Lagrangian analysis of the inter-hemispheric mass transport in the atmosphere

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Introduction

We trace 3D Lagrangian trajectories in the atmosphere to obtain residence time, age, and transit residence time for each hemisphere. We compare these time scales with the turnover time obtained by Eulerian methods. Furthermore, we aim to find transport barriers and compare the transport to/from the different hemispheres.

Each trajectory represents a mass element that is passively advected by the flow. ~2.5 million trajectories are traced, of which 10 are shown in Fig 2. To calculate the trajectories we use horizontal velocity fields and surface pressure from the ERA-Interim reanalysis dataset. Vertical motion is calculated from the continuity equation, ensuring conservation of mass.

Eulerian analysis: Turnover time

An Eulerian analysis can give us the turnover time of a hemisphere

$$t_{\mathrm{T}} = \frac{M_{\mathrm{NH}}}{V_{\mathrm{S}}}$$

where M_{NH} is the total mass on the northern hemisphere, and V_S is the southward mass flux at the equator. To calculate the turnover time for each hemisphere we use temporal averages of surface pressure and meridional velocity at the equator over the period 1994-1995 and compare with trajectories released in 1994. Results are shown in Fig 4b.

Lagrangian analysis: Residence time, Age, & Transit Residence time

The residence time, age, and transit residence time scales are calculated from trajectories as

$$t_{\mathrm{R}} = \overrightarrow{t_{\mathrm{eq}}} - t_{\mathrm{start}} \quad (1)$$

$$t_{\mathrm{A}} = t_{\mathrm{start}} - \overleftarrow{t_{\mathrm{eq}}} \quad (2)$$

$$t_{\mathrm{TR}} = t_{\mathrm{R}} + t_{\mathrm{A}} = \overrightarrow{t_{\mathrm{eq}}} - \overleftarrow{t_{\mathrm{eq}}} \quad (3)$$

where t_R is residence time, t_A is age, and t_{TR} is transit residence time. t_{start} is the time at which the trajectory starts, and t_{eq} is the time when it reaches the equator. Arrows denote forward and backward trajectories. Fig 1 shows the fraction of traced mass from each hemisphere that has not yet reached the equator, as function of time. The decay is more-or-less exponential. The average residence time (AvR) is equivalent to the e-folding time for the forward trajectories. Similar analysis can be done for backward trajectories, giving the average age (AvA).

