The impact of continuing CFC-11 emissions on stratospheric ozone

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Background

- 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

Models

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

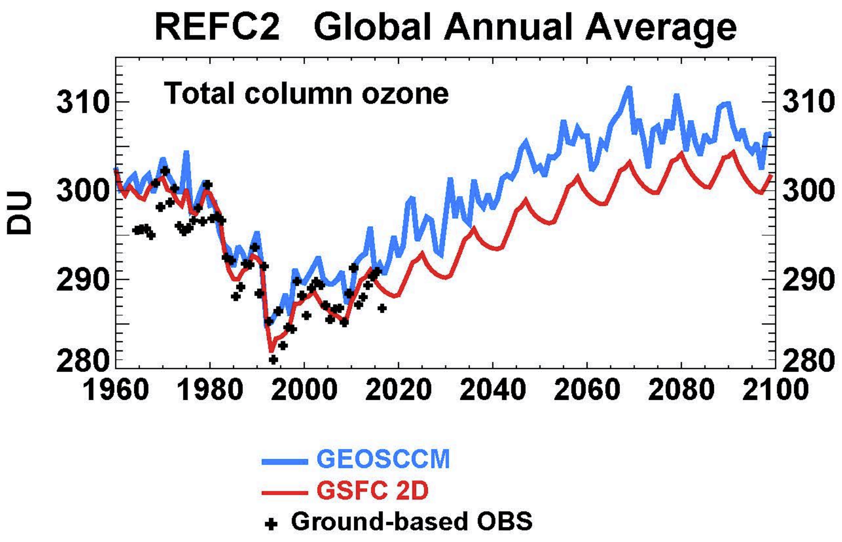
• following slides show comparisons with GEOSCCM total ozone (GEOSCCM simulations will be discussed in Liang presentation)

GSFC2D comparison with GEOSCCM

- **REFC2 total ozone, 1960-2100 incudes:**
  - 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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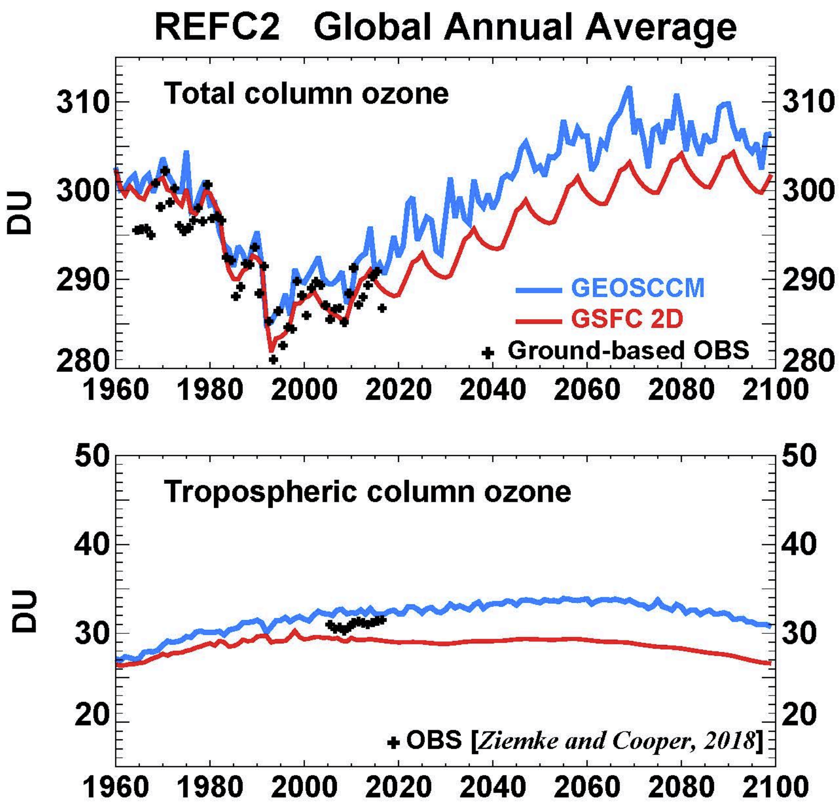
  - due to tropospheric ozone differences
  - incomplete tropospheric chemistry in GSFC2D



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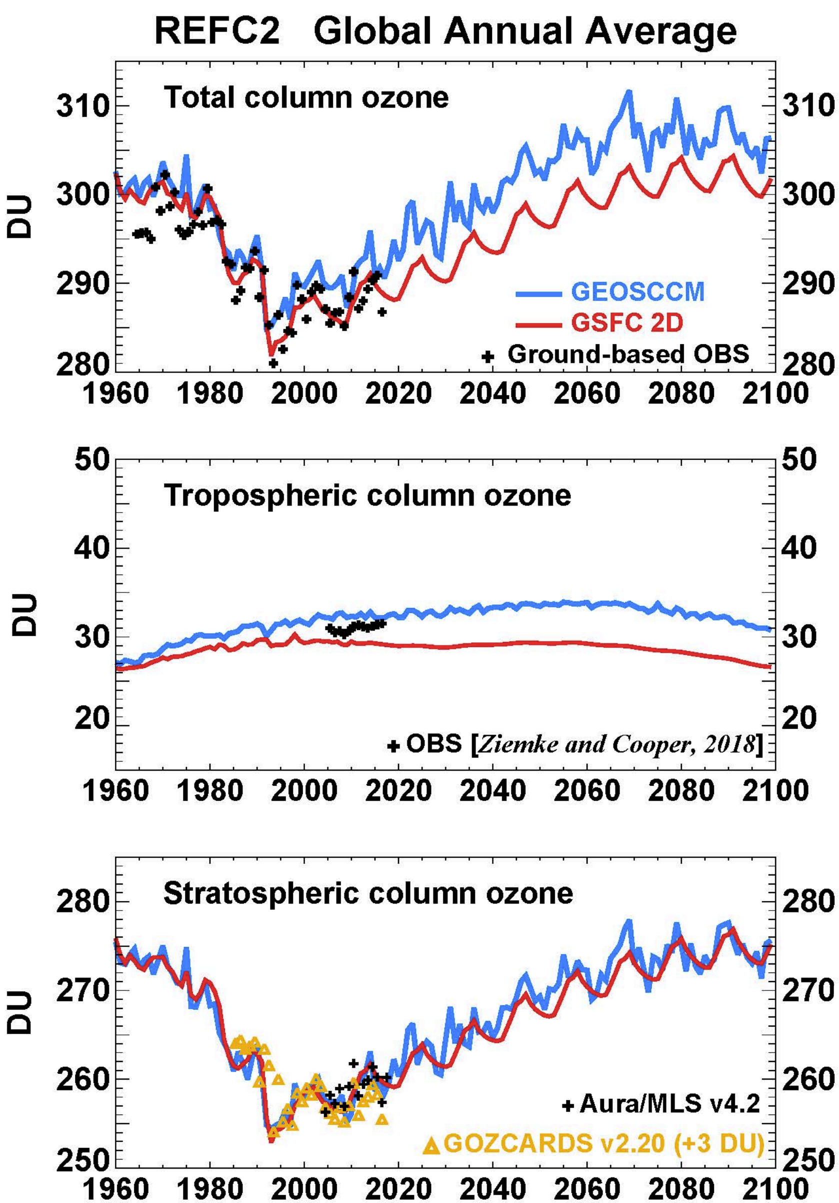
  - incomplete tropospheric chemistry in GSFC2D

