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The Impact of Continuing CFC-11 Emissions on the Stratosphere

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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 CCMVal, CCMVal-2, CCMI).
- 2° x 2.5° horizontal resolution, 72 vertical layers from the surface to 0.01 hPa (~ 80 km).

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 CO_2, CH_4, and N_2O.

2) High CFC-11 scenario :
- constant 72.5 Gg/yr CFC-11 emissions (2013-2016 avg) for 2017-2100 (Fig. 1, red); all other gases = baseline.

3. EESC and Ozone Responses

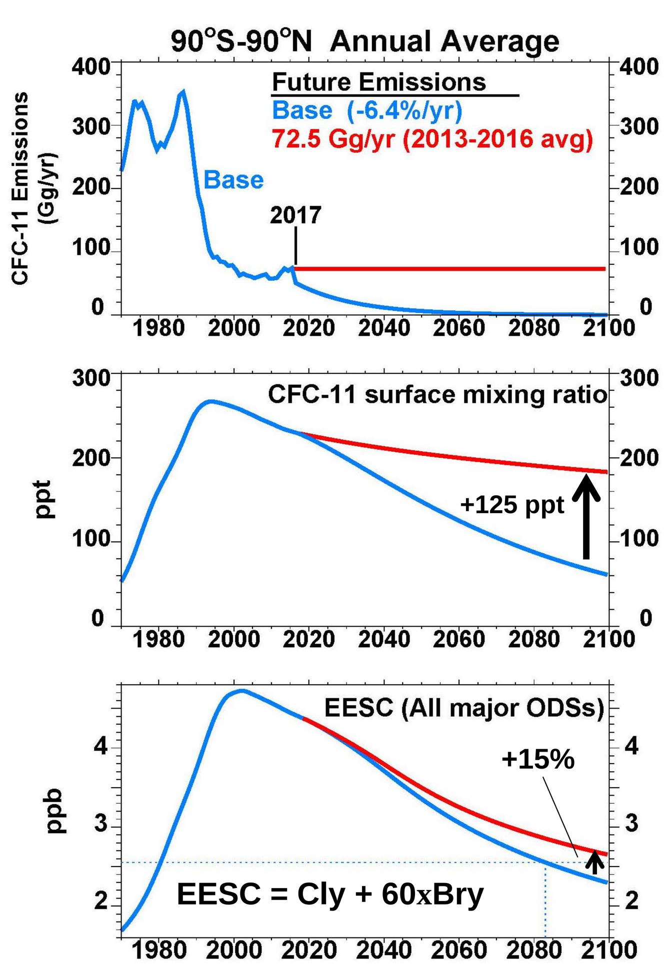

Figure 1. 90°S-90°N annual average CFC-11 emissions (Gg/yr), surface mixing ratio (ppt); and equivalent effective stratospheric chlorine (EESC, ppb) at 50 km (0.8 hPa).

