**1. Overview and Objectives**

- Trichlorofluoromethane (CFC-11) is a man-made, long-lived ozone depleting substance (ODS) and greenhouse gas (GHG).
- CFC-11 production and consumption have been controlled under the Montreal Protocol; atmospheric concentrations peaked in ~1994 and have declined up to the present.
- However, recent studies show that CFC-11 emissions have increased since 2012 (Montzka et al., 2018; Rigby et al., 2019).
- Here we use the NASA Goddard Earth Observing System 3-D chemistry-climate model (GEOSCCM) to investigate the stratospheric ozone, temperature, and circulation responses to future CFC-11 emissions to year 2100.

**2. GEOSCCM and simulations**

- Uses the Global Modeling Initiative (GMI) detailed troposphere-stratosphere chemical mechanism.
- Performed well in process-oriented model intercomparisons (SPARC, CCMA, CCMVal-2, CCM).
- Simulations:
  1. **Baseline scenario**:
     - WMO (2014) A1 for ozone depleting substances; future CFC-11 emissions decay at 6.4%/yr from present day (Fig. 1, blue).
     - IPCC RCP6.0 (medium) scenario for CO₂, CH₄, and N₂O.
  2. **High CFC-11 scenario**:
     - Constant 72.5 Gg/yr CFC-11 emissions to year 2100.

**3. EESC and Ozone Responses**

- High CFC-11 scenario vs. baseline:
  - The surface CFC-11 decline slows significantly, 125 ppt increase by 2100 (Fig. 1, middle).
  - EESC increases 15% (0.35 ppt) by 2100 (Fig. 1, bottom).
  - Global total ozone decreases 2.8 DU (0.9%) by 2040 (Fig. 1, bottom).
  - Antarctic spring total ozone decreases 19 DU (5.6%) in the late 2100s; will not return to 1980 levels before 2100 (Fig. 2, bottom).
  - Significant ozone loss in the Antarctic lower stratosphere (~7%), and global upper stratosphere (~2 ~ 4%).
  - Ozone hole deepens by 12% in October; additional ozone depletion of 2-3% throughout the year poleward of 65°S.
  - Arctic changes in the lower stratosphere and total column are mostly not statistically significant.

**4. Temperature and Zonal Wind Responses**

- **High CFC-11**:
  - Deeper ozone hole reduces spring solar UV heating → colder lower stratosphere (Fig. 4, middle; Fig. 5, top).
  - Via thermal wind balance, stronger stratospheric circulation jet during October → mid-December (Fig. 5, bottom; Fig. 6).
  - The change in the jet shifts planetary wave activity and the variability in lower stratospheric polar temperatures to be later in spring (Fig. 4, bottom, standard deviation).
  - A shift in polar temperature range: maximum temps are colder in August; minimum temps are colder in February (Fig. 6).
  - The change in the jet also increases the day polar stratosphere, causing enhanced descent and warming above the ozone hole (Fig. 5, top) (see also Kiehl et al., 1988; Stolarski et al., 2006).

**5. Age of Air Response**

- CFC-11 increases lead to small changes in stratospheric age of air; at most ~0.3 years younger in the Southern Hemisphere lower stratosphere, but statistically significant.

**6. Conclusions**

- High future CFC-11 emissions vs. baseline:
  - Decline in CFC-11 is significantly slowed; surface concentrations increase from 60 → 185 ppt by 2100.
  - Stratospheric EESC increases by 15% by 2100.
  - Global and Antarctic spring total ozone decrease by 0.9% and 5.6%, respectively, by the late 2100s.
  - The deeper ozone hole reduces solar UV heating in spring, causing a colder lower polar stratosphere, a stronger stratospheric jet, and modification of planetary wave propagation.
  - Changes in stratospheric age of air are small (~0.1 years); only small regions are statistically significant.

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**References**

- Kiehl, J.T., et al. (1988). Response of a climate model to increasing 
- Stolarski, R.S., et al. (2006). An ozone response to global climate model experiments with 
  increasing concentrations of chlorofluorocarbons. Journal of Geophysical Research, 
- Rigby, M., et al. (2019). Increase in CFC-11 emissions from eastern China based on 