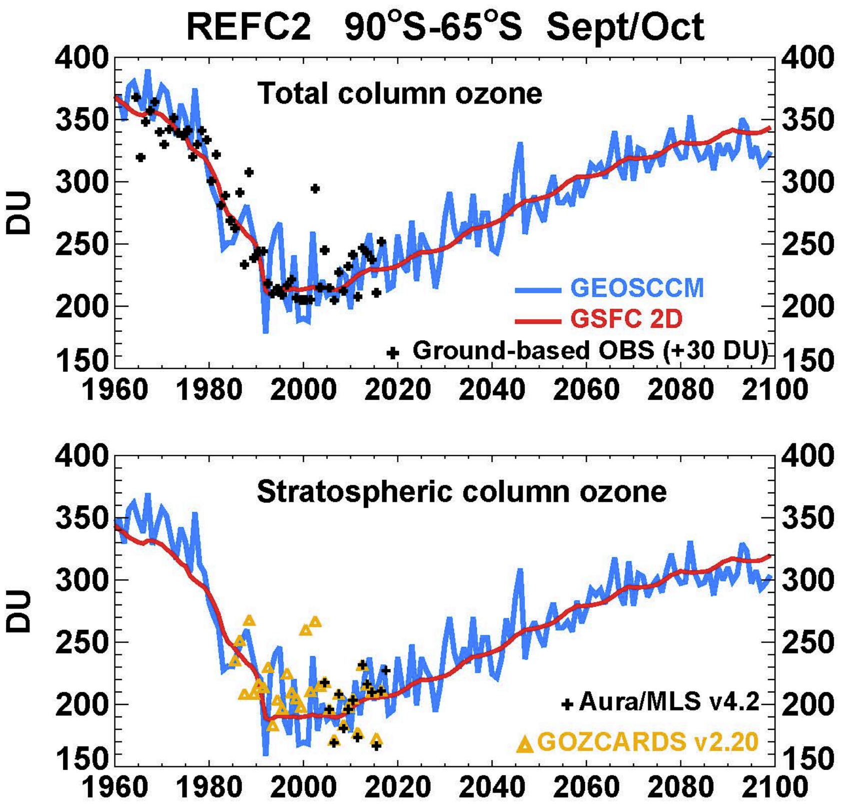
- stratospheric column ozone very similar, including rate of past ozone decline and future recovery



GSFC2D comparison with GEOSCCM

- GSFC2D also compares well with GEOSCCM for **Antarctic spring** total and stratospheric column ozone

- gives confidence in the GSFC2D response to CFC-11 perturbations shown in this study

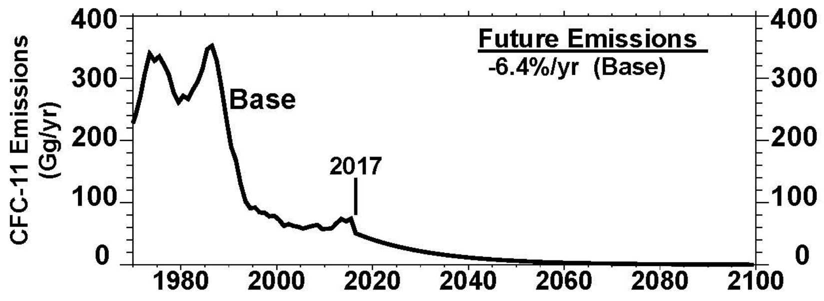


Response to CFC-11 emissions

- 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

Global/Annual average



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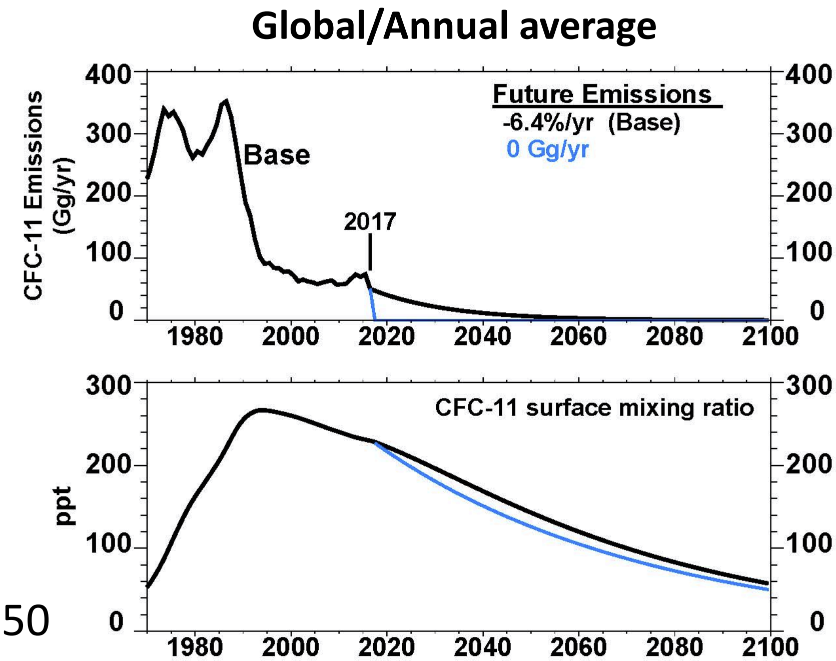
- zero emissions very close to baseline after ~2050 10-20 ppt larger surface concentration



