Trace Gas Transport in the Stratosphere: Opportunities and Challenges

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Today’s Ozone

OMI total ozone 19-11-2019

KNMI/NASA

Ozone density [Dobson Units]

150 175 200 225 250 275 300 325 350 375 400 425 450 475 500
Today’s Ozone: the Brewer-Dobson Circulation

Dobson, Harrison, and Lawrence [1929]
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Today’s Ozone: the Brewer-Dobson Circulation

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The only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration within the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the Pole. Such a current would carry ozone formed in low latitudes to the Pole and concentrate it there. If this were the case the
§ VI.—The Formation and Decomposition of Atmospheric Ozone.

It has generally been supposed in the past that the ozone present in the upper atmosphere was formed from oxygen under the influence of the sun’s ultra-violet radiation of wave-length about 1600 Å., but the results of the present observations make it almost certain that this is not the chief cause of the formation of ozone. We find that the maximum ozone values are associated

\[ \text{Ozone density [Dobson Units]} \]

150 175 200 225 250 275 300 325 350 375 400 425 450 475 500

Dobson, Harrison, and Lawrence [1929]
EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.
Trace gases in the stratosphere
Opportunities and Challenges

- Trace gas observations can still help us better understand the circulation of the stratosphere

- Trace gas transport is a challenge for climate prediction
Trace gases in the stratosphere
Opportunities and Challenges

- Trace gas observations can *still* help us better understand the circulation of the stratosphere
  - The “age-of-air” can be used to connect trace gas measurements to the overturning circulation
  - Modern reanalyses struggle with the overturning circulation; could assimilation of trace gases help?
- Trace gas transport is a challenge for climate prediction
Trace gases in the stratosphere
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  • The “age-of-air” can be used to connect trace gas measurements to the overturning circulation
  • Modern reanalyses struggle with the overturning circulation; could assimilation of trace gases help?
• Trace gas transport is a challenge for climate prediction
  • Ozone recovery projections vary considerably due to differences in transport
  • Transport depends critically on the numerical formulation and resolution; modern atmospheric model cores exhibit significant differences
Age-of-air: an idealized tracer that measures the mean elapsed time since air left the surface.

How long has this air been in the stratosphere?

[Linz et al. 2016]
Age-of-air: an idealized tracer that measures the mean elapsed time since air left the surface

How long has this air been in the stratosphere?

\[
\frac{\partial \Gamma}{\partial t} + \frac{1}{\rho} \mathbf{v} \cdot \nabla \Gamma = 1
\]

[Linz et al. 2016]
Age-of-air: an idealized tracer that measures the mean elapsed time since air left the surface.

How long has this air been in the stratosphere?

In steady state, transport balances local aging:

\[
\frac{\partial \Gamma}{\partial t} + \frac{1}{\rho} \bar{v} \cdot \nabla \Gamma = 0
\]

\[
\frac{1}{\rho} \bar{v} \cdot \nabla \Gamma = 1
\]

[Linz et al. 2016]
Age flux across an isentropic surface must equal the mass above the surface in steady state.

In a steady state:

\[ \vec{u} \cdot \nabla \Gamma = \rho \]

Integrate over the volume above an isentropic surface.

[Linz et al. 2016]
Age flux across an isentropic surface must equal the mass above the surface in steady state

In a steady state:

$$\vec{v} \cdot \nabla \Gamma = \rho$$

Integrate over the volume above an isentropic surface

$$\text{age flux across surface} = \text{mass above the surface}$$

$$- \int_{\theta} \sigma \dot{\theta} \Gamma dA = M(\theta)$$

[\text{Linz et al. 2016}]
Age flux can be linked to mean overturning by considering the gross age gradient:

\[ \int_{\text{up}} \sigma \theta dA = - \int_{\text{down}} \sigma \theta dA = M(\theta) \]

[\text{Linz et al. 2016}]
Age flux can be linked to mean overturning by considering the gross age gradient.

