The Transit-Time Distribution from the Northern Hemisphere Midlatitude Surface

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Abstract:

The distribution of transit times from the Northern Hemisphere (NH) midlatitude surface is a fundamental property of tropospheric transport. Here we present an analysis of the transit time distribution (TTD) since air last contacted the northern midlatitude surface layer, as simulated by the NASA Global Modeling Initiative Chemistry Transport Model. We find that throughout the troposphere the TTD is characterized by long flat tails that reflect the recirculation of old air from the Southern Hemisphere and results in mean ages that are significantly larger than the modal age. Key aspects of the TTD -- its mode, mean and spectral width -- are interpreted in terms of tropospheric dynamics, including seasonal shifts in the location and strength of tropical convection and variations in quasi-isentropic transport out of the northern midlatitude surface layer. Our results indicate that current diagnostics of tropospheric transport are insufficient for comparing model transport and that the full distribution of transit times is a more appropriate constraint.

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Introduction

- Studying the transport of greenhouse gases and ozone depleting substances emitted over Northern Hemisphere (NH) midlatitudes is central to understanding and predicting tropospheric air quality, stratospheric ozone depletion and changes in the earth's radiative balance.
- The mean age since last contact at the NH midlatitude surface, Γ, can be inferred from measurements of SF_6 and has recently been proposed as a way to compare tropospheric transport between models (*Waugh et al., 2013*). The mean age, however, is an incomplete diagnostic.
- By comparison, the transit-time distribution (TTD) -- the distribution of transit times since last surface contact -- has been shown to be a more powerful diagnostic than the mean age in understanding transport in the oceans (e.g. *Primeau and Holzer, 2006*; *Holzer and Primeau, 2010*) and the stratosphere (e.g. *Bonisch et al., 2009*).

Methods

- The TTD is evaluated using one integration of the NASA Goddard Modeling Initiative (GMI) three-dimensional chemistry transport model (CTM) (*Strahan et al., 2007*), driven with MERRA reanalysis metereological fields for the years 2000-2010 (*Rienecker et al., 2011*).
- Two types of tracers are examined and defined with respect to the same surface NH midlatitude region, Ω_{MID} (i.e. first model layer, 30°N-50°N).

(i) TTD Tracers

- Boundary Impulse Response (BIR) tracers are used to approximate the TTD since last contact at the NH midlatitude surface (*Haine et al., 2008*). Each BIR corresponds to a particular instance of the Green's function boundary propagator, $\mathcal{G}(\mathbf{r},t|\Omega_{\mathrm{MID}},t')$, which satisfies:

$$\frac{\partial \mathcal{G}}{\partial t} + \mathcal{T}(\mathcal{G}) = 0 \quad \text{subject to} \quad \mathcal{G}(\mathbf{r}_{\Omega_{\mathrm{MID}}},t|\Omega_{\mathrm{MID}},t') = \delta(t-t')$$

where $\mathcal{T} \equiv$ advective-diffusive transport operator

- Four BIR tracers are released at times t' = January 1, April 1, July 1 and October 1 during the first year of the integration and carried for ten years. The average of the BIRs' responses, centered about transit time $\tau \equiv t - t' = 0$, is denoted as $\mathcal{G}(\mathbf{r},\tau|\Omega_{\mathrm{MID}})$. This approximation of the TTD rests on the fact that the statistics of the BIR and the TTD are identical (*Haine et al., 2008*).

(ii) Idealized Decay Tracers

- Two idealized decay tracers -- a 5-day tracer and a 50-day tracer -- are emitted uniformly over Ω_{MID} and undergo spatially uniform decay at rates τ_c^{-1} of 5 days[1] and 50 days[1]. Tracer concentrations are evaluated over the last year of the integration, after a statistically stationary state is reached.