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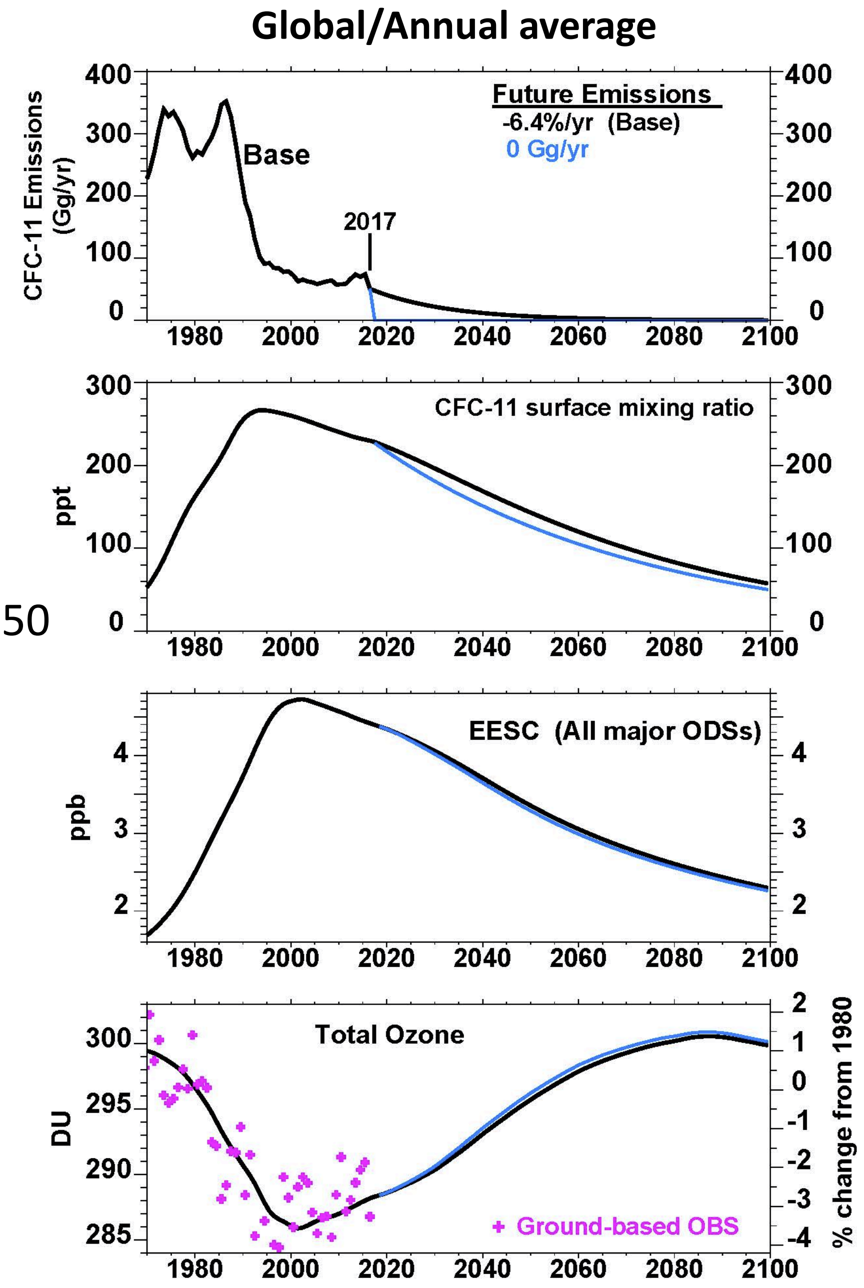
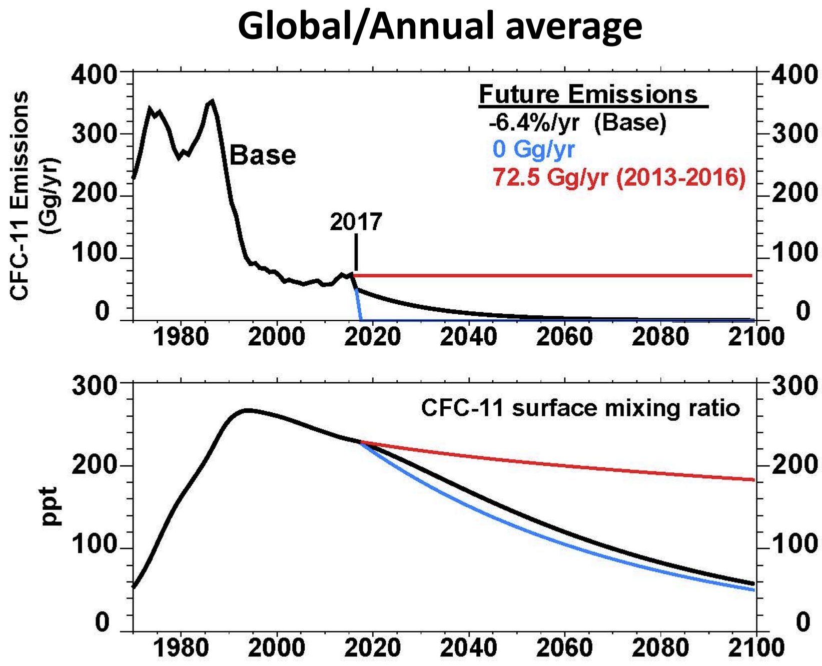
- very small differences in EESC (50 km) and global ozone (+0.1% in 2100)



