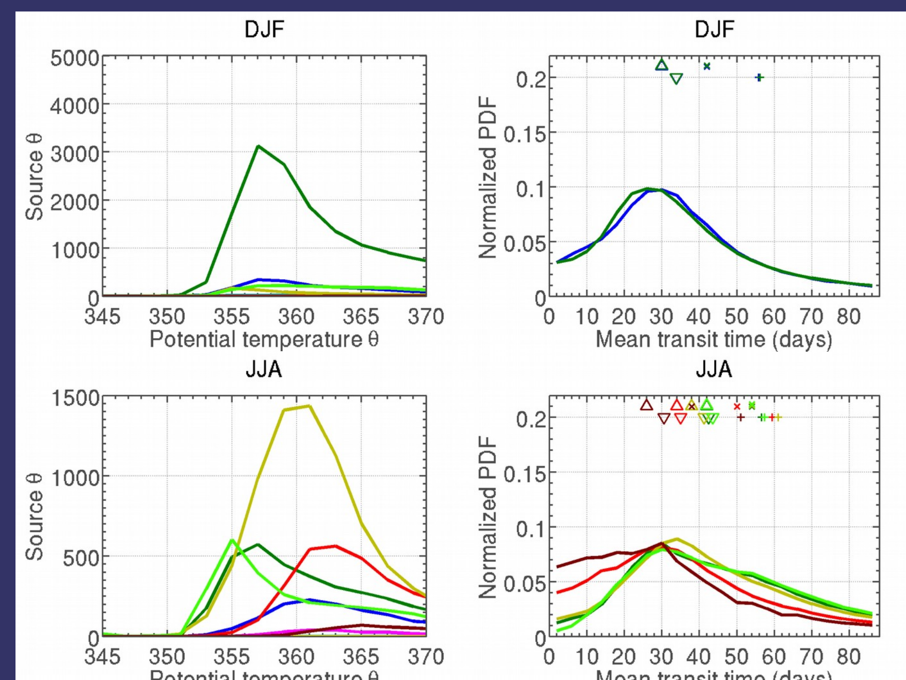


JRA-55



Sources are located higher in JRA-55 and the dominance of SAP is larger during winter.





Convective mass flux at 380K

Convective mass flux across the θ=380 K surface can be estimated from the residual calculation v*, w* as the integral M_{kine} (brown) of

$$\frac{p}{gH}\left(w^{*}-\frac{1}{R}\frac{\partial z_{\theta}}{\partial \varphi}v^{*}\right)$$

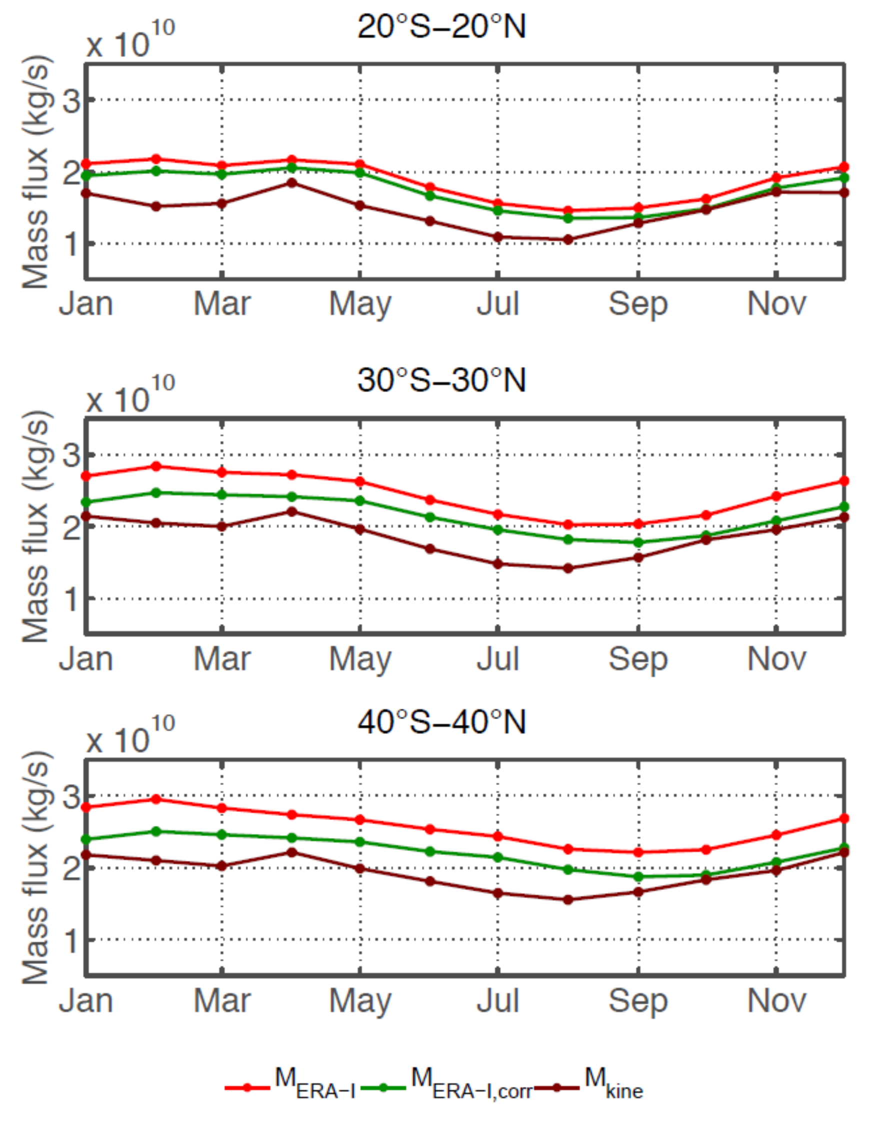
or from the heating rate as the integral M_{ERA-I} (red) of