The Transit-Time Distribution

Zonal mean TTD, $\mathcal{G}(\mathbf{r},\tau|\Omega_{\mathrm{MID}})$

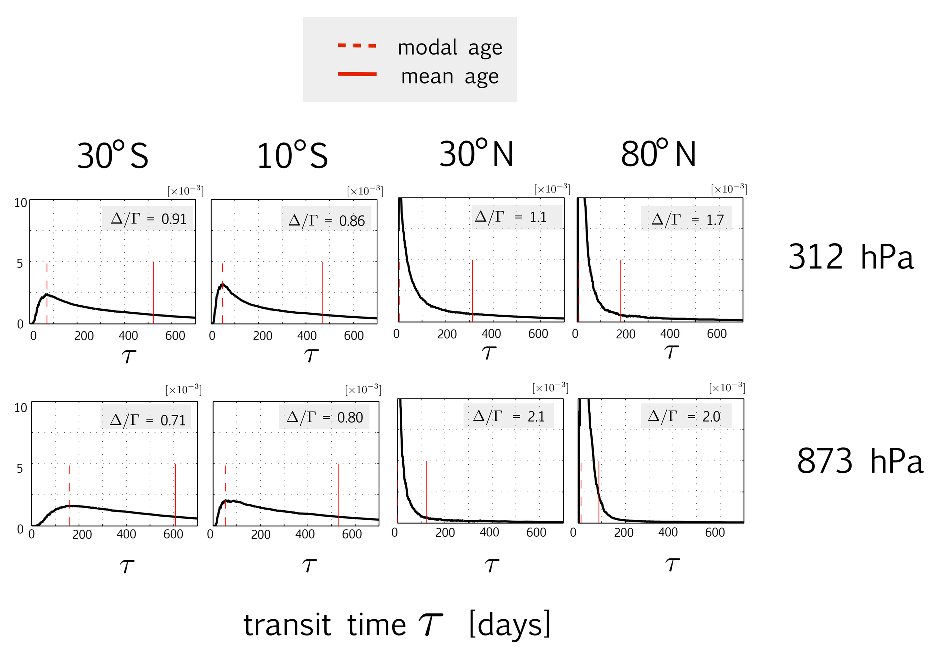

Figure 1: The distribution of transit times (TTD) since last contact at the NH midlatitude surface layer evaluated at 312 hPa (top) and 873 hPa (bottom).

- Throughout the troposphere the TTD is characterized by young modes and long tails so that $\tau_{\mathrm{mode}} << \Gamma$ (the mean transit time or "mean age").

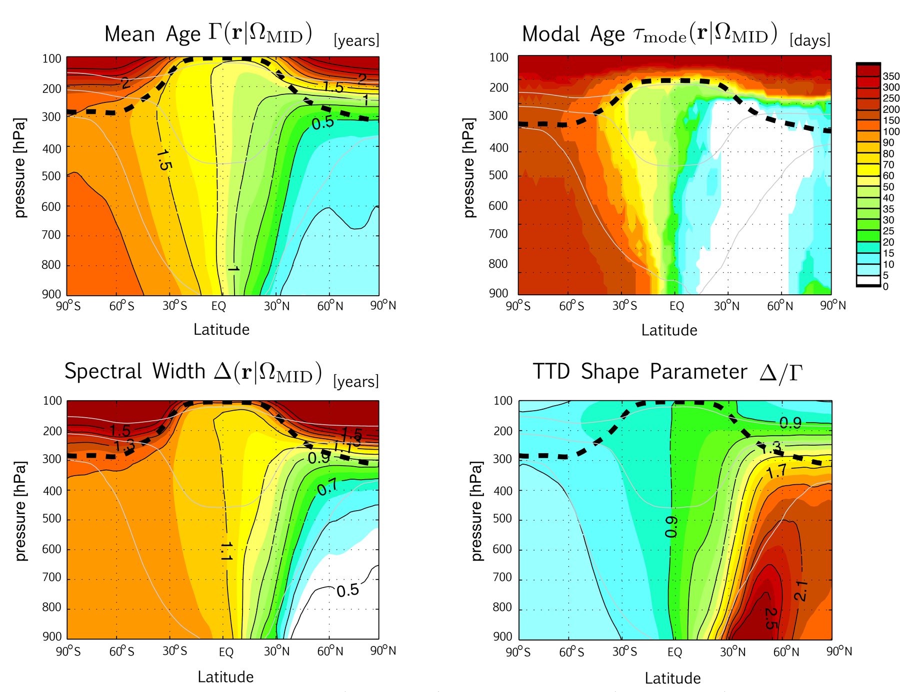

Figure 2: The mean age (top left), modal age (top right), and spectral width (bottom left), calculated from the approximation of the TTD, $\mathcal{G}(\mathbf{r},\tau|\Omega_{\mathrm{MID}})$. The ratio Δ/Γ provides a measure of the shape of the TTD (bottom right).

- The shape of the TTD, Δ/Γ, decreases from ~ 2 in the NH (highly skewed distribution) to ~ 0.7 in the SH (inverse Gaussian).
- Physically, changes in Δ/Γ signal changes in the relative contribution of fast transport paths and slow eddy-diffusive recirculations.