Response to CFC-11 emissions

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



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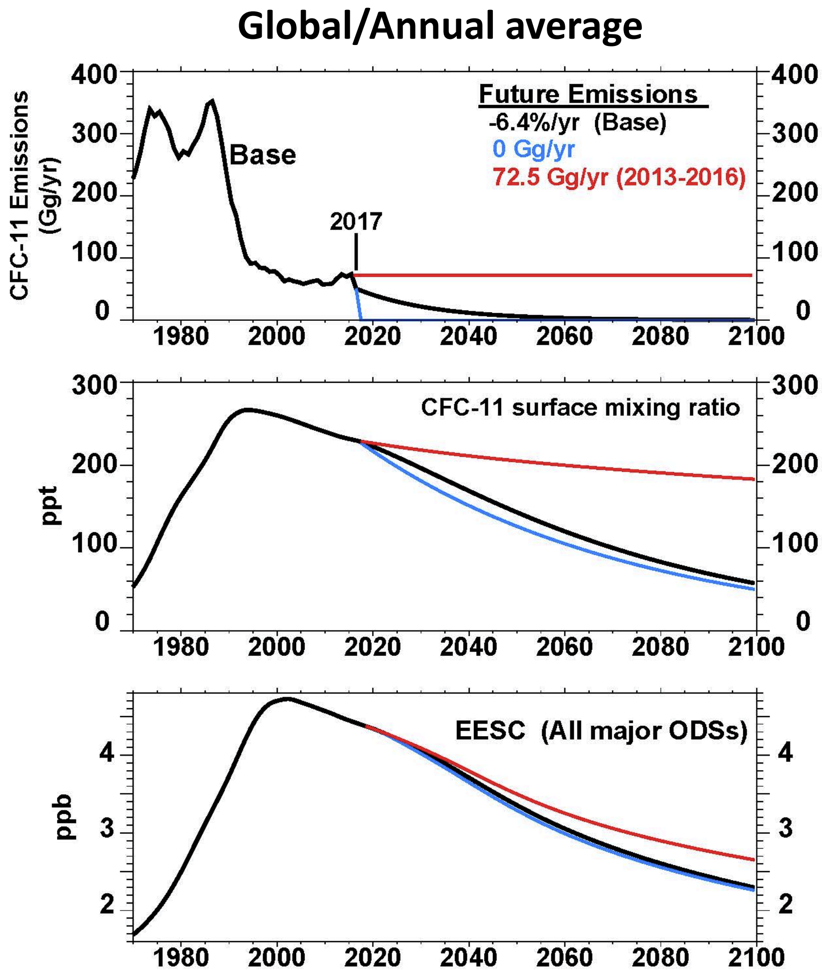
- adds 0.35 ppb (14%) to EESC by 2100



Response to CFC-11 emissions

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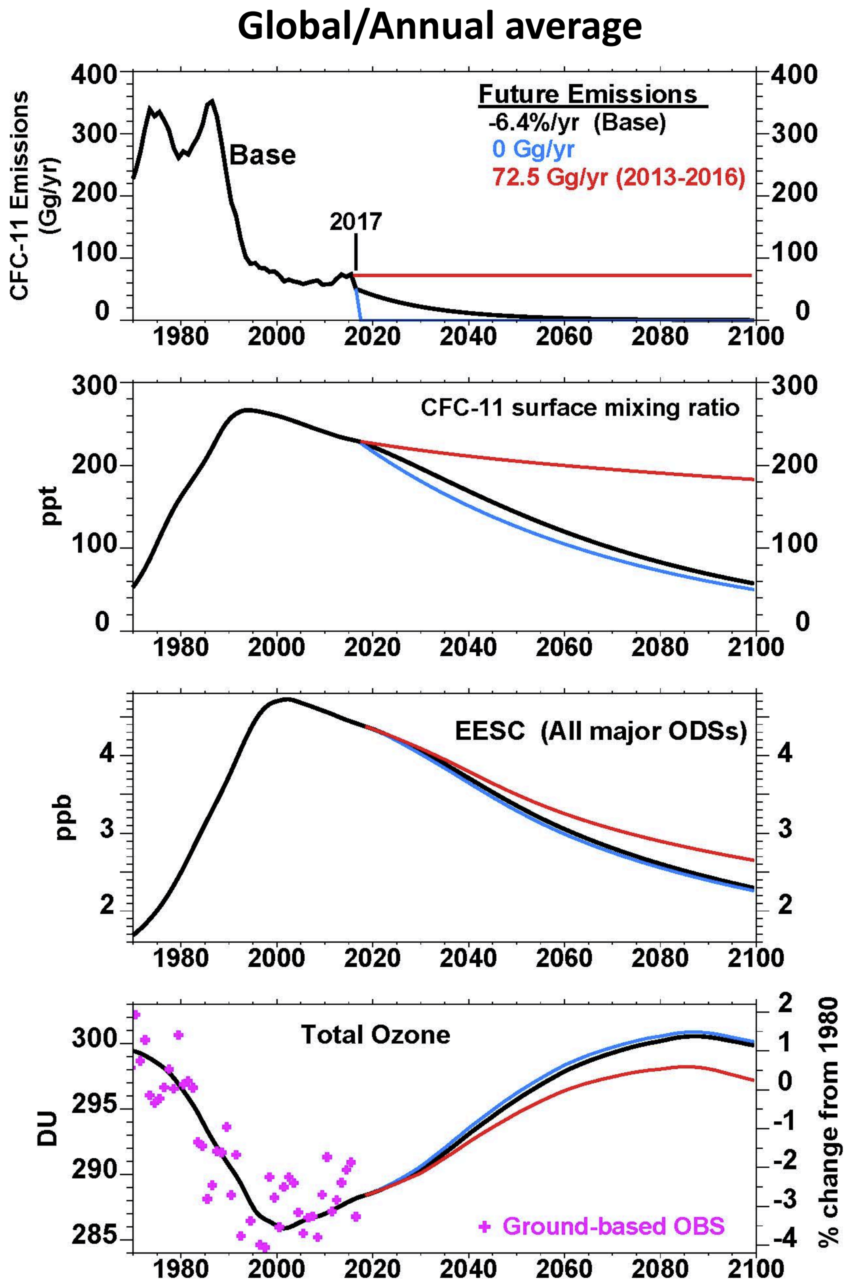
- adds 0.35 ppb (14%) to EESC by 2100

