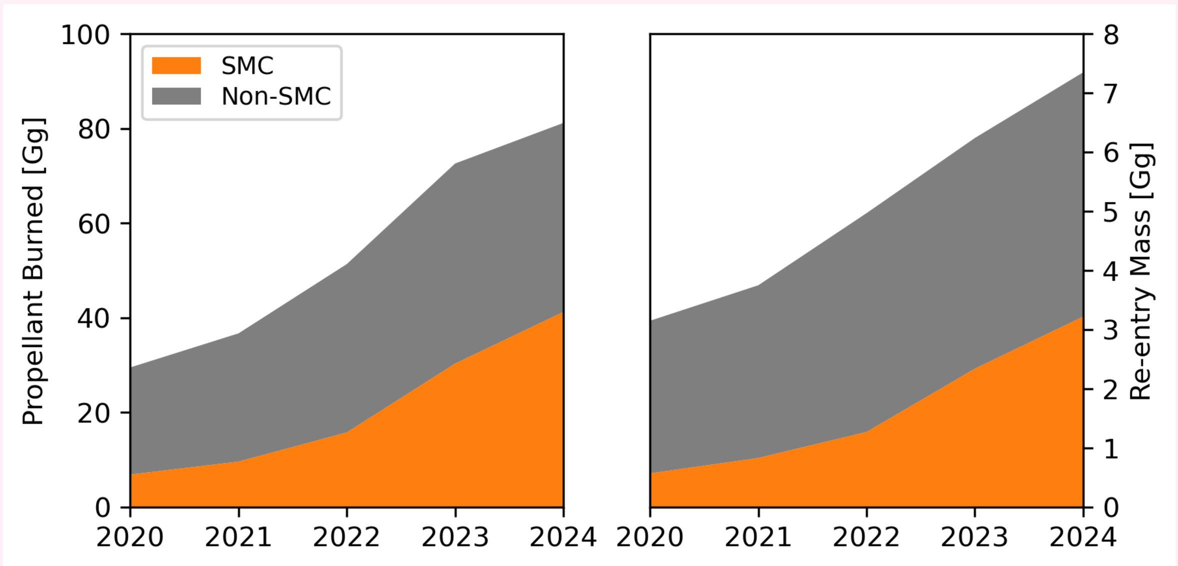
Radiative forcing and ozone depletion of a decade of growth in satellite megaconstellation missions

Connor R. Barker[1] (connor.barker@ucl.ac.uk), Eloise A. Marais[1], Eric Tan[2], Sebastian D. Eastham[3], Glenn S. Diskin[4], Joshua P. DiGangi[4], Yonghoon Choi[4,5], Andrew Rollins[6], Eleanor Waxman[6,7], T. Paul Bui[8], Charles Gatebe[8], Jonathan Dean-Day[9]

Key Findings: Satellite megaconstellation missions, which mostly use kerosene fuel, are **51%** of rocket fuel consumption in 2024, and **44%** of re-entry mass. These missions inject large amounts of black carbon aerosol above the tropopause, contributing **56%** of positive instantaneous and **42%** of stratospherically adjusted negative forcing attributable to all missions. However, SMC impacts on global stratospheric ozone are small (0.003% in 2029).