Transport Pathways

Transport paths, binned according to when air last contacted the NH midlatitude surface, are inferred from:

$$f_{\tau_1}^{\tau_2}(\mathbf{r}|\Omega_{\mathrm{MID}},t') = \int_{\tau_1}^{\tau_2} d\tau \mathcal{G}(\mathbf{r},\tau|\Omega_{\mathrm{MID}},t')$$

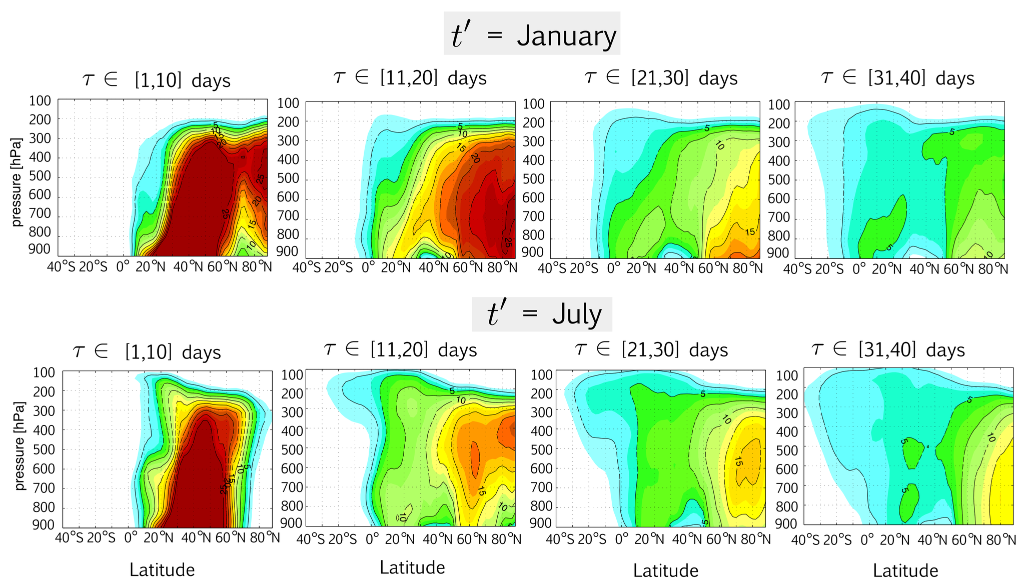

Figure 1: The zonal mean BIR fraction, $f_{\tau_1}^{\tau_2}(\mathbf{r}|\Omega_{\mathrm{MID}},t')$, corresponding to source times t' = January 1 (top) and t' = July (bottom). 10-day successive transit-time bands provide a sense for the fast transport paths that connect the midlatitude surface to the rest of the troposphere (units: %).

- Fast transport paths during boreal winter reflect shifts in the ITCZ and rapid isentropic transport to the upper Arctic. During summer, fast transport paths to the SH upper troposphere reflect strong cross-equatorial monsoon flow.

Constraining the TTD from Observations

- The interior mixing ratio χ of a tracer that is uniformly emitted at Ω and lost uniformly at a rate τ_c^{-1} can be expressed as:

$$\chi(\mathbf{r},t) \equiv \int_{-\infty}^{t} dt' \mathcal{G}(\mathbf{r},t|\Omega,t')\chi(\Omega,t')e^{-(t-t')/\tau_c}$$

Annual Mean $\overline{\chi}_{\tau_c}(\mathbf{r}|\Omega_{\mathrm{MID}})/\chi_{\Omega_{\mathrm{MID}}}$ [%]

