Projections of stratospheric changes and their role in climate

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Introduction

Key questions:

- How will stratospheric ozone evolve (recover) in the 21st century (21C), and what will be the impact of climate change?
- What will be the impact of stratospheric ozone recovery on tropospheric climate and weather?

Examine above using stratospheric-resolving chemistry-climate models (CCMs).
Outline

1. Multi-model projections of stratospheric ozone (+inorganic chlorine, temperature, and circulation) in the 21C (CCMVal-1).

2. Quantification of relative role of different mechanisms (GEOSCCM).

3. Sensitivity to GHG scenario (GEOSCCM).

4. Impact of ozone recovery on tropospheric climate (CCMVal-1, IPCC AR4 models).
Mechanisms influencing $O_3$ in the 21C

As the concentration of halogen containing ozone depleting substances (ODSs) decrease back to pre-1980 values $O_3$ is expected to “recover”.

However, ...

\[ EESC = C_{ly} + 50B_{ry} \]
Mechanisms influencing $O_3$ in the 21C (cont.)

Stratospheric $O_3$ also influenced by changes in greenhouse gases (GHGs) which change, for example, the:

- temperature (reaction rates, PSCs),
- circulation, and
- nitrogen- and hydrogen-containing radicals.

Need to include chemical, dynamical, and radiative processes and couplings

$\Rightarrow$ Three-dimensional chemistry-climate models
**Stratospheric CCMs**

Examine stratospheric projections from 11 stratospheric-resolving chemistry-climate models (CCMs)*. [WMO 2006, Eyring et al., JGR, 2007]

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* Prescribed SSTs, no trop. chemistry
Surface Concentrations

CCMs simulations use the same surface concentrations of

- halogens (scenario Ab, WMO 2002), and
- GHGs ($\text{CO}_2$, $\text{N}_2\text{O}$, $\text{CH}_4$) (scenario A1B, IPCC 2001).
Before examining projections of stratospheric $O_3$ we consider projections of quantities that have a strong influence on $O_3$:

- Inorganic chlorine ($Cl_y$)
- Temperature
- Circulation

Changes in $H_2O$ and $NO_y$ are small.
Cly Projections

- Large spread in simulated Cly.
- Most models underestimate observed Cly (esp. in polar regions).
CCMs with larger peak Cly tend to have a later recovery to 1980 value.
Temperature Trends

All CCMs show large cooling in middle-upper stratosphere.

This cooling slows rate of gas-phase reactions that destroy $O_3$.

[Eyring et al., JGR, 2007]
Projected trends in polar lower stratosphere are very small, with no consistent sign.

[50 hPa temperatures]

[Eyring et al. 2007]
All CCMs predict increasing tropical upwelling and decreasing mean age from 1960 to 2100.
CCMs project similar long-term evolution, but large spread in magnitude.

In most models:

- Tropical column $O_3$ is around or less than 1980 values in 2040-2050.
- Mid-latitude column $O_3$ is larger than 1980 values in 2040-2050.

[Eyring et al. 2007]
**Cl\textsubscript{y} and O\textsubscript{3}**

Differences in the simulated Cl\textsubscript{y} can explain a lot of the differences in the O\textsubscript{3} simulations.
Extra-Polar $O_3$: Vertical Variations

2100 - 1960 $O_3$ (GEOSCCM)

Extra-polar $O_3$ in 2100 is

$> 1960$ values in upper stratosphere, but

$< 1960$ values in the lower stratosphere.
Temperature and Upwelling

Increase in upper stratospheric $O_3$ consistent with cooling

Decrease in lower stratosphere $O_3$ consistent with increased upwelling
Again, CCMs project similar long-term evolution, but large spread in magnitude of anomalies and date of disappearance of ozone hole.

Projection based on empirical relationship with EESC [Newman et al. 2006].

Spread primarily due to Cly differences.

[Eyring et al. 2007]
Polar Cly and $O_3$

Spread in projected Antarctic $O_3$ recovery primarily due to differences in model $Cly$. “Earlier” recovery due to bias in Cly simulations not changing B-D circulation.
CCMs show small trends in Arctic $O_3$, with large year-to-year variability.

No indication of large decreases of Arctic $O_3$ in the future in any model.

[Eyring et al. 2007]
Summary of multi-model projections

- In general, the projected column $O_3$ evolution is mainly determined by decreases in ODSs and continued cooling due to increases in GHGs.

- Extra-polar $O_3$ is projected to increase to 1980 values before ODSs return to 1980 values, because cooling in upper stratosphere.