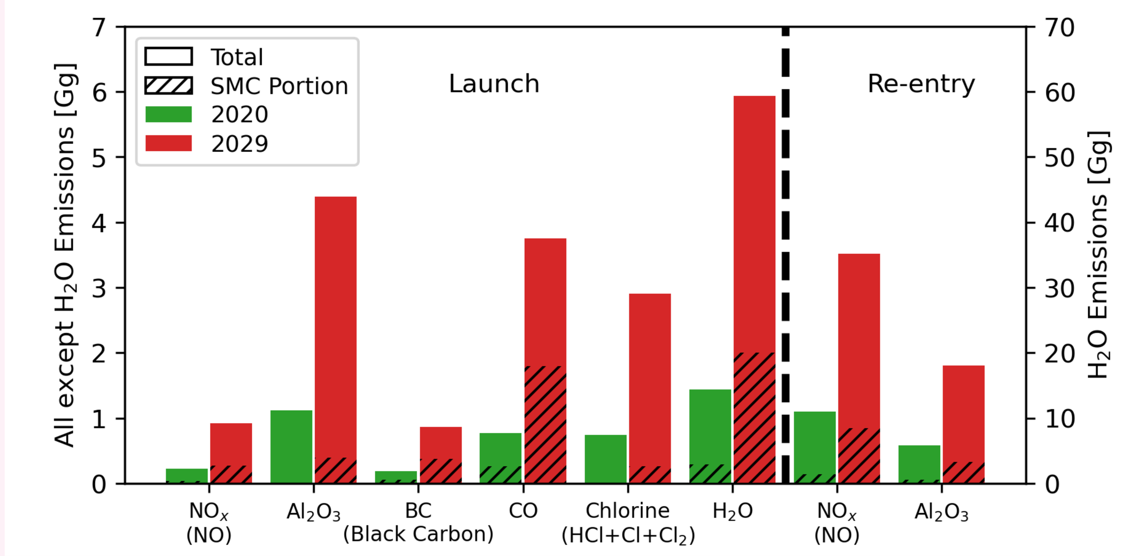
1 Satellite Megaconstellations (SMCs)

- Rocket launches release air pollutant emissions and CO_2 throughout the atmosphere. Re-entries of discarded rocket bodies, payloads and debris pollute the mesosphere. These emissions contribute to stratospheric ozone depletion and impact climate.
- SMCs, which contain hundreds to thousands of satellites in a single constellation, are a growing fraction of propellant consumption and re-entry mass from the space industry.



2 Modelling Space Industry Growth with GEOS-Chem

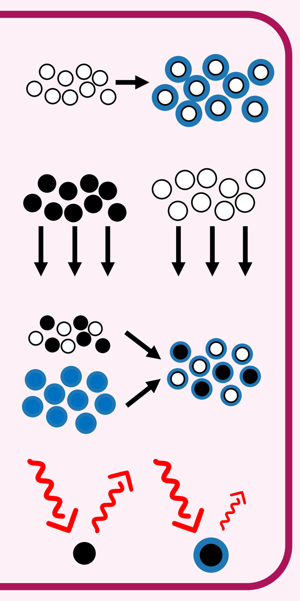
Global, 3D, hourly rocket launch and re-entry emission inventory for 2020-2022 [1], extrapolated to 2029.



- Launch and re-entry emissions are projected to 2029 based on 2020-2022 trends in propellant consumption and re-entry mass.
- Emissions are categorized according to mission type – SMC and non-SMC.

Updates to GEOS-Chem Aerosol Chemistry

1. New hygroscopic Al_2O_3 species with heterogenous chlorine activation.
2. Gravitational settling updated to include Al_2O_3 and hydrophobic BC.
3. Uptake of BC and Al_2O_3 to stratospheric sulfate [2].
4. Lensing effect for sulfate-coated BC in stratosphere.