Age flux related to mean age entering and leaving stratosphere.

\[
\int_\theta \sigma \dot{\theta} \Gamma dA = \Gamma_u \mathcal{M}(\theta) - \Gamma_d \mathcal{M}(\theta)
\]

What goes up must come down.

(key: define mean upwelling/downwelling age as a mass weighted average)
Putting all together

\[- \int_{\theta} \sigma \dot{\theta} \Gamma dA = M(\theta) \quad \int_{\theta} \sigma \dot{\theta} \Gamma dA = \Gamma_u M(\theta) - \Gamma_d M(\theta)\]

\[\Gamma_d - \Gamma_u = \frac{M(\theta)}{M(\theta)}\]

gross age difference = mean residence time

[Linz et al. 2016]
Putting all together

\[- \int_\theta \sigma \dot{x} \Gamma dA = M(\theta) \quad \int_\theta \sigma \dot{x} \Gamma dA = \Gamma_u M(\theta) - \Gamma_d M(\theta)\]

\[\Gamma_d - \Gamma_u = \frac{M(\theta)}{\bar{M}(\theta)}\]

gross age difference = mean residence time

mean overturning relates directly to age difference

*not necessarily the age itself*

\[\bar{M}(\theta) = \frac{M(\theta)}{\Gamma_d - \Gamma_u}\]

[Linz et al. 2016]
Age from satellite SF$_6$ measurements by MIPAS

[Haenel et al. 2015]

[Kovacs et al. 2017]
Age can also be estimated from N$_2$O due to its compact relationship with CO$_2$.

\[ \Gamma_{LAG}(N_2O) = 0.0581(313 - N_2O) - 0.000254(313 - N_2O)^2 + 4.41 \times 10^{-7}(313 - N_2O)^3 \]

Age from SF$_6$, N$_2$O, and models vary a lot

Age on the 500 K isentrope (c. 21 km)

MIPAS - SF$_6$ age

GOZCARDS - N$_2$O age

WACCM - SF$_6$ age

WACCM - ideal age

[Linz et al. 2017]
Theory holds well in a model (WACCM) allowing us to test assumptions
The Overturning Circulation: Two observational sets agree (where they both exist)

The strength of the total overturning circulation through each port of stratospheric ozone, stratosphere–troposphere exchange, the stratospheric ozone circulation helps determine trans-port of stratospheric ozone, stratosphere–troposphere exchange, the stratospheric ozone circulation helps determine transport and chemistry of ozone in the stratosphere.

We have calculated the strength of the overturning circulation with the model and reanalyses, there is significant disagreement between different reanalyses. MERRA has a circulation strength that is 30% lower than JRA55, and the ERA-Interim has a circulation strength that is 50% lower than JRA55. The circulation strength is lower by a factor of three in the stratosphere compared to the troposphere. The circulation strength is uncertain to within at least 100%.

The mean diabatic circulation is a bias in either the data or the model. The circulation strength estimate is much greater because of its very low standard deviation. In the range where we have estimates from both observational data sets, they agree closely and are flanked by the reanalyses, which vary more widely. Accounting for the potential high bias induced by the method, this estimate becomes 6.3–7.6 kg s⁻¹.

For the potential high bias induced by the method, this estimate becomes 6.3–7.6 kg s⁻¹, would provide an independent estimate of age diabatic circulation at 1,200 K, and we cannot estimate an upper bound on the bias. The reanalyses may correctly represent the circulation and not the residual circulation is used, the computation for each data product, the model and the reanalyses are not the same. Despite this wide range, two of the six estimates of the strength of the circulation are quite consistent, while the mean diabatic circulation estimate is much greater because of its very low standard deviation. At the lowermost levels, the reanalyses tend to agree, while for the potential high bias induced by the method, this estimate becomes 6.3–7.6 kg s⁻¹, would provide an independent estimate of age diabatic circulation at 1,200 K, and we cannot estimate an upper bound on the bias. The reanalyses may correctly represent the circulation and not the residual circulation is used, the computation for each data product, the model and the reanalyses are not the same. Despite this wide range, two of the six estimates of the strength of the circulation are quite consistent, while the mean diabatic circulation estimate is much greater because of its very low standard deviation.
The Overturning Circulation: Significant disagreement with modern reanalyses