- Antarctic $O_3$ is projected to follow decrease in ODSs.

- Differences in Cly among CCMs are key to diagnosing intermodels differences in $O_3$ recovery.

[from Eyring et al. 2007]
Eyring et al. (2007) did not quantify the contribution of different mechanisms to changes in ozone.

Such quantification is performed using GEOSCCM simulations:

(1) Comparison of simulations with time-varying and fixed ODS, and

(2) Multi-Linear Regression analysis of “standard” projections.
**Impact of Increasing GHGs on O₃ Recovery**

The impact of increasing GHGs on recovery of O₃ is examined by comparing two simulations:

1. “Reference”: time-varying GHGs and ODSs.
2. “Fixed-ODS”: time-varying GHGs but ODSs fixed at 1960 values.

(2) => changes in O₃ due to increasing GHGs,

(1) - (2) => changes in O₃ due to changing ODSs [direct + indirect].

GEOSCCM model, 1960 to 2100.

[Waugh et al. 2008]
Impact of GHGs: Upper Stratosphere

- Fixed ODSs (1960 ODSs, time-varying GHGs)
- Reference (Time-varying ODSs & GHGs)
- Change due to ODSs (difference between above simulations)
- EESC
**Impact of GHGs: Upper Stratosphere**

- $O_3$ decreases during last part of 20th century due primarily to increasing ODSs.
- $O_3$ increases during 21st century due to rough equal contribution from decreasing ODSs and increasing GHGs.
Ozone Recovery Milestones

Climate changes due to increasing GHGs can also impact the date $O_3$ recovery milestones are reached. Two established milestones of full recovery are:

1. The date when $O_3$ returns to specified historical value (e.g., 1980).

2. The date when $O_3$ is no longer significantly affected by ODSs [“full ozone recovery from ODSs”, WMO 2007].

Milestone (2) involves attribution but not (1).
Recovery of Upper Stratosphere

O₃ returns to 1960s values around 2030

Full recovery from ODSs not until 22nd century.

Change due to ODSs and GHGs.

Change due to ODSs (difference between above simulations)

EESC
Regional Variations

The recovery process differs between regions:

In some regions, $O_3$ may never return to 1980 or 1960 values even when anthropogenic ODSs are all removed from the atmosphere.

[Waugh et al. 2008]
**Multi-Linear Regression (MLR)**

Above analysis does not isolate the contribution of different mechanisms to the changes in ozone. To do this multiple linear regression is performed, i.e.,

\[
\Delta O_3(t) = \sum_j m_{X_j} \Delta X_j(t) + \epsilon(t).
\]

where \(X_j\) are the different factors that could influence ozone (e.g., \(T\), EESC) and the coefficients \(m_X\) are the sensitivity of ozone to the factor \(X\), e.g,

\[
m_T = \frac{\partial O_3}{\partial T}
\]

is the sensitivity to temperature changes.

MLR method has been applied to GEOSCCM simulations. \(X=\text{EESC, } T, \text{ NOy, HOx.}\)
MLR reconstruction reproduces ozone variations.

Long-term changes in O$_3$ are dominated by changes in EESC and T, with cooling the cause of long-term ozone increase.

Contribution due to changes in EESC

Contribution due to changes in T

[Oman et al., in prep]
MLR: Vertical Variation

**Upper Stratosphere**: $O_3$ change is due to changes in EESC and T.

1960-2000 $O_3$ decrease due to increasing EESC ~ twice as large as increase due to cooling.

2000-2100 similar $O_3$ increase due EESC and T changes.

**Mid-Stratosphere (20 hPa)**: Limited $O_3$ changes.

**Lower Stratosphere**: $O_3$ decrease correlated with changes in T.

Changes in $O_3$ and T both due to increased upwelling.
Decrease in tropical lower stratospheric is due to increased upwelling (and not changes in overhead $O_3$).
Sensitivity to GHG scenario

Above simulations all used a single GHG scenario. To examine sensitivity to GHG we compare GEOSCCM simulations using A1B and A2 scenarios (IPCC 2001).

[Oman et al.; in prep]

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Conc. of CO$_2$, CH$_4$, and N$_2$O are larger in A2 than A1B.
Sensitivity to GHG scenario: Change in $O_3$

The change in $O_3$ between 1960 and 2100 is similar in the 2 simulations, even though the changes in $T$, $NO_y$, and $HO_x$ are larger in A2 (consistent with larger $CO_2$, $CH_4$, and $N_2O$).
The change in $O_3$ is similar in the 2 simulations as the larger increase in $O_3$ in A2 due to the increased **cooling** is balanced by larger $O_3$ decreases due to increased NOy and HOx.