- global total ozone is reduced by 2.7 DU (-0.9%) in 2100



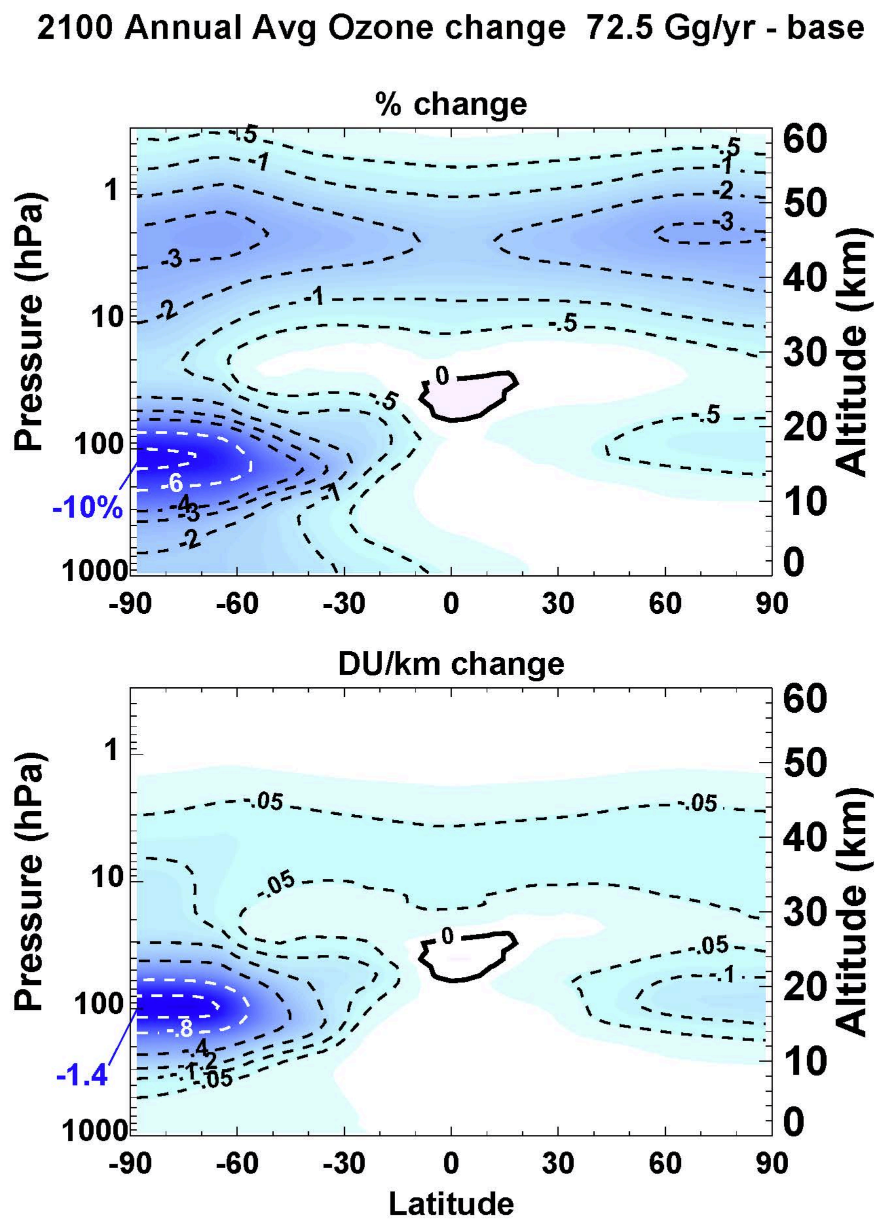
Response to CFC-11 emissions

• 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

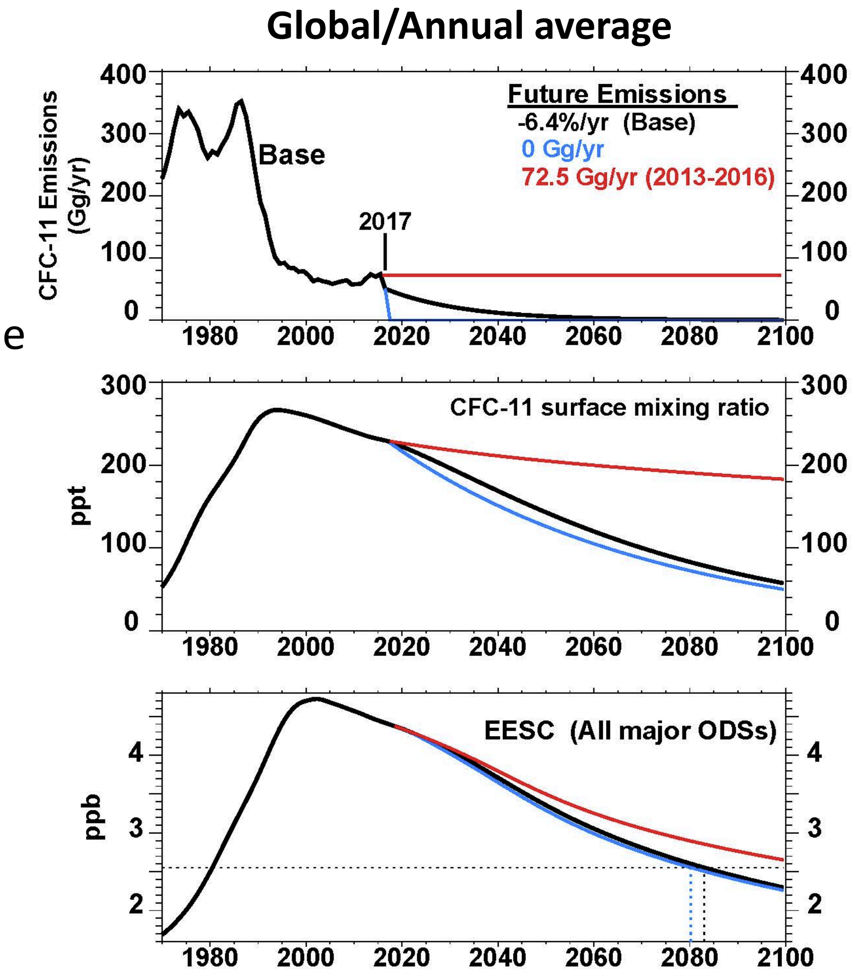
• largest DU/km change occurs in the polar lower stratosphere, especially in the SH