$$\frac{-1}{g}\frac{\partial p}{\partial \theta}\dot{\theta}$$

Uniform correction can be applied to the heating rate in order to satisfy zero total flux (green).

The estimates differ by less than 20 % in the tropics

Integrated upward mass flux (mean over 2005-2008)

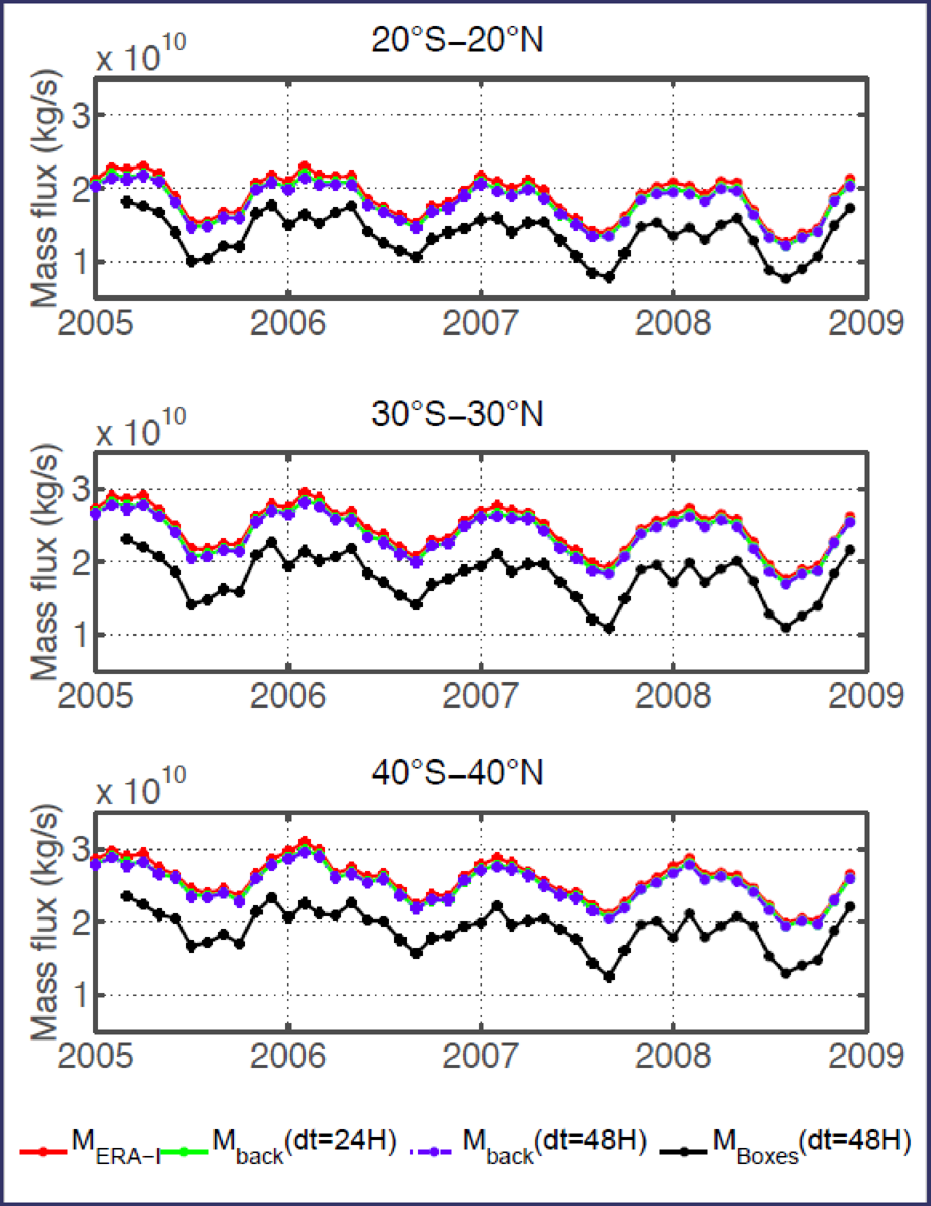


Upward flux

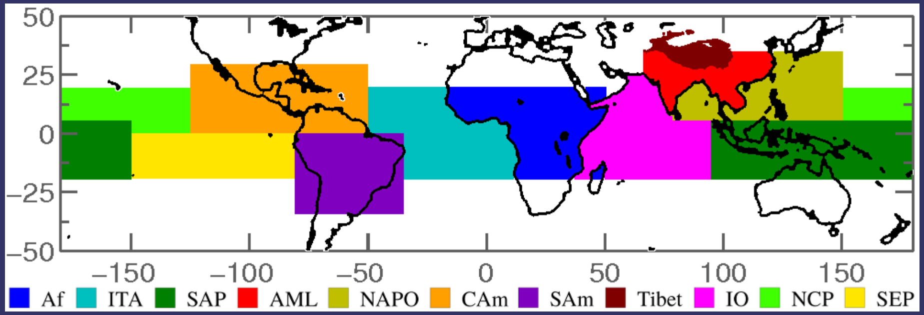