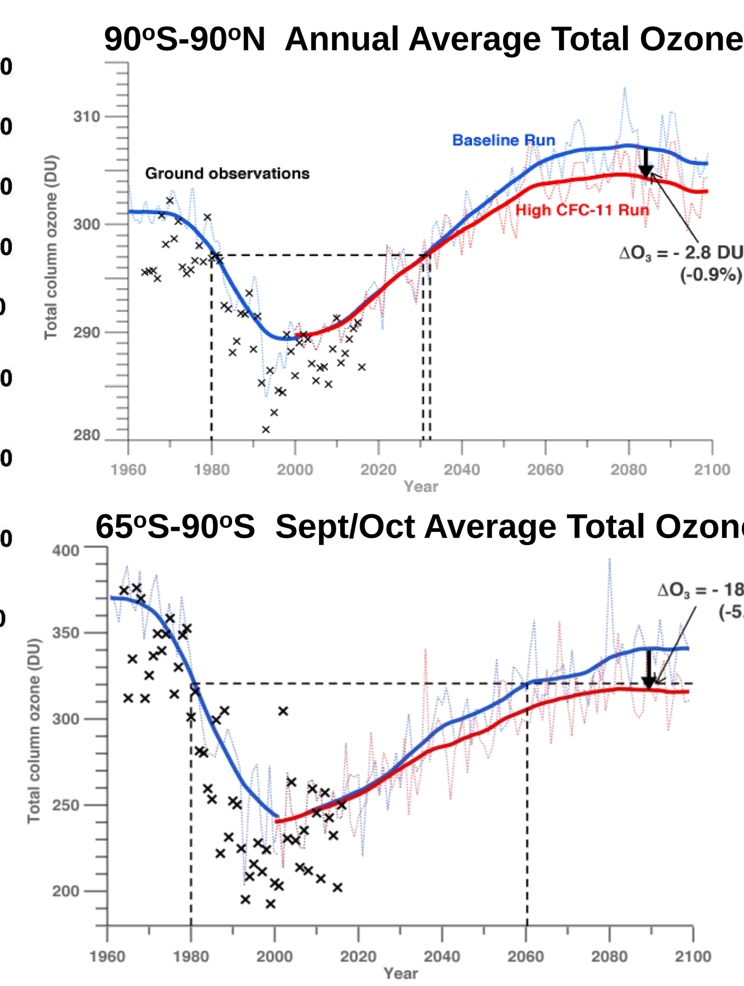

Figure 2. 90°S-90°N annual (top) and 65°S-90°S Sept/Oct average (bottom) total ozone; **x** = ground-based obs.