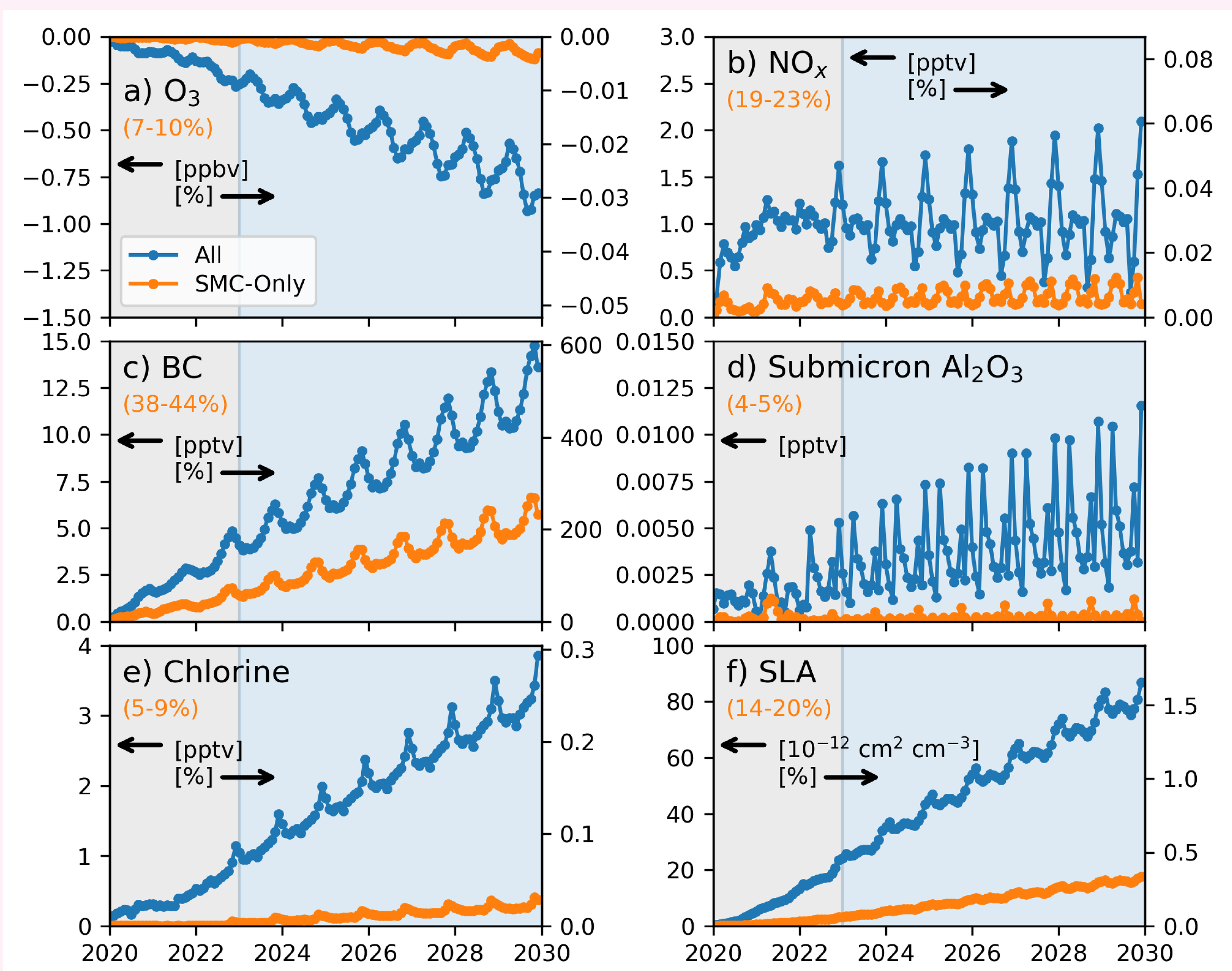
GEOS-Chem + Radiative Transfer Model v14.3.0, 4° x 5° x 47 layers

2020-2029
1. No missions
2. All missions
3. SMC missions only

3 Impact on Stratospheric Composition

- Annual global mean stratospheric O_3 depletion from the space industry is 0.03% in 2029, mainly due to NO_x and chlorine. BC and Al_2O_3 contribute minor ozone depletion via increased surface area of stratospheric liquid aerosol (SLA, +1.5%).

