Flux Distributions as Robust Diagnostics of Stratosphere-Troposphere Exchange

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Introduction

The chemical and radiative properties of the troposphere and lower stratosphere are strongly influenced by the stratosphere-troposphere exchange (STE) of mass and tracers (e.g., Morgenstern 2001, Park 2004). Changes in STE with a changing climate will have important implications for the distribution of ozone, for the oxidizing capacity of the troposphere (Kentarchos 2003), and hence for tropospheric air quality (e.g., Cooper 2005).

➢ The one-way S→T flux is a rapidly changing function of how long air resides in the stratosphere before crossing into the troposphere. This explains the widely divergent estimates of STE fluxes reported in the literature (Gettelman 2000, Hall and Holzer 2003).

➢ We perform the first well defined diagnosis of one-way S→T transport in terms of flux distributions. The flux density distribution partitions the one-way cross-tropopause mass flux with respect to residence time in the stratosphere τ, entry region Ω_i, and exit region Ω_f.

Methodology

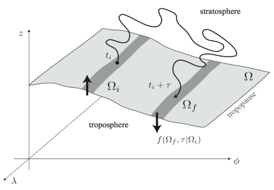

Fig 1 Schematic illustration of tropopause-to-tropopause transport through the stratosphere. Air is labelled with tracer as it enters the stratosphere through tropopause patch Ω_i during (t_i, t_i+dt_i). The flux of this labelled air out of the stratosphere through tropopause patch Ω_f, after a residence time in the interval (τ, τ+dτ), is given by $f(\Omega_f,\tau|\Omega_i)$.

To track air parcels during their transit from Ω_i to Ω_f we use the boundary propagator Green's function $\mathcal{G}$ (Holzer and Hall 2000). $\mathcal{G}(\mathbf{r},t|\Omega_i,t_i)dt_i$ is the mass fraction of air at position **r** and time t that had last Ω_i contact during (t_i, t_i+dt_i).

The boundary propagator is computed as the passive tracer response to a pulse at time t_i:

$$\frac{\partial}{\partial t}(\rho\mathcal{G})+\nabla\cdot\mathbf{J}=0 \quad \mathbf{J}\equiv(\rho\mathbf{u}-\rho\kappa\nabla)\mathcal{G}$$

$$\mathcal{G}(\mathbf{r}_\Omega,t|\Omega_i,t_i)=\Delta^2(\mathbf{r}_\Omega,\Omega_i)\delta(t-t_i)$$

➢ The area-averaged mass flux of Ω_i-air through patch Ω_f that has resided in the stratosphere for a time in (τ, τ+dτ) is:

$$f(\Omega_f,t_i+\tau|\Omega_i,t_i)d\tau=d\tau\frac{1}{A(\Omega_f)}\int_{\Omega_f}d^2r\,\hat{\mathbf{n}}\cdot\mathbf{J}(\mathbf{r},t_i+\tau|\Omega_i,t_i)$$

➢ For steady flow:

$$\mathcal{R}(\tau,\Omega_i,\Omega_f)=\frac{1}{M}\,A(\Omega_f)f(\Omega_f,\tau|\Omega_i)\tau$$

$\mathcal{R}(\tau,\Omega_i,\Omega_f)d\tau$ is the mass fraction of the stratosphere that has entered through Ω_i and will exit through Ω_f after a residence time in (τ, τ+dτ). $\mathcal{R}$ is easily summarized by its temporal moments.

We illustrate f and $\mathcal{R}$ in an idealized AGCM:

- ☐ Idealized physics
- ☐ T42 (horizontal) and L40 (vertical) resolutions
- ☐ Dry dynamical core (primitive equations on the sphere)
- ☐ Held-Suarez (1994) tropospheric forcing
- ☐ Stratospheric forcing as in (Polvani and Kushner 2002) run under perpetual DJF
- ☐ Wavenumber 2 topography (Gerber and Polvani 2009)
- ☐ High model top (80 km)

Our experiment:

- ☐ Spin up and choose an initial pulse time t_i
- ☐ Patch the WMO-defined thermal tropopause into 7 non-overlapping equal-area regions
- ☐ Pulse 7 passive tracers, one tracer for each patch
- ☐ At every time step and for every tracer collect the cross-tropopause flux
- ☐ Repeat for 5 t_i and ensemble average

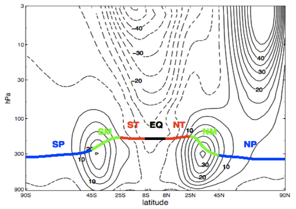

Fig 2 The time and zonal mean thermal tropopause (thick line) and contoured zonal winds. The contour interval is 5 m/s and the zero and negative contours are dashed. Different colors at the tropopause label equal-area axisymmetric patches.

Results

We illustrate our diagnostics for the case of air entering the stratosphere at the tropical tropopause.