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**



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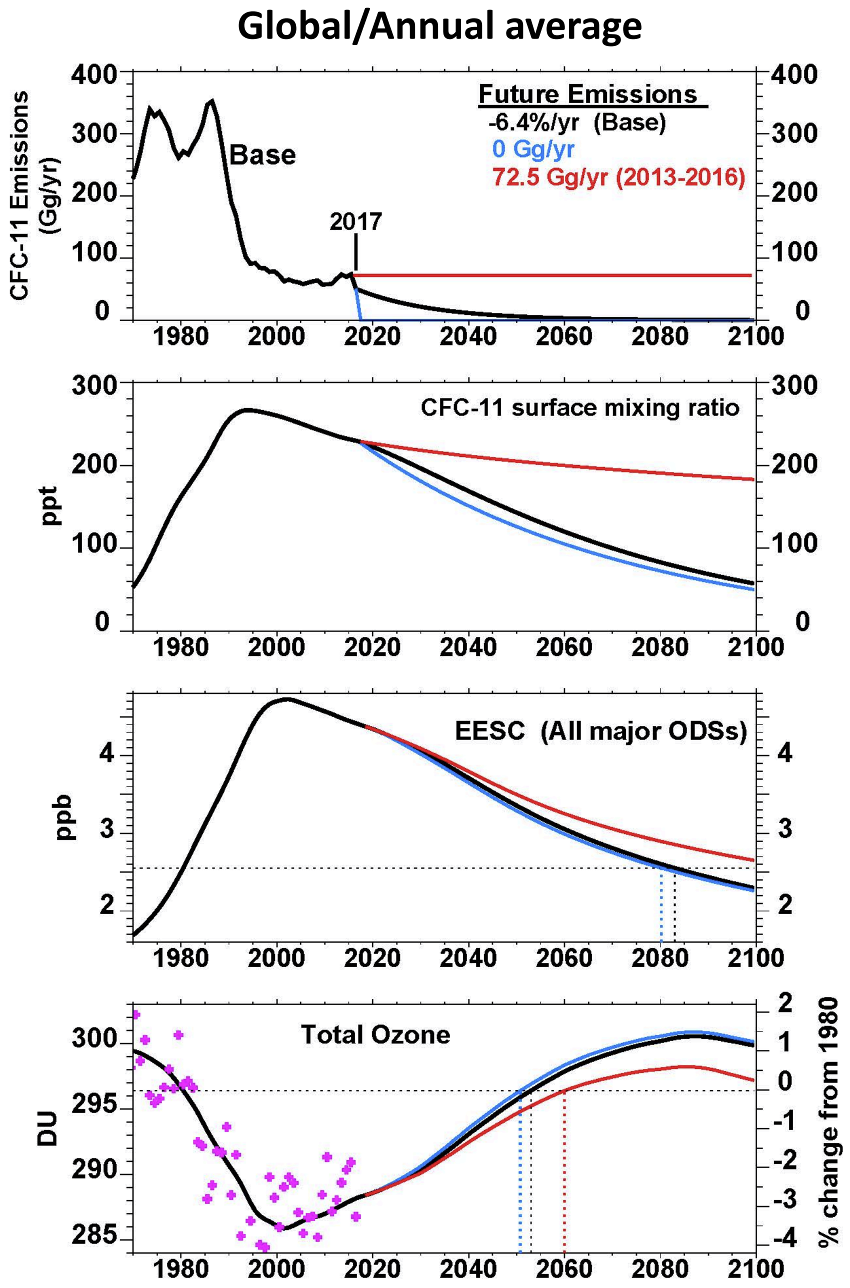
- EESC return to 1980 level:
  - zero emissions : 2080
  - baseline : 2083
  - 72.5 Gg/yr : 2108