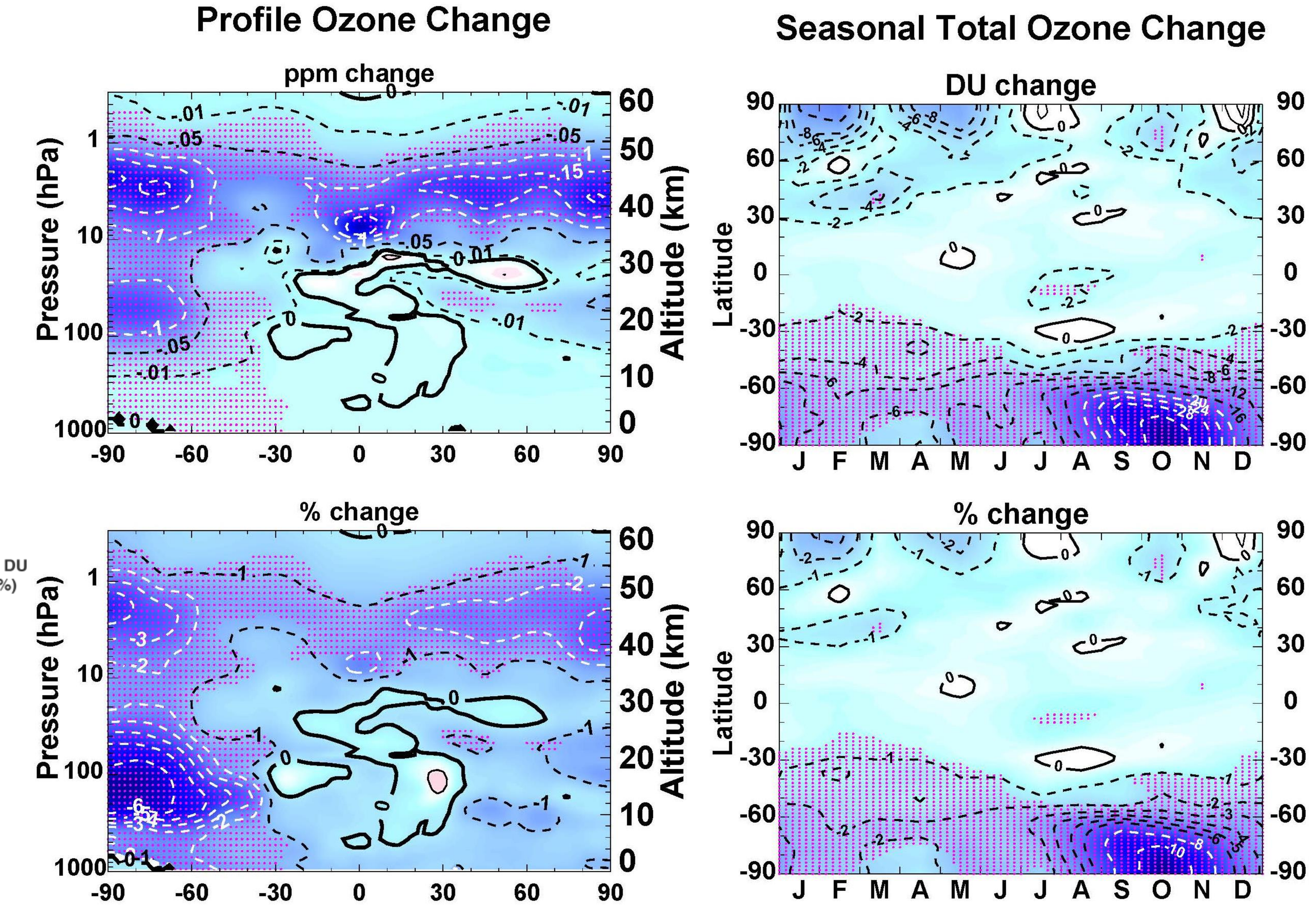

Figure 3. 2080-2100 average ozone change (high CFC-11 minus – baseline): (Left) Annual ozone profile change, (Right) Seasonal total column ozone change . Red stippling is statistically significant at the 95% level.

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 ppb) by 2100 (Fig. 1, bottom).
- Global total ozone decreases 2.8 DU (0.9%) by the late 21st century; return to 1980 levels delayed by 1 yr, 2031→2032 (Fig. 2, top).
- 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%) (Fig. 3, left).
- Ozone hole deepens by 12% in October; additional ozone depletion of 2-3% throughout the year poleward of 60°S (Fig. 3, right).
- Arctic changes in the lower stratosphere and total column are mostly ***not*** statistically significant.

