Analyzing the effects of Brewer-Dobson circulation upwelling and horizontal transport on the TTL composition

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UTLS composition impacts radiation & temperature!

⇒ tropics: 30% T ann. ampl. linked to $O_3$  
[Fueglistaler, 2011]

which processes drive seasonal trace gas variations in TTL?

Analyzing the effects of Brewer-Dobson circulation upwelling and horizontal transport on the TTL composition
Annual cycles in TTL for various species (e.g., H$_2$O, O$_3$, CO)

Motivation

In-mixing/upwelling impact on TTL

In-mixing & sensitivities

Conclusions

Mixing ratio: $\partial_t \chi = S(t) - \dot{\theta}(t) \partial_\theta \chi - \mathbf{v}(t) \partial_y \chi + D$

⇒ seasonality due to:

$\dot{\theta}$ (BD-circulation, convection)
$v$ (horizontal in-mixing from extratropics)
$S$ (sources & sinks)

seasonality linked to vert. transport [e.g., Randel, 2007; Schoeberl, 2006; Folkins, 2006]

O$_3$: in-mixing impact [Konopka, 2009]
Annual cycles in TTL for various species (e.g., H$_2$O, O$_3$, CO)

Goals & Outline:
Disentangle in-mixing & BD-upwelling effects on TTL seasonality
1. In-mixing & BD-upwelling effect on H$_2$O, O$_3$, CO
2. Characteristics of in-mixing
3. Sensitivities

Mixing ratio: $\partial_t \chi = S(t) - \dot{\theta}(t) \partial_\theta \chi - v(t) \partial_y \chi + D$
- Source-sink
- Upwelling
- In-mixing
- Eddy diff.
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Method 1: 3D backtrajectories

- reconstruct
- $\text{H}_2\text{O}$: freeze-drying
- $\text{O}_3$: photochem. production
- $\text{CO}$: chemical loss

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Separation of pathways:

- in–mixing: eq.lat. > 50° & θ > 350 K
- tropical (BD-upwelling): rest

TTL mixing ratio:

\[ \chi_{TTL} = f_{trop} \chi_{trop} + f_{NH} \chi_{NH} + f_{SH} \chi_{SH} \]
Seasonality of tropical and in-mixed mixing ratios ($\chi$’s)

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**Seasonality of tropical and in–mixed mixing ratios ($\chi$’s)**

**O$_3$:** tropics + in–mixing

**CO:** tropics + in–mixing

**Seasonality due to:**

- **O$_3$:** tropics + in–mixing
- **CO:** tropics + in–mixing

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**Seasonality of tropical and in–mixed mixing ratios ($\chi$’s)**

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Seasonality due to:
- **$\text{O}_3$:** tropics + in–mixing
- **$\text{CO}$:** tropics + in–mixing
- **$\text{H}_2\text{O}$:** tropical transport
Seasonality of tropical and in–mixed mixing ratios ($\chi$’s)

Seasonality due to:
- $O_3$: tropics + in–mixing
- $CO$: tropics + in–mixing
- $H_2O$: tropical transport

TTL seasonality:
Tropical view not sufficient $\Rightarrow$ in–mixing important!
Origin of TTL O$_3$ ann. cycle (@400K)

a) In-mixed air fraction ($f$’s):
- In-mixed air $\approx$ ann. cycle
- NH/SH inversely phased
- ERA-Int agrees with obs. estimate [Volk,1996]

b) Contributions to TTL O$_3$:
- $\chi_{TTL} = f_{trop}\chi_{trop} + f_{NH}\chi_{NH} + f_{SH}\chi_{SH}$
- 50% summer O$_3$ in-mixed (ann. amplit. main forcing!)

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Fraction of in-mixed air ≈ 20%, O₃ ≈ 50%:
⇒ in-mixing impact depends on species’ meridional gradient!

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What drives in-mixing?

- PV & hor. wind @ 370 K (NH summer)
- 50°-crossing PDF (summer)

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In–mixing caused by:
monsoon circulations! (⇒ strong seasonality)
In-mixing & sensitivities: vert. velocity

- Vert. velocity $\dot{\theta}$ in TTL (rad. calculation $\leftrightarrow$ ERA-Interim)

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In-mixing & sensitivities: vert. velocity

- Vert. velocity $\dot{\theta}$ in TTL (rad. calculation $\Leftrightarrow$ ERA-Interim)

Rad. calculation $\Leftrightarrow$ ERA-Interim:
TTL upwelling in ERA-Interim $\approx 40\%$ too fast!