The upward diabatic mass flux across the θ=380 K surface can be estimated from backward Lagrangian trajectories initialized on this surface by counting those that descend below this surface and summing over surface elements

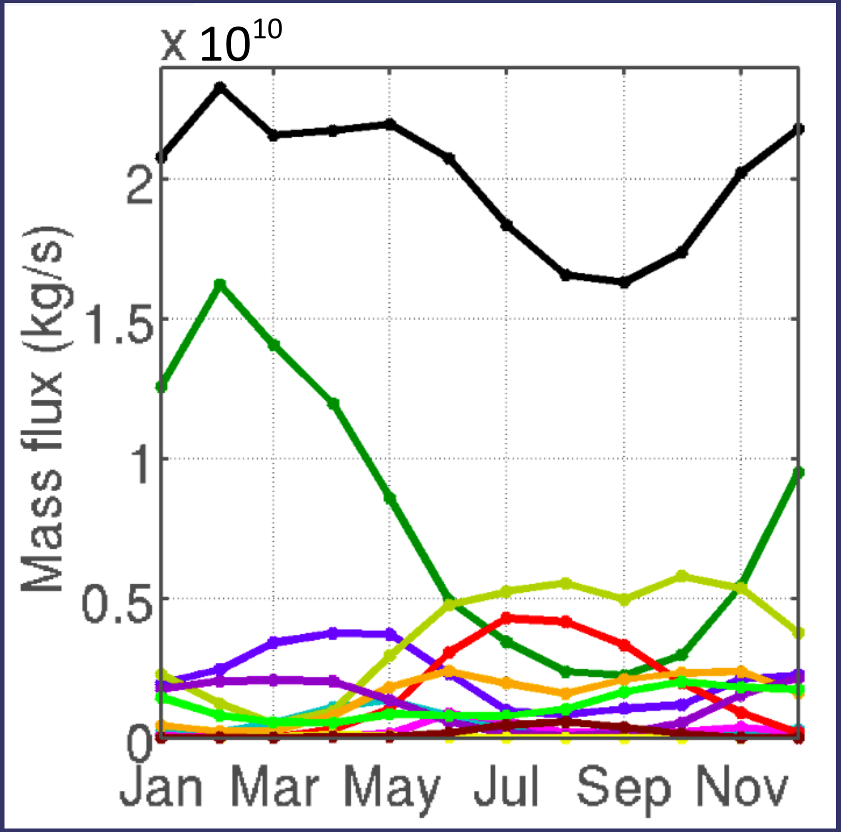
$$M_{back} = \sum_{descending} \delta s \left(\frac{-1}{g} \frac{\partial p}{\partial \theta} \dot{\theta} \right)$$