4. Temperature and Zonal Wind Responses

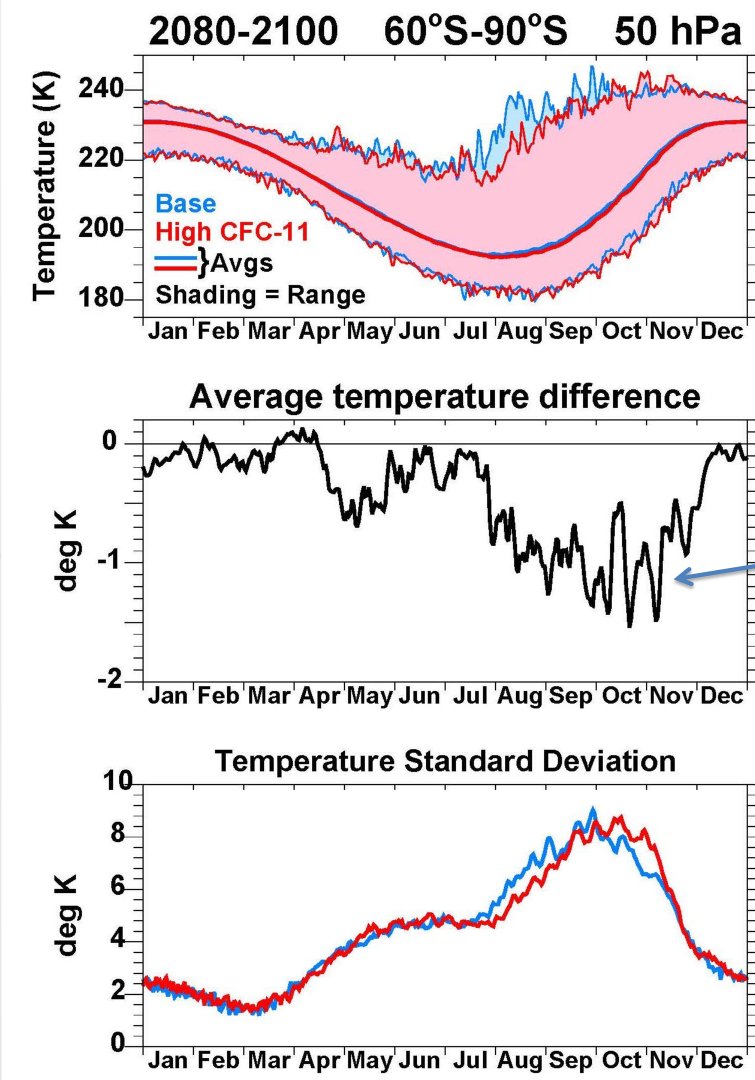

Figure 4. Daily Antarctic temperature at 50 hPa for the baseline (blue) and high CFC-11 (red). Top: shading shows the range over all polar grid points, heavy lines show the corresponding averages. Middle: average difference, high CFC-11 minus baseline. Bottom: standard deviation of all polar grid points, 2080-2100.

November (2080-2100 avg)

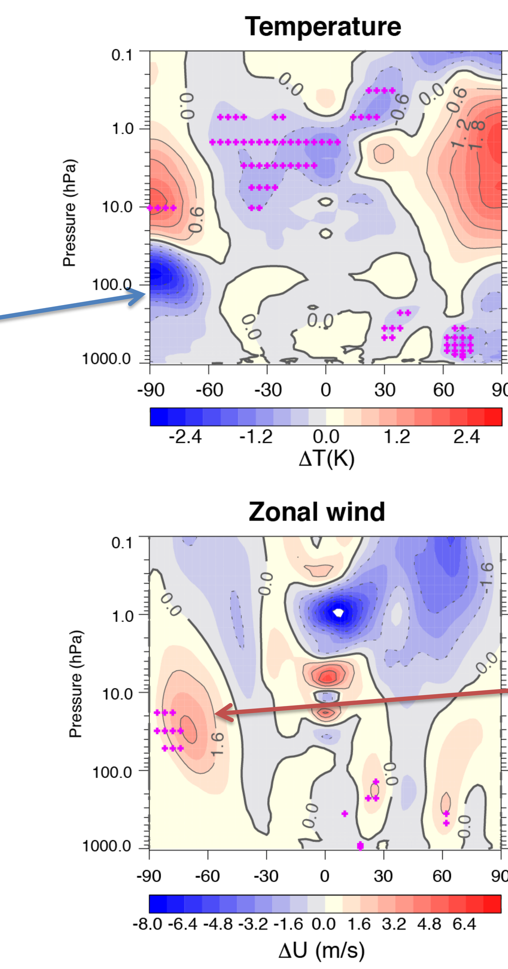

Figure 5. November temperature and zonal wind difference, high CFC-11 minus baseline averaged over 2080-2100. Red stippling is statistically significant at the 95% level.