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



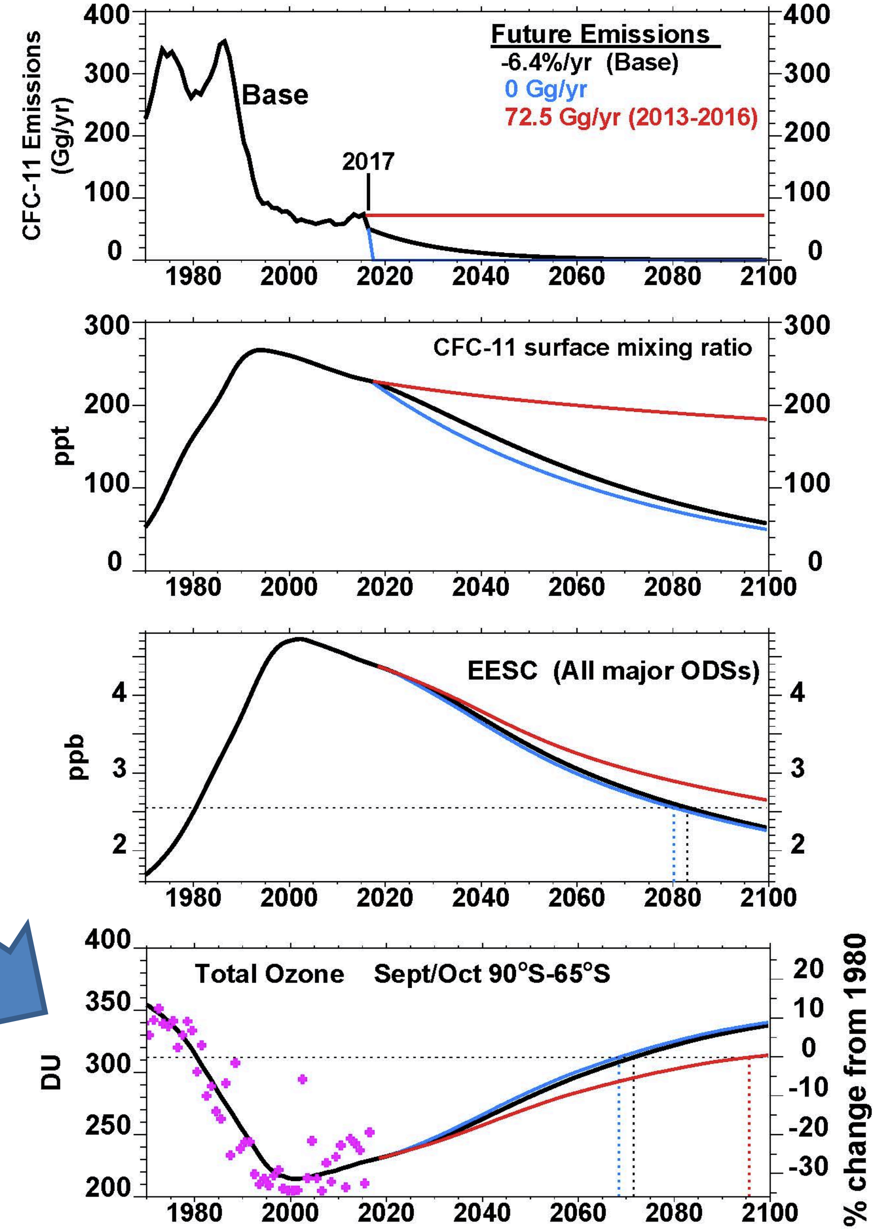
Return to 1980 levels

- **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)**

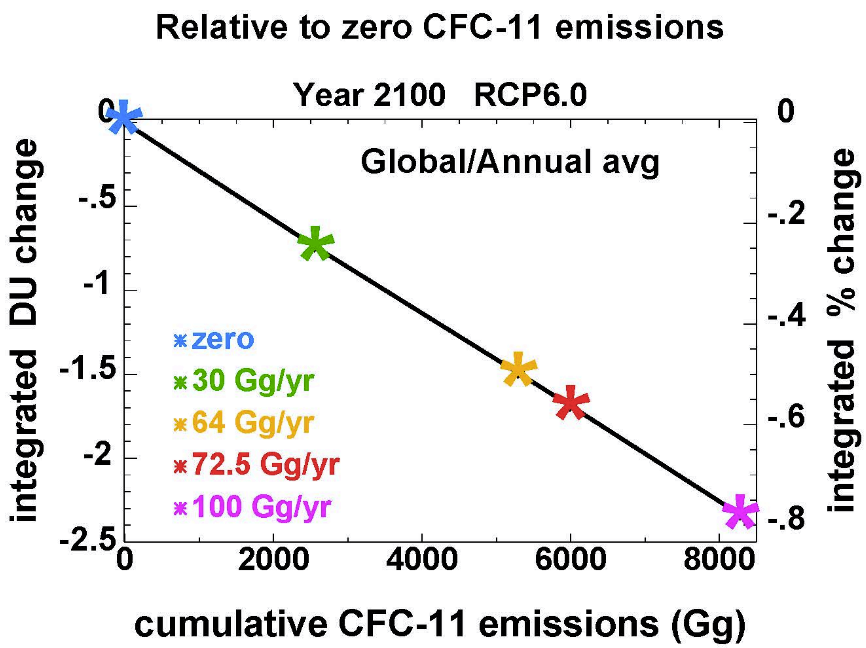
(see Liang presentation this afternoon)



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)



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

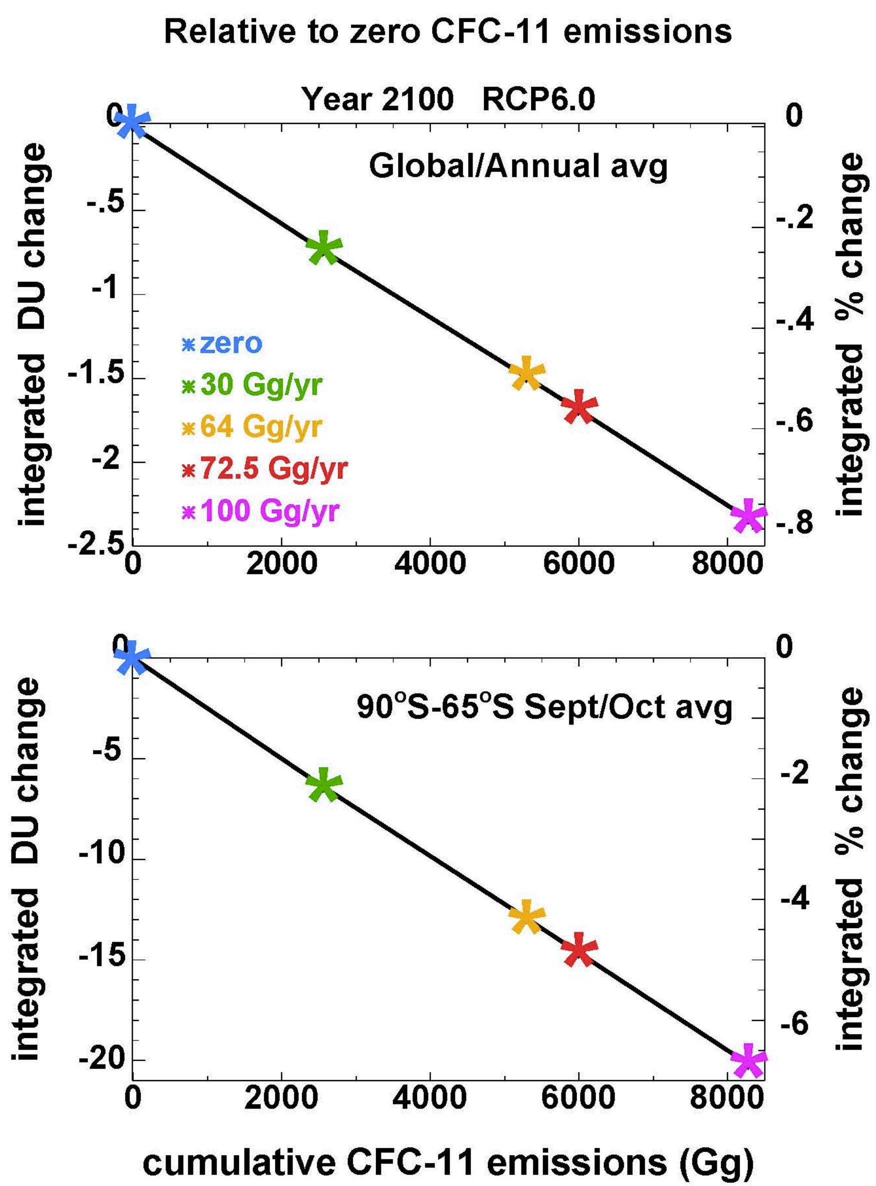
- shown in 2100 (RCP6.0), relative to zero emissions (includes 30 Gg/yr, 64 Gg/yr and 100 Gg/yr sustained emissions)