Mboxes : upward flux originating from convective clouds



Distribution of the upward flux among the source regions and over the months.
2005-2008 average for ERA-Interim

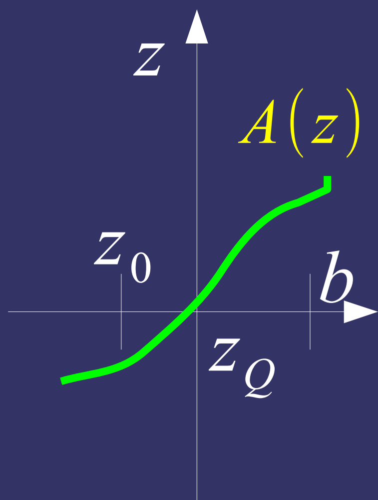




The mass flux inherits the properties of the source distribution with slight modifications (SAP flux still larger than CAm flux during summer) .
CAUTION : This is not the mass flux of convective air across 380K surface as it does not account for mixing of detrained air with the environment at the top of clouds.

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 $\delta z = A\,\delta t + B^{1/2}\,\delta w$

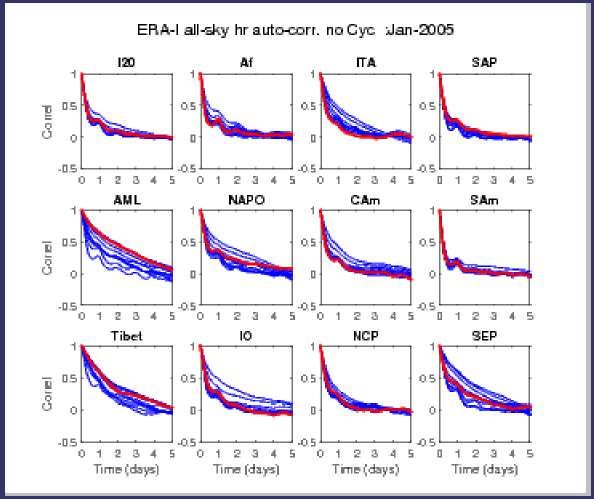
LZRH : $A(z_Q) = 0$

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

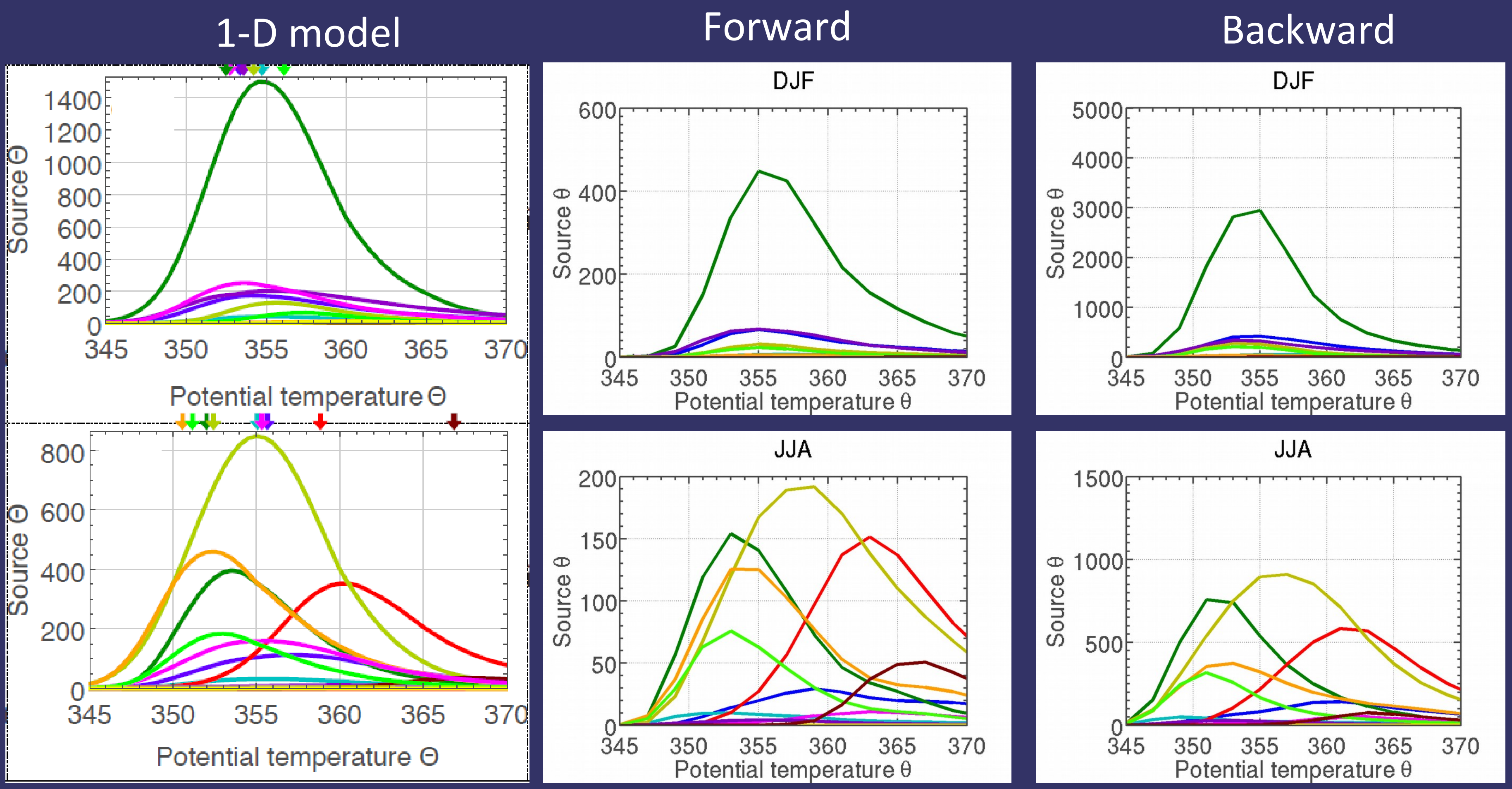
$$\partial_t p = -\partial_z A\,p + \frac{1}{2}\partial^2_{z^2} B\,p$$

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.



