The impact of continuing CFC-11 emissions on stratospheric ozone

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CFC-11 (trichlorofluoromethane, CFCl$_3$) is a powerful ozone depleting substance and greenhouse gas.

CFC-11 production and consumption were controlled under the Montreal Protocol. Emissions began declining in the late 1980s. Tropospheric concentrations of CFC-11 peaked ~1994 and have been declining up to the present.

Montzka et al. [2018] showed that CFC-11 emissions increased over 2013-2016. The source of emissions remains unclear.

It is important to understand and quantify the stratospheric ozone response to potential future CFC-11 emissions increases.
Objectives

- Examine the model stratospheric EESC and ozone responses for 2017-2100 to a range of future CFC-11 emission scenarios:
  - base: -6.4%/yr decrease (WMO-2018)
  - 0 emissions (lower limit)
  - 72.5 Gg/yr sustained (2013-2016 avg)

  Additional sensitivity tests (to test linearity of response):
  - 30 Gg/yr sustained (medium scenario)
  - 64 Gg/yr sustained (2002-2012 avg)
  - 100 Gg/yr sustained (very high scenario)

- Examine relationship of the ozone response to the amount of emissions

- Also investigate the ozone response under the range of RCP greenhouse gas scenarios
GSFC 2D Chemistry Climate Model

- full stratospheric chemistry, limited tropospheric chemistry
- compares well with long lived tracer observations in reproducing transport-sensitive features in the meridional plane
- uses GEOSCCM 3-D model output to account for long term GHG-induced changes in tropospheric temperature and water vapor
  → important for changes in strat Brewer-Dobson circulation, CFC-11 lifetime
- agrees well with GEOSCCM simulations over 1950-2100:
  - temperature, stratospheric age of air, emission-based CFC-11 distribution
- following slides show comparisons with GEOSCCM total ozone
  (GEOSCCM simulations will be discussed in Liang presentation)
GSFC2D comparison with GEOSCCM

- REFC2 total ozone, 1960-2100 includes:
  - baseline (A1) ODS scenario
  - past stratospheric aerosol changes
  - past and future solar cycle variations

- GSFC2D compares mostly well with observations and GEOSCCM

- GSFC2D 3-5 DU lower than GEOSCCM during 21st century
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  - due to tropospheric ozone differences
  - incomplete tropospheric chemistry in GSFC2D
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• GSFC2D 3-5 DU lower than GEOSCCM during 21st century
  - due to tropospheric ozone differences
  - incomplete tropospheric chemistry in GSFC2D

• stratospheric column ozone very similar, including rate of past ozone decline and future recovery
GSFC2D also compares well with GEOSCCM for **Antarctic spring** total and stratospheric column ozone. This gives confidence in the GSFC2D response to CFC-11 perturbations shown in this study.
Response to CFC-11 emissions

- baseline emission scenario (WMO-2018) derived from past global mixing ratio obs and 1-box model (Velders and Daniel, 2014)
  - future emissions: assume -6.4%/yr decay
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  10-20 ppt larger surface concentration
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  - future emissions: assume -6.4%/yr decay
- zero emissions very close to baseline after ~2050
  10-20 ppt larger surface concentration
- very small differences in EESC (50 km) and global ozone (+0.1% in 2100)
Response to CFC-11 emissions

- sustained 72.5 Gg/yr (2013-2016 avg)
  significantly increases surface concentration,
  adds 125 ppt above baseline by 2100
Response to CFC-11 emissions

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- adds 0.35 ppb (14%) to EESC by 2100
Response to CFC-11 emissions

- sustained 72.5 Gg/yr (2013-2016 avg) significantly increases surface concentration, adds 125 ppt above baseline by 2100
- adds 0.35 ppb (14%) to EESC by 2100
- global total ozone is reduced by 2.7 DU (-0.9%) in 2100
**Response to CFC-11 emissions**

- Latitude-height distribution shows expected stratospheric ozone response to chlorine perturbations

- Largest percentage ozone depletion:
  - Antarctic lower stratosphere (-10%)
  - Upper stratosphere globally (-3-4%)
  - Arctic lower stratosphere (-0.5-1%)

- DU/km change shows the altitudinal contribution to the total column

- Largest DU/km change occurs in the polar lower stratosphere, especially in the SH
• additional CFC-11 emissions impact the dates of return to 1980 levels of EESC and total ozone

• EESC return to 1980 level:
  - zero emissions : 2080
  - baseline : 2083
  - 72.5 Gg/yr : 2108
Return to 1980 levels

- additional CFC-11 emissions impact the dates of return to 1980 levels of EESC and total ozone

- EESC return to 1980 level:
  - zero emissions: 2080
  - baseline: 2083
  - 72.5 Gg/yr: 2108

- Global total ozone return to 1980 level:
  - zero emissions: 2051 (-2 yrs)
  - baseline: 2053
  - 72.5 Gg/yr: 2060 (+7 yrs)
Return to 1980 levels