- 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%)



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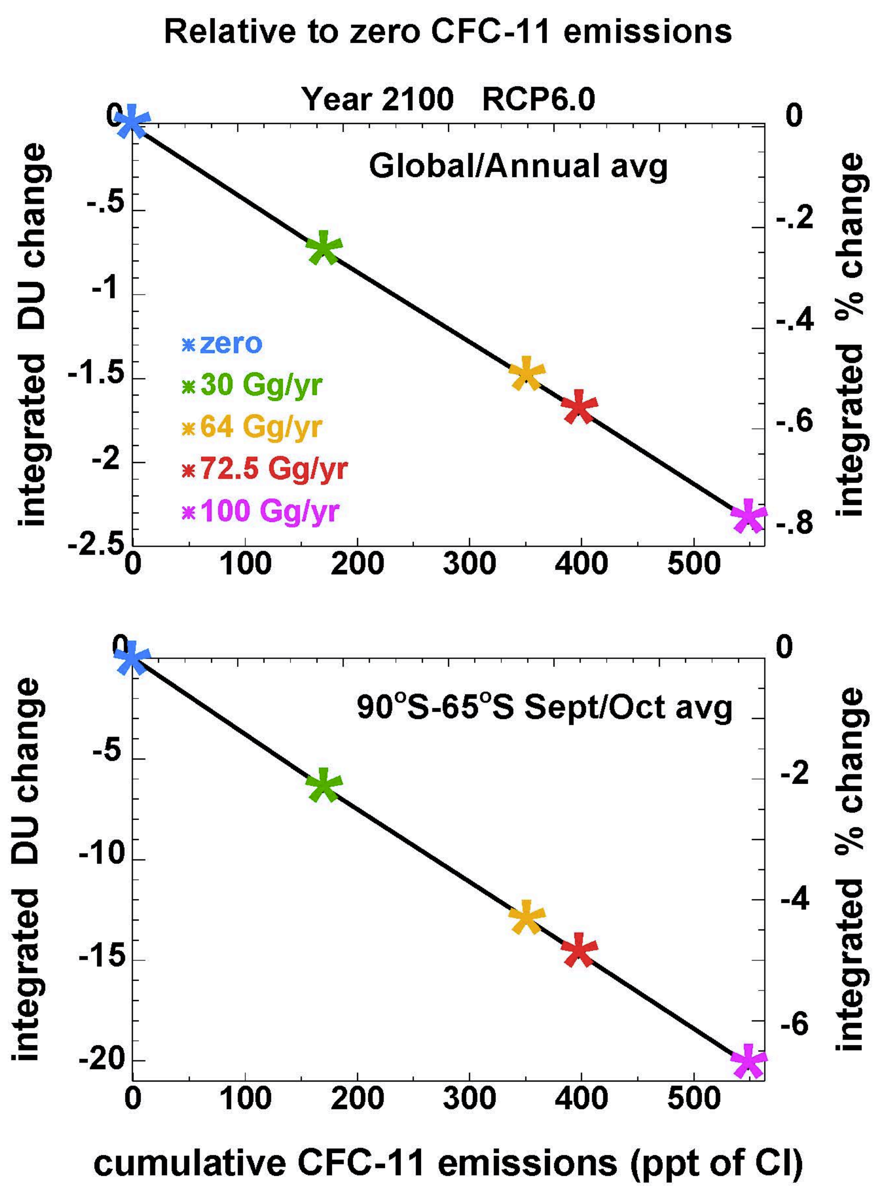

Sensitivity (per 100 ppt emission of chlorine):

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) CH_4, and NOx from N_2O oxidation convert active chlorine to reservoir forms via :

$$Cl + CH_4 \rightarrow HCl + CH_3$$
$$ClO + NO_2 + M \rightarrow ClONO_2 + M$$

→ these **reduce** Cl-induced ozone loss

2) increasing CO_2 :
   - accelerates the Brewer-Dobson circulation, reducing the CFC-11 lifetime
   - cools the stratosphere, reducing ozone loss rates (weak effect for Cl-O_3 loss)

   → these **reduce** Cl-induced ozone loss

3) stratospheric cooling and increased stratospheric H_2O from CH_4 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 :**

	Global/annual	Antarctic spring
RCP2.6	**-0.30 DU** (-0.1%)	**-2.5 DU** (-0.9%)
RCP4.5	**-0.29 DU** (-0.1%)	**-2.4 DU** (-0.9%)
RCP6.0	**-0.29 DU** (-0.1%)	**-2.4 DU** (-0.9%)
RCP8.5	**-0.25 DU** (-0.08%)	**-2.4 DU** (-0.9%)

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

CFC-11 lifetime (yrs) :

	2000	2100
GSFC 2D[1]	**55 yrs**	**50 yrs**
GEOSCCM[2]	**58 yrs**	**54 yrs**

1 this study
2 from SPARC (2013)