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1D tropical tracer model

1D tropics with in–mixing rates $\alpha$ (entrainment) \cite{Volk,1996}

$$\partial_t \chi = -\dot{\theta}(t) \partial_\theta \chi - \alpha_n(t)(\chi - \chi_n) - \alpha_s(t)(\chi - \chi_s) + P - L\chi$$

$\dot{\theta}$ from ERA-Interim (corrected), in-mixing from 3D trajectories

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- 1D tropics with in–mixing rates $\alpha$ (entrainment) [Volk, 1996]
  \[
  \frac{\partial t}{\partial x} = -\dot{\theta}(t) \frac{\partial \theta}{\partial x} - \alpha_n(t)(x - x_n) - \alpha_s(t)(x - x_s) + P - Lx
  \]

- $\dot{\theta}$ from ERA-Interim (corrected), in-mixing from 3D trajectories

Sensitivity TTL composition to upwelling & in-mixing:
⇒ vary annual **mean & amplitude** of upwelling & in-mixing!
Sensitivity $O_3$ & CO profiles to annual mean upwelling $\langle \dot{\theta} \rangle$

- Increased $\langle \dot{\theta} \rangle$ \(\Rightarrow\) weaker $O_3$ gradient (less production)
  \(\Rightarrow\) weaker CO gradient (less loss)

- Best fit for $0.6 \cdot \langle \dot{\theta}_{ERA} \rangle \Rightarrow$ ERA-Interim $\dot{\theta} \approx 40\%$ too fast!
Sensitivity of $O_3$ annual cycle to upwelling/in-mixing:

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Sensitivity of $O_3$ annual cycle to upwelling/in-mixing:

**O$_3$ control:**
upwelling & in-mixing amplitudes!
Sensitivity of CO annual cycle to upwelling/in-mixing:

CO control: Brewer-Dobson upwelling!
**In-mixed O₃ fraction throughout ‘realistic’ vert. velocity range:**

- very weak dependence on upwelling ($\geq 37\%$ O₃ in-mixed)
- ann. amplitude fraction linked to in-mixing $\geq 70\%$

(NH summer)
In-mixed $O_3$ fraction throughout ‘realistic’ vert. velocity range:

- **In-mixed $O_3$ fraction:** throughout the ‘realistic’ vertical velocity range, there is very weak dependence on upwelling. A minimum of at least 37% $O_3$ is in-mixed.
- **Ann. amplitude fraction linked to in-mixing:** ≥ 70%

**How much $O_3$ in-mixed?**

- **Min. in-mixing case (ERA – 20%):**
  - ≥ 30% $O_3$ mixing ratio
  - ≥ 65% $O_3$ ann. anomaly

**NH summer**

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Sensitivity of in-mixed O$_3$ to vert. velocity?

Mean tropical ascent along 1D trajectory $\theta(t)$:

\[
\frac{d\chi}{d\theta} = -\gamma \chi + \frac{\alpha \chi_m + P}{\dot{\theta}}
\]

$P$...chem. production; $\alpha$...in-mixing rate; $\chi_m$...mid-latitude value; $\gamma = L + \alpha$, $L$...chem. loss

$\chi = \chi_0 + \Delta \chi_{in} + \Delta \chi_{chem}$

$\Delta \chi_{chem} = (P/\dot{\theta}) \Delta \theta'$

$\Delta \chi_{in} = (\alpha \chi_m/\dot{\theta}) \Delta \theta'$

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$$\chi(\theta) = \int_{\theta_0}^{\theta} \left( \frac{\alpha \chi_m + P}{\dot{\theta}} \right) G(\theta, \theta') d\theta' + \chi_0 G(\theta, \theta_0), \quad G(\theta, \theta') = e^{-\int_{\theta}^{\theta'} \gamma d\theta''}$$

$\Rightarrow$ **production & in-mixing** along trajectory

$+$ upward propagation of boundary $\chi_0$

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Contribution of in-mixing:

relative to photochem. production ($= \alpha \chi_m / P$) independent of $\dot{\theta}$!

$\Rightarrow \geq 30\%$ O$_3$ in-mixed independent of $\dot{\theta}$

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Conclusions:

- in-mixing important for TTL seasonality (merid. gradient!)
- annual cycle of in-mixing (summer: ~20%, monsoons!)
- impact on composition
  - $\text{O}_3$: large (summer: 30-50%, anomaly control $\geq 65$%)
  - $\text{CO}$: weak
  - $\text{H}_2\text{O}$: vanishing
- ERA-Interim upwelling $\sim$40% too fast
- in-mixed $\text{O}_3$ fraction independent of BD-upwelling velocity
- if seasonal $\text{O}_3$ variations amplify trop. temperature cycle
  $\Rightarrow$ link between in-mixing and trop. temperatures
Appendix
What if no in-mixing???

no in-mixing: vary $\dot{\theta}_a$

$\Rightarrow$ need extremely large $\frac{\dot{\theta}_a}{\langle \dot{\theta} \rangle} \geq 65\%$

$\Rightarrow$ mean O$_3$ too low!
What if no in-mixing???

no in-mixing: vary $\dot{\theta}_a$

$\Rightarrow$ need extremely large $\langle \dot{\theta}_a \rangle \geq 65\%$

$\Rightarrow$ mean $O_3$ too low!

$\Rightarrow$ at least some in-mixing needed!!!
Fraction of in-mixed air (a) and of in-mixed O$_3$ (b)

- in-mixing occurs in TTL (370–420K)
- upward propagation of in-mixed air
- impact on O$_3$ largest in TTL (400–430K) (no upward propagation)
What drives in-mixing?

- PV & hor. wind @ 370 K (NH winter)
- 50°-crossing PDF (winter)