Overturning (10^9 kg/s) at 460 K

<table>
<thead>
<tr>
<th>Model</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIPAS SF_6</td>
<td>7.4</td>
</tr>
<tr>
<td>GOZCARDS N_2O</td>
<td>7.2</td>
</tr>
<tr>
<td>JRA55</td>
<td>7.9</td>
</tr>
<tr>
<td>MERRA</td>
<td>5.5</td>
</tr>
<tr>
<td>ERA-I</td>
<td>6.5</td>
</tr>
<tr>
<td>WACCM</td>
<td>7.1</td>
</tr>
</tbody>
</table>

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6.3 - 7.6 (uncertainty)
```
And it matters for future climate projections…
Tracer transport important for climate prediction: When will the ozone hole heal?

![Graph showing total ozone, 60-90S, October](image)

[Karpechko et al. 2013]
Tracer transport important for climate prediction: Ozone recovery

Karpechko et al. 2013: spread between models most strongly correlates with transport
Numerics and Transport

- *Karpechko et al. (2013)*: uncertainty in ozone recovery due more to transport than chemistry or climatology

- *Kent et al. (2014)* establish short term test of transport by dynamical cores, the numerical heart of an AGCM

- Today: an update of the *Held and Suarez (1994)* test to assess the climatological properties of transport (and stratosphere-troposphere coupling more generally)
In the last 25 years, growing awareness of importance of strat-trop coupling + chemistry

\[
\frac{\partial v}{\partial t} = -k_v(\sigma)v
\]

\[
\frac{\partial T}{\partial t} = -k_T(\phi, \sigma)[T - T_{eq}(\phi, p)]
\]

\[
T_{eq} = \max \left( 200K, 315K - (\Delta T) \sin^2 \phi - (\Delta \theta) \log \left( \frac{p}{p_0} \right) \cos^2 \phi \left( \frac{p}{p_0} \right)^\kappa \right)
\]

\[
k_T = k_a + (k_s - k_a) \max \left( 0, \frac{\sigma - \sigma_b}{1 - \sigma_b} \right) \cos^4 \phi
\]

\[
k_v = k_f \max \left( 0, \frac{\sigma - \sigma_b}{1 - \sigma_b} \right)
\]

\[
\sigma_b = 0.7, \quad k_f = 1 \text{ day}^{-1},
\]

\[
k_a = \frac{1}{40} \text{ day}^{-1}, \quad k_s = \frac{1}{4} \text{ day}^{-1}
\]

\[
(\Delta T)_y = 60K, \quad (\Delta \theta)_z = 10K
\]

\[
p_0 = 1000 \text{ mb}, \quad \kappa = \frac{R}{c_p} = \frac{2}{7}, \quad c_p = 1004 \text{ J kg}^{-1} \text{ K}^{-1}
\]

\[
\Omega = 7.292 \times 10^{-5} \text{ s}^{-1}, \quad g = 9.8 \text{ m s}^{-2}, \quad a_e = 6.371 \times 10^6 \text{ m}.
\]
In the last 25 years, growing awareness of importance of strat-trop coupling + chemistry

Update $T_{eq}$ to Polvani and Kushner (2002): polar night jet (perpetual January)

$$
\frac{\partial T}{\partial t} = \cdots - k_T(\phi, \sigma) [T - T_{eq}(\phi, p)]
$$

$$
T_{eq} = \max \left\{ 200K, \left[ 315K - (\Delta T)_y \sin^2 \phi - (\Delta \theta)_z \log \left( \frac{p}{p_0} \right) \cos^2 \phi \right] \left( \frac{p}{p_0} \right)^k \right\}
$$

$$
k_T = k_a + (k_s - k_a) \max \left( 0, \frac{\sigma - \sigma_b}{1 - \sigma_b} \right) \cos^4 \phi
$$

$\gamma = 4 \text{ K/km}$
In the last 25 years, growing awareness of importance of strat-trop coupling + chemistry

- Update $T_{eq}$ to Polvani and Kushner (2002): polar night jet (perpetual January)

- Topography to stimulate SSWs [Gerber and Polvani 2009]
In the last 25 years, growing awareness of the importance of strato-trop coupling + chemistry.


Topography to stimulate SSWs [Gerber and Polvani 2009].

Add clock tracer to evaluate age-of-air.
Compare 4 dynamical cores

- **GFDL-PS**
  - PSEUDOSPECTRAL