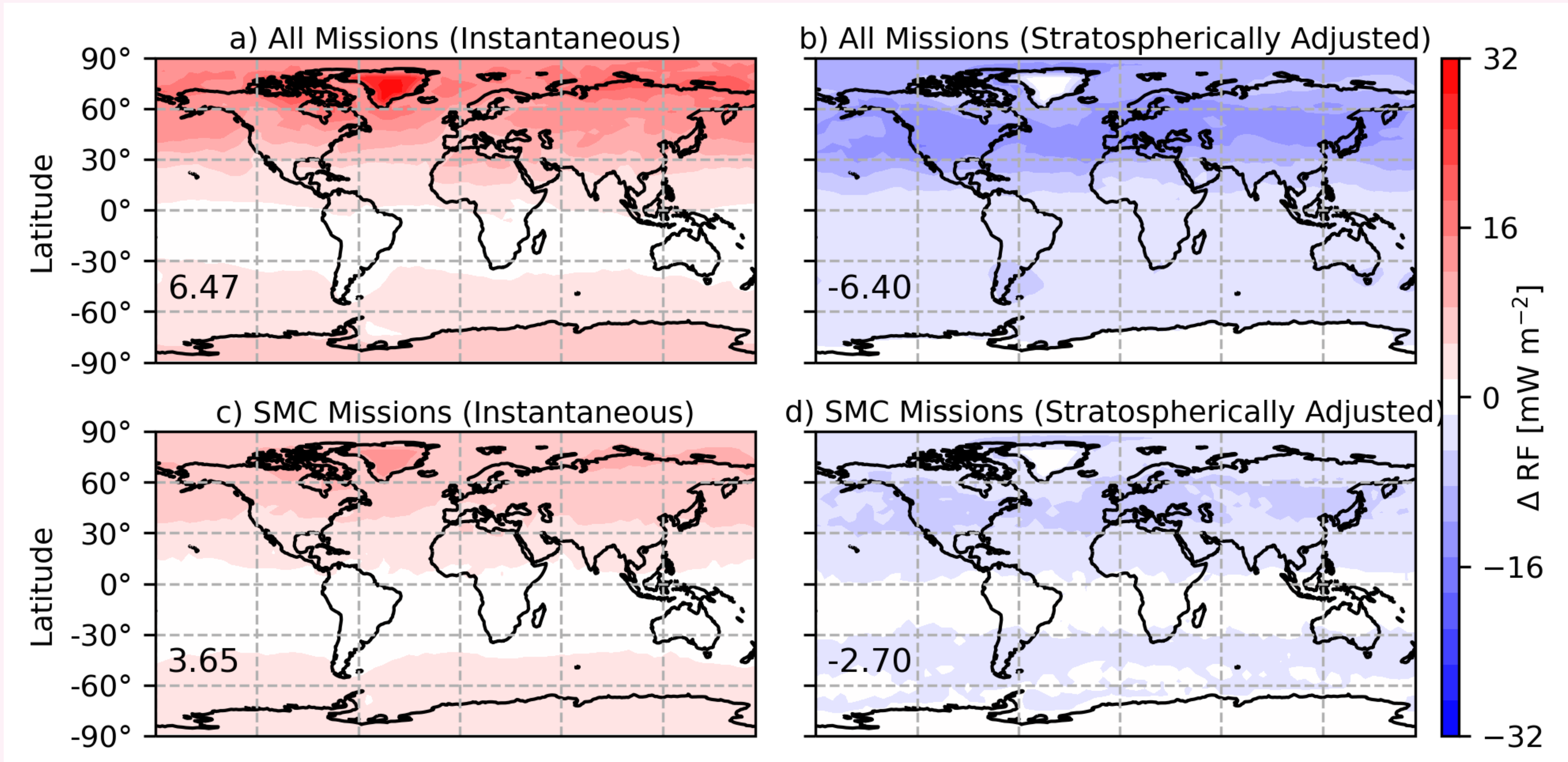
Monthly Mean Change in Stratospheric Concentration