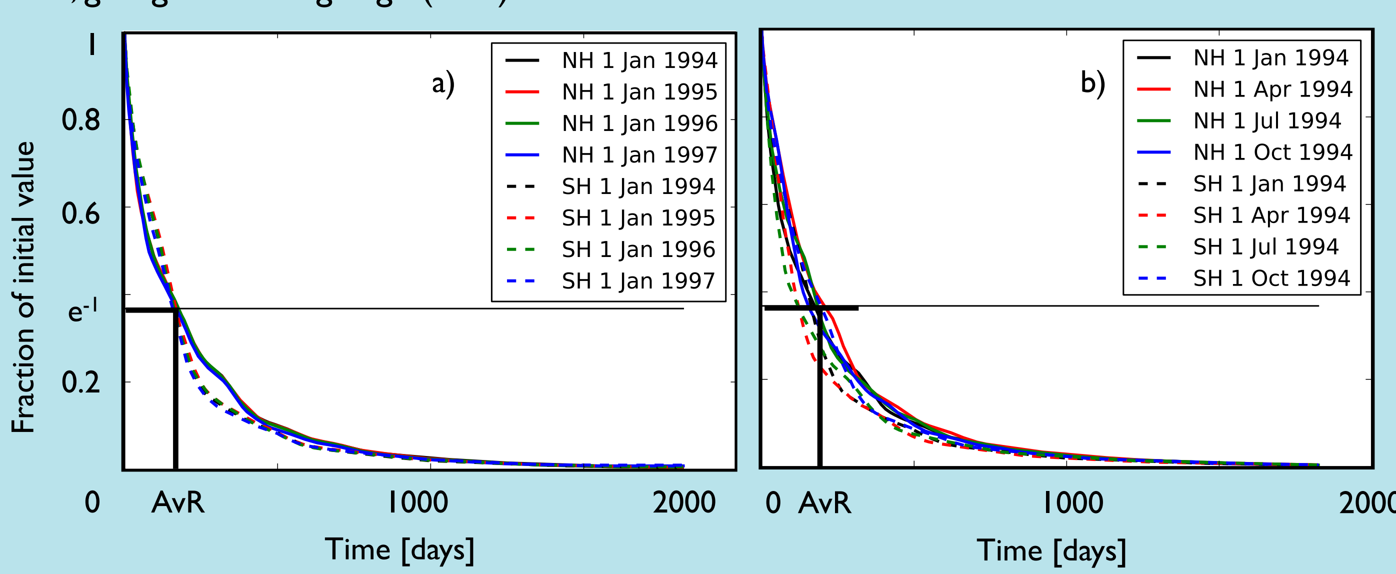

Fig 1: Amount of traced mass that has not yet reached the equator as function of time. Trajectories are traced forward in time from 1 January 1994, 1995, 1996, and 1997 (a) or 1 Jan, 1 Apr, 1 Jul, and 1 Oct 1994 (b). Solid lines are for northern hemisphere and dashed lines for southern hemisphere. Colors are for different years (a) or seasons (b). The e-folding time is the average residence time for the hemisphere.

Results

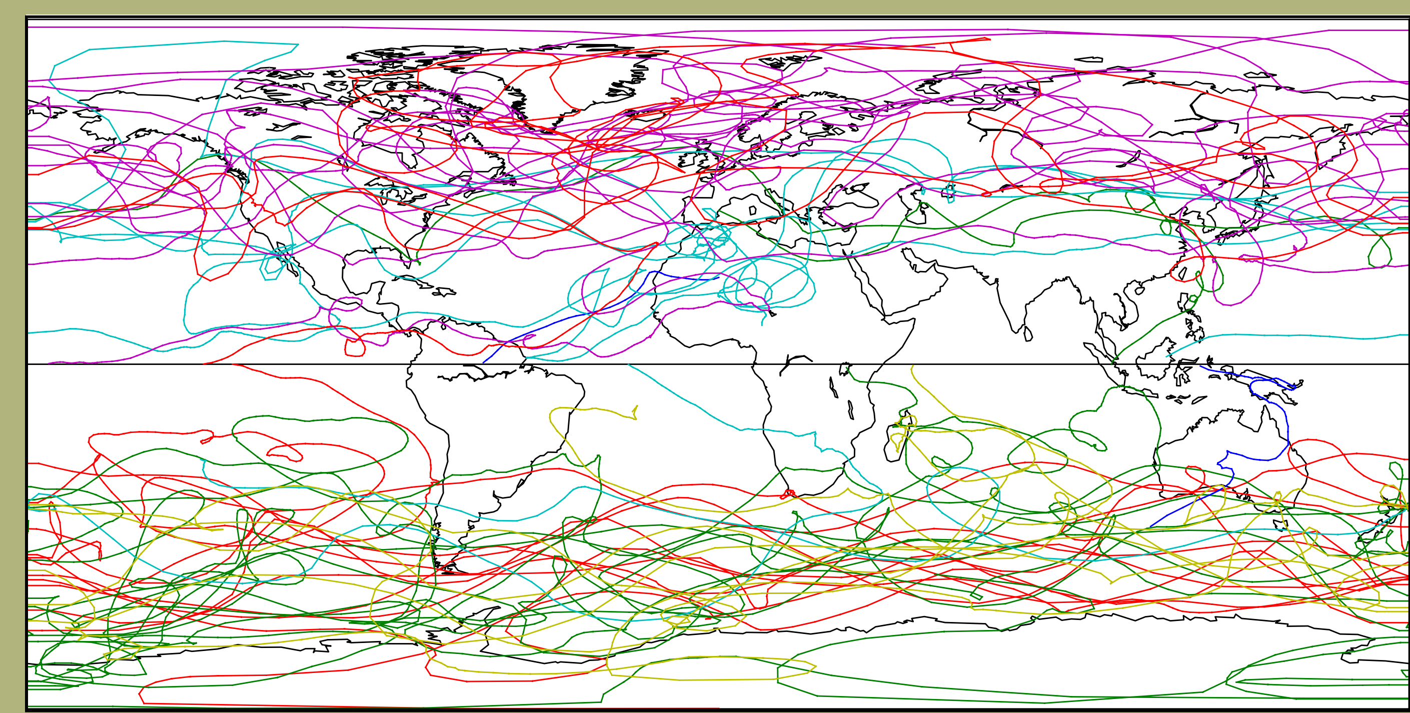

Fig 2: 10 trajectories released from the 45th layer (~750 hPa) on 1 January 1994 and traced forward in time until they reach the equator. Note how most trajectories at midlatitudes make several laps around the earth.