- **Antarctic spring:**

  72.5 Gg/yr sustained emissions yields -24 DU (-9%) additional total ozone loss in 2100

- Total ozone return to 1980 level:
  - zero emissions: 2069 (-3 yrs)
  - baseline: 2072
  - 72.5 Gg/yr: 2096 (+24 yrs)

(see Liang presentation this afternoon)
Linearity of Ozone Response

- cumulative CFC-11 emissions vs. the time integrated total ozone response for 2017 – 2100 for each emission scenario

- shown in 2100 (RCP6.0), relative to zero emissions (includes 30 Gg/yr, 64 Gg/yr and 100 Gg/yr sustained emissions)
**Linearity of Ozone Response**

- cumulative CFC-11 emissions vs. the time integrated total ozone response for 2017 – 2100 for each emission scenario

- shown in 2100 (RCP6.0), relative to zero emissions (includes 30 Gg/yr, 64 Gg/yr and 100 Gg/yr sustained emissions)

- strong linear dependence in both global and Antarctic spring total ozone

→ **Sensitivity** (per 1000 Gg emission):

- Global annual = -0.29 DU (-0.1%)
- Antarctic spring = -2.4 DU (-0.9%)
Sensitivity (per 100 ppt emission of chlorine):

Global annual = -0.44 DU (-0.15%)
Antarctic spring = -3.6 DU (-1.4%)

(baseline EESC = 2300 ppt in 2100)
Impact of GHGs on the Ozone Response

• increasing greenhouse gases modify the chlorine impact on ozone:

1) CH₄, and NOx from N₂O oxidation convert active chlorine to reservoir forms via:

\[
\text{Cl} + \text{CH}_4 \rightarrow \text{HCl} + \text{CH}_3 \\
\text{ClO} + \text{NO}_2 + \text{M} \rightarrow \text{ClONO}_2 + \text{M}
\]

→ these reduce Cl-induced ozone loss

2) increasing CO₂:
- accelerates the Brewer-Dobson circulation, reducing the CFC-11 lifetime
- cools the stratosphere, reducing ozone loss rates (weak effect for Cl-O₃ loss)

→ these reduce Cl-induced ozone loss

3) stratospheric cooling and increased stratospheric H₂O from CH₄ and GHG-induced tropospheric warming enhance PSCs → enhance polar ozone loss
Impact of GHGs on the Ozone Response

• net impact of increasing GHGs is to **mitigate** the ozone response to chlorine in the late 21st century

• net GHG impact on global ozone is modest;
  GHG impact on Antarctic spring ozone is weak

**Sensitivity** (per 1000 Gg emission) **in 2100**:

<table>
<thead>
<tr>
<th>RCP</th>
<th>Global/annual</th>
<th>Antarctic spring</th>
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</thead>
<tbody>
<tr>
<td>2.6</td>
<td>-0.30 DU (-0.1%)</td>
<td>-2.5 DU (-0.9%)</td>
</tr>
<tr>
<td>4.5</td>
<td>-0.29 DU (-0.1%)</td>
<td>-2.4 DU (-0.9%)</td>
</tr>
<tr>
<td>6.0</td>
<td>-0.29 DU (-0.1%)</td>
<td>-2.4 DU (-0.9%)</td>
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<tr>
<td>8.5</td>
<td>-0.25 DU (-0.08%)</td>
<td>-2.4 DU (-0.9%)</td>
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Conclusions

- Examined the model stratospheric EESC and ozone responses to a range of future CFC-11 emission scenarios

- For 72.5 Gg/yr (2013-2016 avg) sustained emissions (2017-2100), in 2100:
  → surface CFC-11 concentrations increase by 125 ppt above baseline
  → EESC increases by 0.35 ppb (14%)
  → global total ozone decreases by 2.7 DU (-0.9%)
  → global ozone recovery to 1980 levels delayed by 7 yrs

- Strong linear dependence between cumulative CFC-11 emissions and time-integrated ozone response

Sensitivity per 1000 Gg emissions:

→ global ozone : -0.29 DU (-0.1%)
→ Antarctic spring : -2.4 DU (-0.9%)

→ global ozone response sensitivity to GHG scenario is modest: range of -0.30 DU → -0.25 DU (RCP2.5 → RCP8.5)
Back-up Slides
CFC-11 Lifetime

- CFC-11 lifetime decreases over 2000-2100 due to:
  - BDC increase
  - overhead ozone change which impacts CFC-11 photolysis and O($^1D$) loss

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<thead>
<tr>
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<th>GSFC 2D$^1$</th>
<th>GEOSCCM$^2$</th>
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<tbody>
<tr>
<td>2000 lifetime</td>
<td>55 yrs</td>
<td>58 yrs</td>
</tr>
<tr>
<td>2100 lifetime</td>
<td>50 yrs</td>
<td>54 yrs</td>
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$^1$ this study
$^2$ from SPARC (2013)