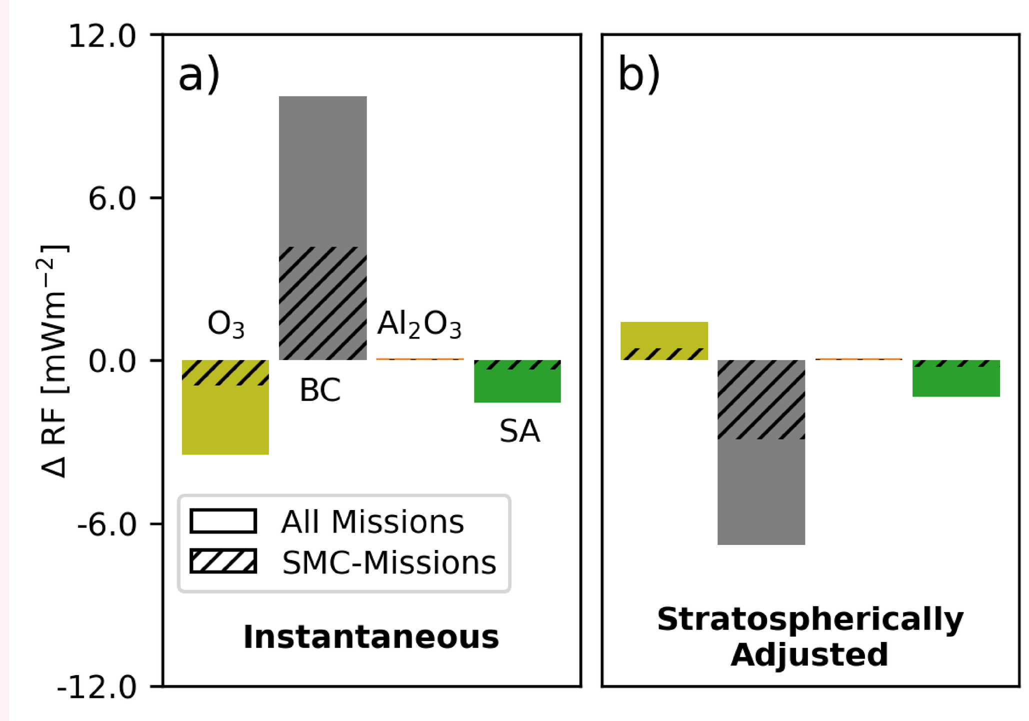
- Only 10% of this O_3 depletion is from SMCs, due to kerosene fuel used for 98% of SMC launches. Kerosene fuel does not emit ozone-depleting Al_2O_3 and chlorine.

4 Impact on Global Radiative Forcing

Annual Mean Global Radiative Forcing in 2029



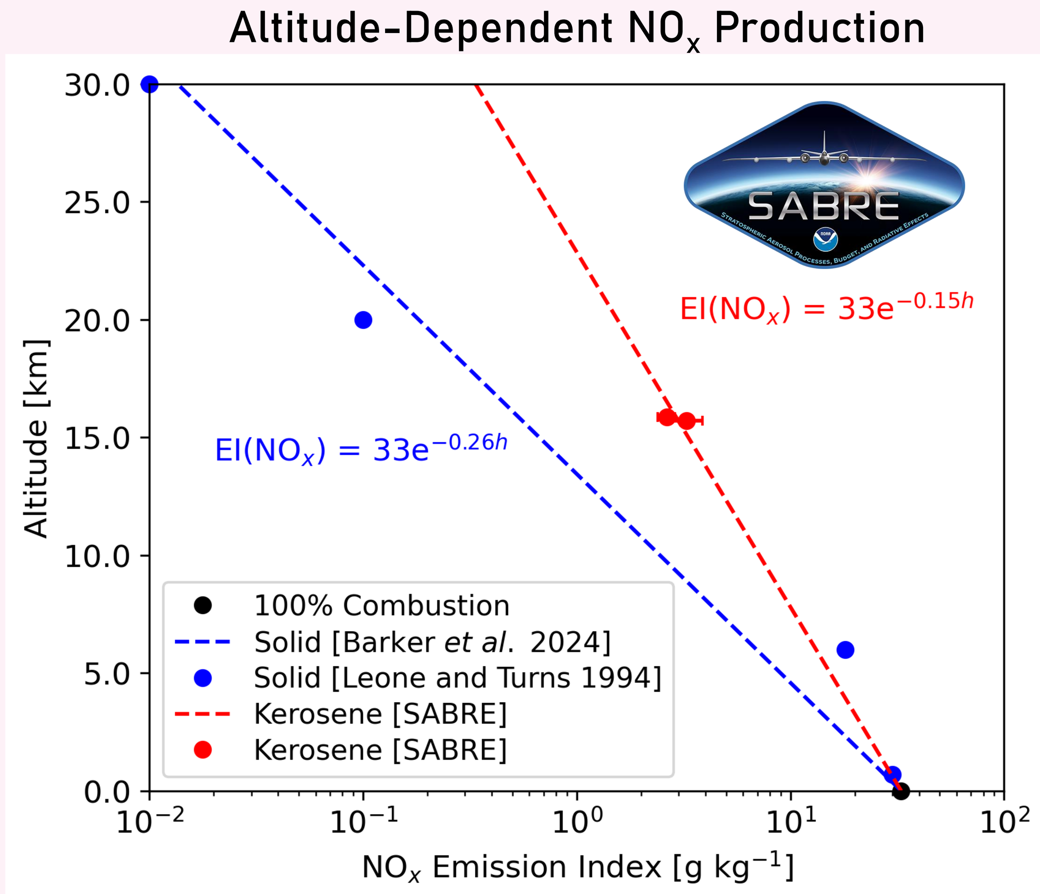
- Radiative forcing is mainly in the northern hemisphere where nearly all launches occur, driven by absorption of SW radiation by sulfate-coated BC above the tropopause.
- Removal of UV-absorbing ozone works to reverse BC forcing.
- Increase in surface area of stratospheric aerosol increases reflectivity, cooling the atmosphere.
- All missions instantaneous BC forcing is 7% of the global total [3].
- SMCs inject a large proportion of the total BC (44%).
- As a result, SMCs contribute 42% and 56% of instantaneous and stratospherically adjusted global mean radiative forcing.