=> Increase in upper stratospheric $O_3$ in 21C will depend on relative increases of $CO_2$, $CH_4$, and $N_2O$ [e.g. Chipperfield & Feng 2003].
IMPACT ON TROPOSPHERE

What will be the impact of stratospheric ozone recovery on tropospheric climate and weather?

Examine changes in

- Tropopause [Son et al., 2008a]
- Jet Location [Son et al. 2008b, Perlwitz et al. 2008]
- Hadley Cell [Son et al., in prep.]

in CCMs (and IPCC AR4 models).

See Son et al., POSTER P91
**Tropopause**

CCMs indicate tropopause pressure will continue to decrease, but future trends weaker than in the past.

Weakening due to ozone recovery.

[Temperature trends 2000-2099](#)

[Son et al., 2008a]
Future tropopause trend in CCMs are weaker than in IPCC models.

Consistent with differences in stratospheric temperature trends.

[Tropopause pressure graph]

[Temperature trends 2000-2099 graphs]

[Son et al., 2008a]
SH Tropospheric Jet

Analysis of GEOSCCM simulations Perlwitz et al [2008] shows that
Recovery of ozone hole in 21C
-> warming of polar UT/LS
-> weakening of mid-latitude (50-70S) zonal winds (in DJF)
-> decrease in SAM.

[Reverse of 1970 to 2000 changes]
**Tropospheric Jet: Comparison with AR4**

2000-2050 trend in 70-90S Temperature

- Similar T change for multi-CCM mean.
- Much weaker change in IPCC AR4 simulations.
- Importance of ozone can be seen by comparing AR4 models with and without ozone recovery.

[Son et al., 2008]
Deceleration poleward side of jet (decrease in SAM) also found in for multi-CCM mean.

Opposite response in mean of IPCC AR4 simulations.

Importance of ozone can be seen by comparing AR4 models with and without ozone recovery.

Weaker response in AR4 models with O$_3$ recovery.

[Son et al., 2008]
Hadley Cell

Changes in polar ozone may also affect the width of the Hadley Cell (and hence location of subtropical dry regions).

Compare multi-model mean trends in IPCC models, with and without $O_3$ trends:

- **Polar Temperatures**
  - Increase in polar $O_3$ -> polar warming
  - $O_3$ recovery
  - No $O_3$ change
  - $O_3$ depletion

- **Jet Location**
  - Equatorward shift of subtropical jet and contraction of Hadley Cell.

- **Hadley Cell Width**

[Son POSTER P91]
What causes the differences between CCMs and AR4 models with recovery?

Possible causes of differences include:

1. Poorly resolved stratosphere in AR4 models,
2. Lack of dynamical ocean in CCMs,
3. Lack of interactive chemistry in AR4 models.

Test (3) with GCM run using monthly-mean zonal-mean $O_3$ from CCM, and everything else the same in GCM and CCM. [See also Sassi et al. 2005, Crook et al. 2007]
Testing impact of interactive chemistry.

2000-2050 trend in Zonal Wind

1. CCM “REF2” run.

2. GCM run with monthly-mean zonal-mean $O_3$ from CCM “REF2” run.

Response in GCM is weaker than CCM, with difference similar to CCM vrs AR4 with recovery.

[Luke Oman]
Testing impact of interactive chemistry.

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[Luke Oman]
SUMMARY

- Climate change due to increased GHGs will impact $O_3$ recovery, primarily through cooling and changes in circulations (details depend on GHG scenario).

- CCMs project similar long-term $O_3$ evolution, but large spread in magnitude of anomalies and “recovery dates”.

- Differences in Cly among CCMs are key in diagnosing intermodel differences in $O_3$ recovery.

- The timing of established milestones varies between milestones and regions.

- Ozone recovery is likely to have a profound affect on SH tropospheric climate (e.g., jet location, Hadley Cell extent).
THE END
Hadley Cell II

GEOSCCM simulations also indicate that an decrease (increase) in polar O₃ leads to an poleward (equatorward) shift of subtropical jet and expansion (contraction) of Hadley Cell.

However, SSTs also important and ensemble runs needed.

[Son et al., in prep]
Impact of GHGs: Polar Stratosphere

(a) SP lower stratosphere, Winter

(b) SP lower stratosphere, Spring

(c) NP lower stratosphere, Winter

(d) NP lower stratosphere, Spring