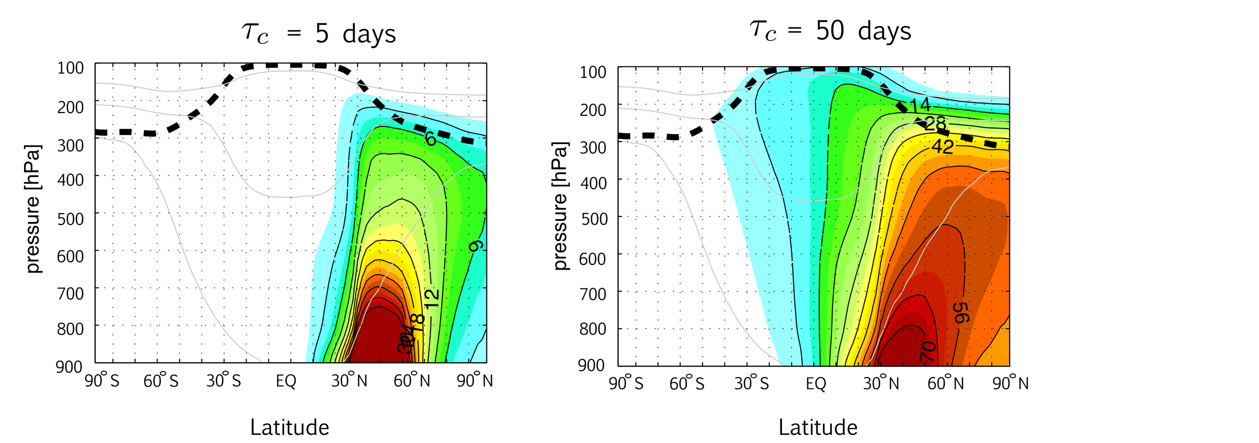

Figure 4: The annually averaged concentrations of the idealized 5-day and 50-day tracers. Reconstructions of χ_{τ_c} using the convolution $\overline{\chi}_{\tau_c}(\mathbf{r}|\Omega_{\mathrm{MID}})/\chi_{\Omega_{\mathrm{MID}}} \equiv \int_0^{\infty} d\tau \mathcal{G}(\mathbf{r},\tau|\Omega_{\mathrm{MID}})e^{-\tau/\tau_c}$ compare well with the explicitly calculated tracers.

Idealized Decay Tracer Concentrations and TTD Timescales

Upper Troposphere (312 hPa)

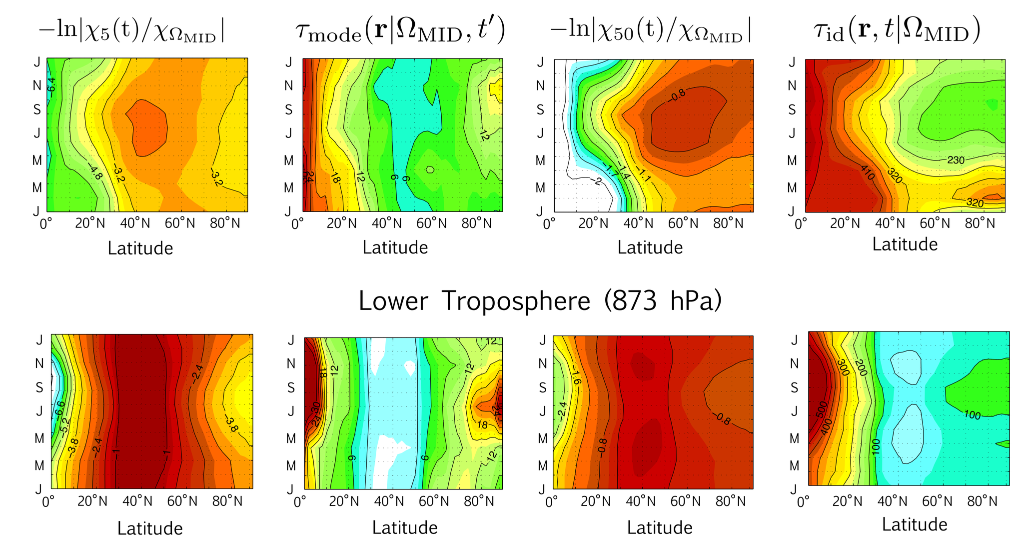

Figure 5: The seasonal cycles $\chi_{\tau_c}(\mathbf{r},t|\Omega_{\mathrm{MID}})/\chi_{\Omega_{\mathrm{MID}}}$ for τ_c = 5 days (column 1) and τ_c = 50 days (column 3). The seasonal cycles of the modal age and the ideal age (equivalent to the mean age) are shown in columns 2 and 4.

- The spatial patterns and seasonal cycles of idealized 5-day and 50-day tracers resemble the modal age, τ_{mode}, and the mean age, Γ, respectively.

Conclusions

- The mean age reflects the average of a highly skewed TTD. Thus, the full distribution of transit times provides a more physically meaningful description of the transport.
- Large gradients in the shape of the TTD, Δ/Γ, imply changes in the relative importance of fast transport paths and slow eddy-diffusive recirculations.
- The correspondence between the idealized decay tracers and TTD timescales suggests that suites of tracers with different lifetimes may be used to constrain the TTD from observational data, as has been done in the SH using measurements of CFCs and CFC replacement compounds (*Holzer and Waugh, 2015*).

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