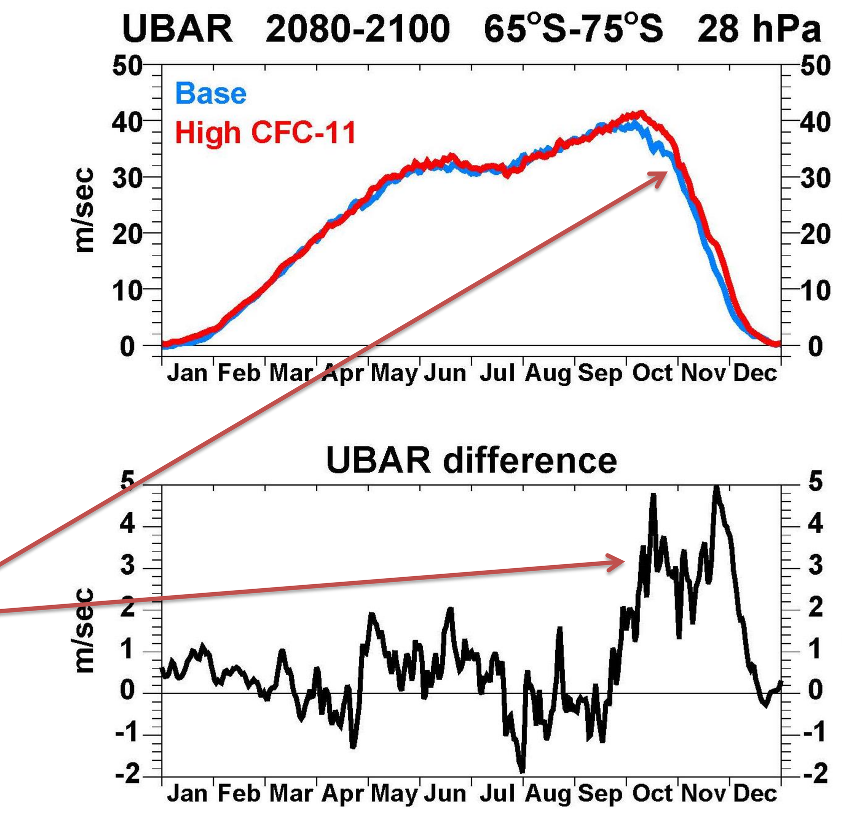

Figure 6. Daily zonal wind at 28 hPa averaged over 65°S-75°S, 2080-2100 for the baseline and high CFC-11 (top), and high CFC-11 minus baseline difference (bottom).

- 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 circumpolar 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 Aug-Sept with high CFC-11 (Fig. 4, top, red vs. blue shading).
- The change in the jet also focuses more planetary wave activity to the polar upper 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 ~0.1 years younger in the Southern Hemisphere lower stratosphere, but statistically significant.

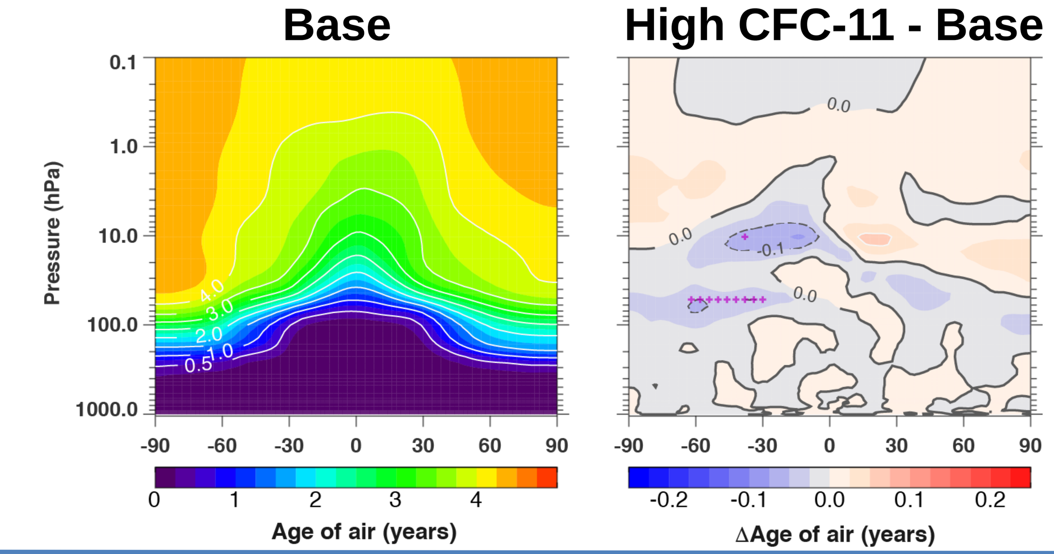

Figure 7. 2080-2100 annual average age of air from the baseline (left), and the high CFC-11 minus baseline difference (right). Red stippling is statistically significant at the 95% level.

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 polar lower stratosphere, a stronger circumpolar jet, and modification of planetary wave propagation.
- Changes in stratospheric age of air are small (> ~-0.1 years); only small regions are statistically significant.

References:

Kiehl, J.T., et al. (1988). Response of a general circulation model to a prescribed Antarctic ozone hole, *Nature*, **332**, 501-504.

Montzka, S.A., et al. (2018). An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature*, **557**, 413-417, doi:10.1038/s41586-018-0106-2.

Rigby, M., et al. (2019). Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature*, **569**, 546-549, doi:10.1038/s41586-019-1193-4.

Stolarski, R.S., et al. (2006). An ozone increase in the Antarctic summer stratosphere: A dynamical response to the ozone hole, *Geophys. Res. Lett*, **33**, L21805, doi:10.1029/2006GL026820.