Stratosphere

Figure 3 shows the zonal mean of t_R and t_A for trajectories released on 1 January 1994. It shows a shorter t_R in the winter stratosphere than in the summer, most significantly over the poles. This can be explained by the overturning Brewer-Dobson circulation that is only active during winter time. Figure 3b shows that t_A is maximum in the polar stratosphere. The sharp difference in time scales between stratosphere and troposphere indicates that the tropopause is a quite strong transport barrier.

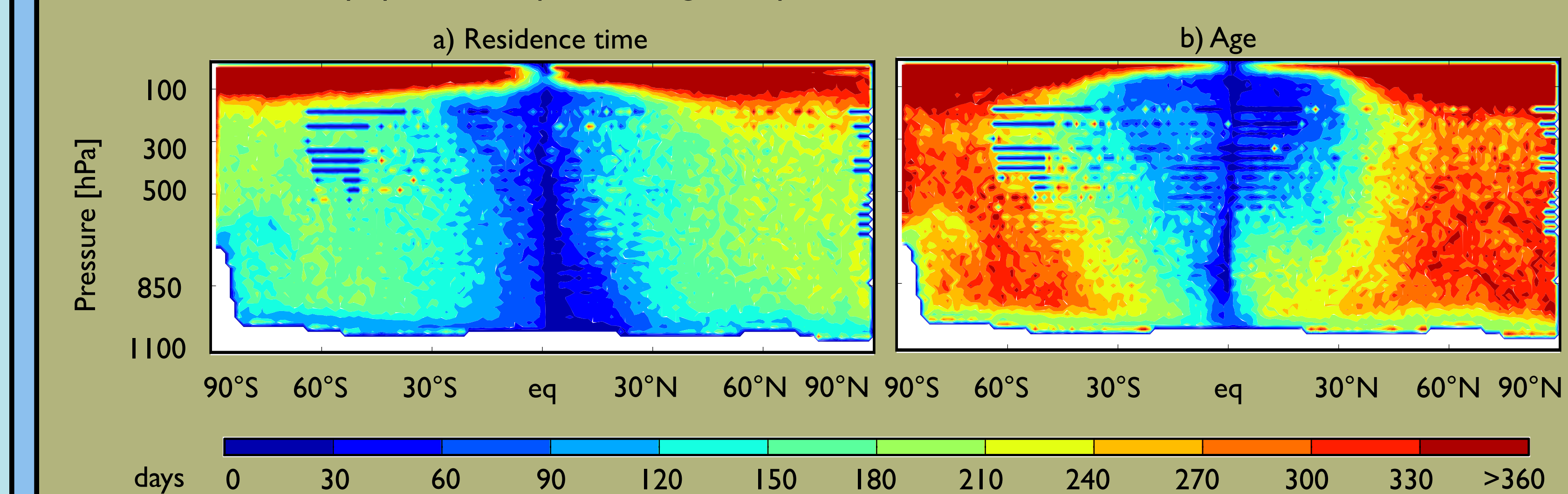

Fig 3: Zonal mean of residence time (a) and age (b) for trajectories released on 1 January 1994 as function of latitude and pressure of starting point. Transit residence time can be obtained by adding these two figures.

Troposphere

Our results (Fig 3) show that the t_R, in general, is shorter on the southern hemisphere than on the northern. This can be explained by the fact that the meridional overturning circulation, on an annual average, is stronger on the southern hemisphere. The colors also show a general increase with latitude for t_R and t_A. However, this increase is not uniform with height; t_R is shorter in the equatorward branch of the Hadley Circulation, while t_A is shorter in its poleward branch. Furthermore, the atmospheric boundary layer (where the flow is more turbulent) seems to have shorter time scales than the air above. This could indicate that the boundary layer top is a transport barrier.

Regional, temporal, and methodological differences

The trajectories were separated into classes to distinguish between tropical, midlatitude, and polar air as well as troposphere and stratosphere. Each class has a AvR, AvA and ATR (=AvR + AvA). Fig 4a shows all classes as well as entire Northern (NH) and Southern Hemispheres (SH). The tropospheric air has a faster transport than the stratospheric, but because of the smaller mass of the latter, the NH-curve is dominated by the former. In the troposphere AvR increases with latitude, while the situation is opposite in the stratosphere. AvA (not shown) increases with latitude both in troposphere and stratosphere.