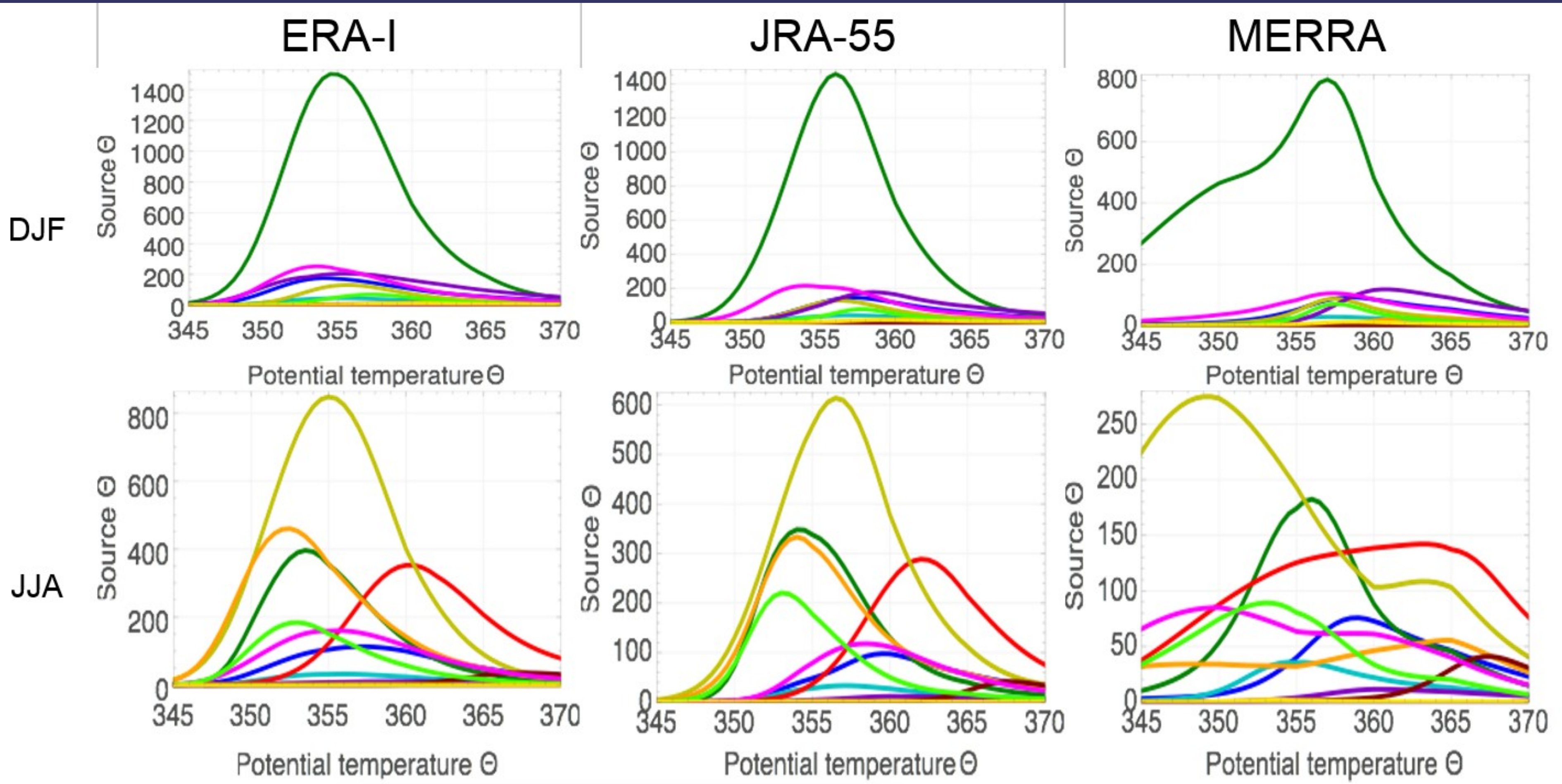
Sources in the 1D model compared to forward and backward 3D calculations



The 1D model accounts for the relative distribution among sources obtained from 3D Lagrangian trajectories.Differences in magnitude between 1D and forward are due to horizontal motion and parcels leaking to the extra-tropics.

Source distraibution among modern reanalysis

ECMWF Japan Met Agency NASA GMAO



Average 2005-2008

Good agreement between ERA-Interim and JRA-55. Upward shift of JRA-55 accounted. MERRA at odd.

Conclusion

Reproducible results by both forward and backward calculations show that even a fairly rough sampling (50 km/2 days in backward, one parcel per high 30kmx30kmX3h pixel in forward) provides cloud to 380K transport statistics for most regions.

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.

Trapping within the Asian Monsoon Anticyclone is most effective for parcels released by convection over the Tibetan plateau but the Tibetan plateau remains an overall small contributor to transport of convective air to the stratosphere.

The mass flux across the 380K surface that originates from the region of convective outflow has been estimated.

Among modern reanalysis, ERA-Interim and JRA-55 show qualitatively similar results but also some differences (higher sources and shorter transfer times in JRA-55) .

A 1-D model does a reasonable job at reproducing the source distribution (mostly because this depends on the vicinity of the LZRH) and shows that MERRA is at odd with the two other reanalysis.

Questions

What is the uncertainty induced by differences between the re-analysis ? Which heating rates are the most reliable ? Unresolved motion and LZRH crossing?

How to estimate the flux of air across the 380K surface that has been recently processed by convection ? In other words, how to estimate detrainment and mixing at and above the level of convective outflow ?