5 Validation of afterburning NO_x production using SABRE Aircraft Campaign

- We compare emissions from our utilized inventory [1] to aircraft measurements from the NOAA SABRE campaign [4], which intercepted a rocket plume from a Falcon 9 launch twice at ~16 km altitude.
- All rocket launches produce NO_x in the rocket plume via afterburning – high temperature oxidation of ambient N_2 to NO. In contrast, H_2O production is constant with altitude, so we use the $\Delta NO_x/\Delta H_2O$ ratio to compare.
- The $\Delta NO_x/\Delta H_2O$ is 5-6 times more for the SABRE campaign than the inventory, suggesting afterburning continues at higher altitudes than previously thought.
- We use the SABRE $\Delta NO_x/\Delta H_2O$ ratio to calculate an updated NO_x production curve.

Altitude-Dependent NO_x Production



Conclusions

- Global ozone depletion is 0.03% from all mission types, and 0.003% from SMCs, compared to 2% from surface sources [5].
- Sulfate-coated black carbon absorbs shortwave radiation above the tropopause, leading to positive instantaneous forcing and negative stratospherically adjusted forcing.
- SMCs contribute approximately half of the radiative forcing.

Check out our space activity emissions trackers!

References

1. Barker, C.R., Marais, E.A. & McDowell, J.C. Global 3D rocket launch and re-entry air pollutant and CO2 emissions at the onset of the megaconstellation era. Sci Data 11, 1079 (2024).
2. D.M. Murphy *et al.*, Metals from spacecraft reentry in stratospheric aerosol particles, Proc. Natl. Acad. Sci. U.S.A. 120 (43) e2313374120 (2023).
3. Dong, X. *et al.*, Evaluating recent updated black carbon emissions and revisiting the direct radiative forcing in Arctic. Geophysical Research Letters, 46, 3560–3570 (2019).
4. https://csl.noaa.gov/projects/sabre/
5. World Meteorological Organization (WMO) (2022).

[1]Department of Geography, University College London, [2]Department of Physics and Astronomy, University College London, [3]Department of Aeronautics, Imperial College London, [4]NASA Langley Research Center, Hampton, Virginia, USA, [5]Analytical Mechanical Associates, Hampton, VA 23666, USA, [6]NOAA Chemical Sciences Laboratory, Boulder, CO, USA, [7]CIRES, University of Colorado Boulder, Boulder, CO, USA, [8]NASA Ames Research Center, Moffett Field, CA, USA, [9]Bay Area Environmental Research Institute, Sonoma, CA, USA