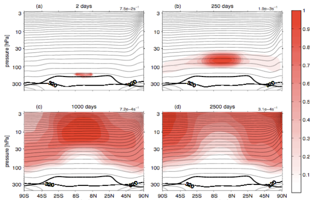

Fig. 3 The ensemble-averaged zonal mean boundary propagator $\mathcal{G}(\mathbf{r},\tau|\Omega_{EQ})$ (colored field) after (a) 2 days, (b) 250 days, (c) 1000 days, and (d) 2500 days since last contact with tropopause patch Ω_{EQ}.

- ☐ Air that enters the stratosphere at Ω_{EQ} undergoes diabatic upwelling in the tropics and isentropic quasi-horizontal transport into higher latitudes (e.g., Holton 1995, Plumb 2002).
- ☐ In less than ∼ 2500 days isopleths of Ω_{EQ}-air have approached ``slope equilibrium" for long-lived constituents (Plumb and Mahlman 1987).

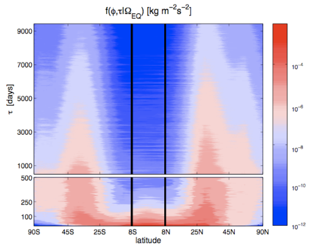

Fig. 4 The ensemble and zonally averaged flux density of Ω_{EQ}-air. The vertical lines mark the edges of Ω_{EQ}.

- ☐ The flow of Ω_{EQ}-air back through the tropical tropopause is dominated by short-τ diffusive fluxes. Physically, these are singular and arise from quasi-random back-and-forth motion of fluid elements across the tropopause at the shortest resolved times.
- ☐ The short-τ fluxes of Ω_{EQ}-air back through the equatorial patch rapidly decay with increasing τ. This is consistent with a barrier to horizontal transport.
- ☐ For air older than ∼200 days, the largest and most persistent fluxes are back through the midlatitudes where isentropes cross the tropopause.
- ☐ $f(\phi,\tau|\Omega_{EQ})$ reveals strong hemispheric asymmetry at midlatitudes for a wide distribution of residence times, particularly for old air.

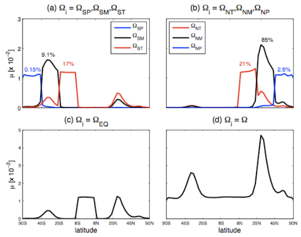

Fig. 5 The ensemble averaged mass fraction $\mu(\Omega_i, \Omega_f)$ of the stratosphere that undergoes $\Omega_i \rightarrow \Omega_f$ transport for Ω_i in (a) the Southern Hemisphere, (b) the Northern Hemisphere, (c) Ω_{EQ}, and (d) the full tropopause, Ω.

$\mu(\Omega_i, \Omega_f)$ quantifies the ensemble averaged mass fraction of the stratosphere in transit from Ω_i to Ω_f.

- ☐ Most stratospheric air mass returns to the troposphere via two pathways. Air recrosses the tropopause: (i) where it entered and (ii) isentropically at midlatitudes.
- ☐ The largest mass fraction of the stratosphere regardless of entry location returns through midlatitudes.
- ☐ $\mu(\Omega_i, \Omega_f)$ conveniently quantifies the transport response to a hemispherically asymmetric circulation: air is 3 times as likely to leave the NH than the SH.

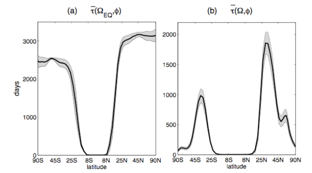

Fig. 6 (a) The mean residence time, $\bar{\tau}(\Omega_{EQ},\phi)$, of Ω_{EQ}-air exiting the stratosphere at latitude ϕ. The thick line indicates the ensemble average, and the grey shading indicates one standard deviation of the ensemble spread. (b) The mean residence time, $\bar{\tau}(\Omega,\phi)$, of air regardless of where it entered.

The mean residence time gives the mean time that air spends in the stratosphere en route from Ω_i to Ω_f.

- ☐ For exit at midlatitudes, $\bar{\tau}$ is nearly twice as large in the NH as in the SH.
- ☐ Longer mean residence times in the NH are not obvious. The stronger NH BDC circulation might be expected to flush the NH stratosphere more efficiently.

Conclusions

STE is well-posed provided it is computed as a flux distribution in residence time.

➢ The passive tracer response to a pulse in mixing ratio at the tropopause gives the one-way S→T flux of air as a function of stratospheric residence time.

➢ For steady flow the one-way flux can be integrated to give the **mass fraction** and **mean residence time** of the stratosphere undergoing transport into the troposphere.

➢ Most of the stratospheric air returns to the troposphere at the midlatitudes.

➢ Mean residence times are *larger* in the NH where the circulation is stronger. A higher-reaching residual circulation and a more turbulent, eddy-diffusive stratosphere with more breaking Rossby waves both lengthen the advective-diffusive paths through the NH.

➢ For more please see: Orbe, C., M. Holzer, and L.M. Polvani, "Flux distributions as well-posed diagnostics of stratosphere-troposphere exchange." *J. Geophys. Res.,* submitted, 2011

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