  - Horizontal: $2^\circ \times 2^\circ$
  - Vertical: 40 levels
- **GFDL-FV3**
  - CUBED SPHERE FINITE VOLUME
  - Horizontal: $1^\circ \times 1^\circ$
  - Vertical: 40 levels
- **CAM-SE**
  - CAM SPECTRAL ELEMENT
  - (NCAR’s CESM2 core)
  - Horizontal: $2^\circ \times 2^\circ$
  - Vertical: 80 levels
- **CAM-FV**
  - CAM FINITE VOLUME (CAM-FV)
  - Horizontal: $1^\circ \times 1^\circ$
  - Vertical: 80 levels

... and their robustness to changing resolution
Initial Results: Large spread between models (in layman’s terms, a real mess!)

Figure 7. Ensemble mean age of air (years) in the stratosphere in solid contours for (a) the FR integrations and (b) the specified runs. The colors in the background show the fractional age deviation from the ensemble mean. A deviation of 0.1 at a position where the ensemble mean age is 10 yrs means a total standard deviation of 1 yr across the ensemble.

large differences in midlatitude surf zone + the tropical pipe

fractional deviation across the four cores
Differences are stratospheric in origin

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[Gupta et al. (in review)]
Differences are stratospheric in origin reflecting a split between spectral and FV cores

[Gupta et al. (in review)]
Key is divergence of tropical winds: spectral models develop westerly jets

[cf. Yao and Jablonowski 2015]

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Key is divergence of tropical winds: spectral models develop westerly jets

westerlies permit enhanced mixing into tropics

[cf. Yao and Jablonowski 2015]
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Update $T_{eq}$ to Polvani and Kushner (2002): polar night jet (perpetual January)

Topography to stimulate SSWs [Gerber and Polvani 2009]

Add clock tracer to evaluate age-of-air

Specify winds in the tropics (i.e., constrain QBO region)
Greater agreement amongst cores but differences persist

Figure 7. Ensemble mean age of air (years) in the stratosphere in solid contours for (a) the FR integrations and (b) the specified runs. The colors in the background show the fractional age deviation from the ensemble mean. A deviation of 0.1 at a position where the ensemble mean age is 10 yrs means a total standard deviation of 1 yr across the ensemble.

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[b] Ensemble mean age - specified (SP) 

[Gupta et al. (in review)]
CAM-SE and GFDL-FV3 Converge towards different solutions!

Figure 11. Age of air (in years) from the specified (SP) integrations from all four dycores at all four resolutions are shown. (a) and (b) show the age for GFDL-FV3 and CAM-SE at (a) 30hPa and (b) 65hPa. (c) and (d) show the age for GFDL-PS and CAM-FV at (c) 30hPa and (d) 65hPa. The low (high) horizontal resolution runs are shown using lighter (dark) curves and the low (high) vertical resolution runs are shown using dashed (solid) curves. The GFDL-pseudospectral is shown in blue, the GFDL-FV3 in orange, the CAM-SE in green and the CAM-FV in red. Higher horizontal (0.5L80; NE60L80) and higher vertical (1L160; NE30L160) CAM-SE runs are shown using dashed-dotted and dotted black curves in (a) and (b) respectively.

Gupta et al. (in review)
Uncertainty in diabatic circulation dominates difference between CESM-SE and GFDL-FV3

[Gupta et al. (in prep.)]
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