Trajectories were started 1 January, 1 April, 1 July, and 1 October in 1994, 1995, 1996, and 1997. We were able to see some seasonal variability in the results (Fig 1b), but only a very small year-to-year variability (Fig 1a). It should be noted that the temporal variations are more pronounced when looking at different classes, especially tropical troposphere and polar stratosphere.

Figure 4b shows the Lagrangian results for NH and SH, but also exponential curves with an e-folding time equal to the turnover time. The turnover time was obtained using both biennial and monthly averages. The former give $t_T > t_R$ and the latter $t_T < t_R$. This is most likely because of the Hadley Cells, which, in an annual or biennial average, give a steady in- and outflow, while monthly means take the seasonal variations into account.

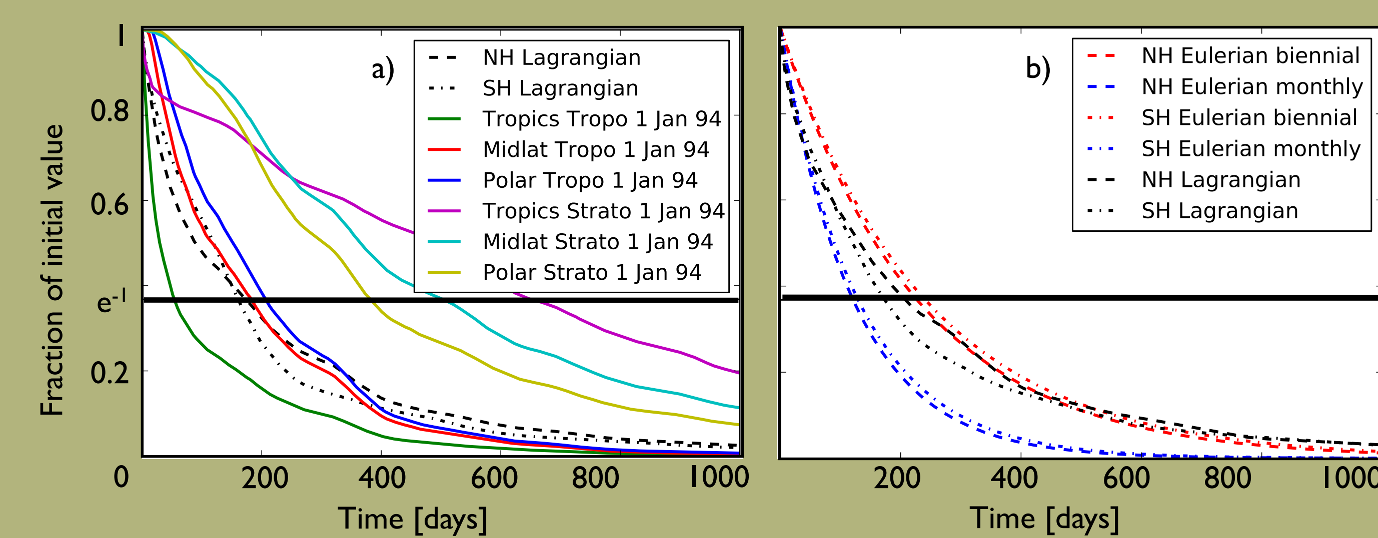

Fig 4a): Fraction of traced mass that has not yet reached the equator as function of time. Trajectories are traced forward from 1 January 1994. Black dashed and dashed-dotted lines are for all trajectories on the entire northern and southern hemisphere respectively. Solid lines are for different classes of the northern hemisphere. b): The black lines are the same as in a). The red lines are calculated from Eulerian turnover times based on biennial averages of surface pressure and meridional velocity. For the blue lines, the turnover times are based on monthly averages.

Main findings

- Eulerian turnover time is very dependent on averaging method and thus non-robust and inaccurate.
- Inter-hemispheric mass transport is much faster in the troposphere than stratosphere. The air with maximum age is found in the polar stratosphere, while the maximum residence time is found in the tropical stratosphere.
- AvR, AvA, and ATR for the hemispheres varies slightly with season, and very little year-to-year.

Future outlook

- Method can be used to diagnose large-scale circulations; Monsoon, Hadley Cells and/or Ferrel Cells.
- Work has been done to produce meridional overturning (y,p) and barotropic (x,y) Lagrangian stream functions.
- Possibility to couple ocean and atmosphere to determine transport time scales for mass and/or energy transport.