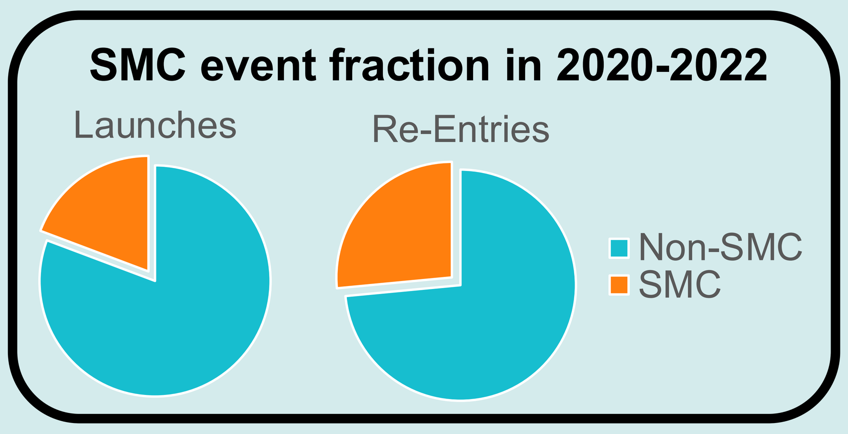
Environmental impacts of satellite megaconstellation missions during rapid space sector growth

Connor Barker[1], Eloise Marais[1], and Sebastian Eastham[2]

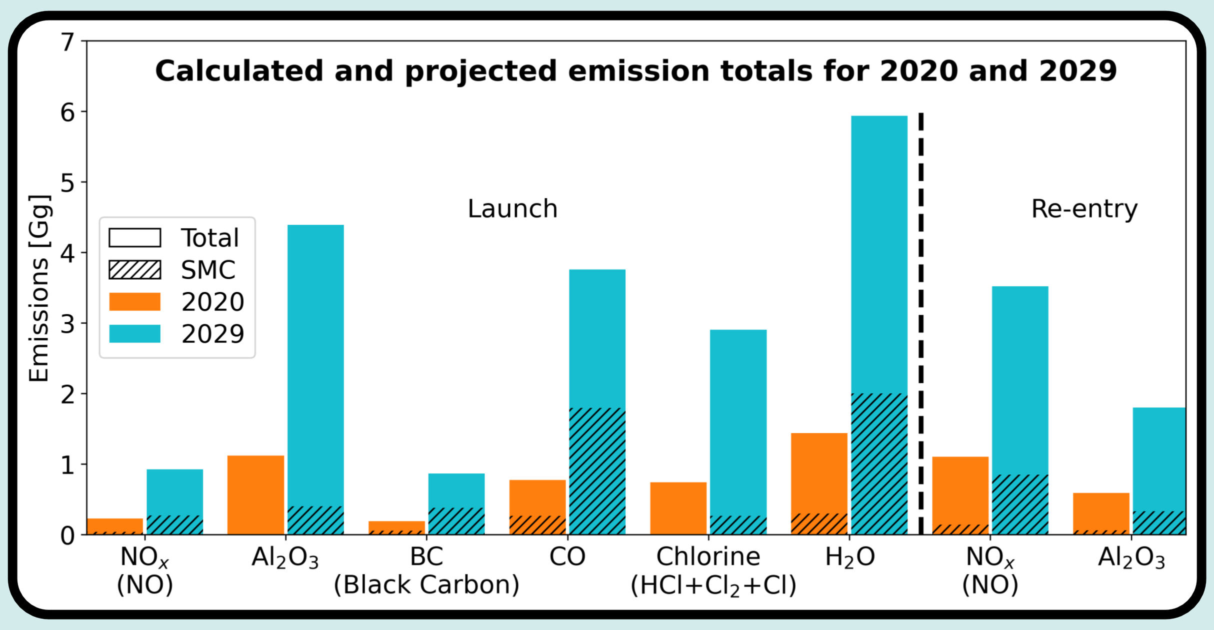
Key Findings: Global ozone depletion is 0.03% from all mission types. Absorption of shortwave radiation by black carbon above the tropopause leads to tropospheric cooling (-6.40 mWm^{-2}) and top-of-atmosphere warming (6.47 mWm^{-2}). Megaconstellations such as Starlink and OneWeb contribute 10% of the ozone depletion and half of the warming.

1. Satellite Megaconstellations (SMCs)

- 70% of satellites in low-Earth orbit (LEO) are from SMCs such as Starlink and OneWeb.
- Rocket launches release air pollutant emissions and CO_2 throughout the atmosphere.
- Re-entry of discarded rocket bodies, payloads and debris pollute the mesosphere.



2. Modelling Space Industry Growth with GEOS-Chem



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

GEOS-Chem + Radiative Transfer Model

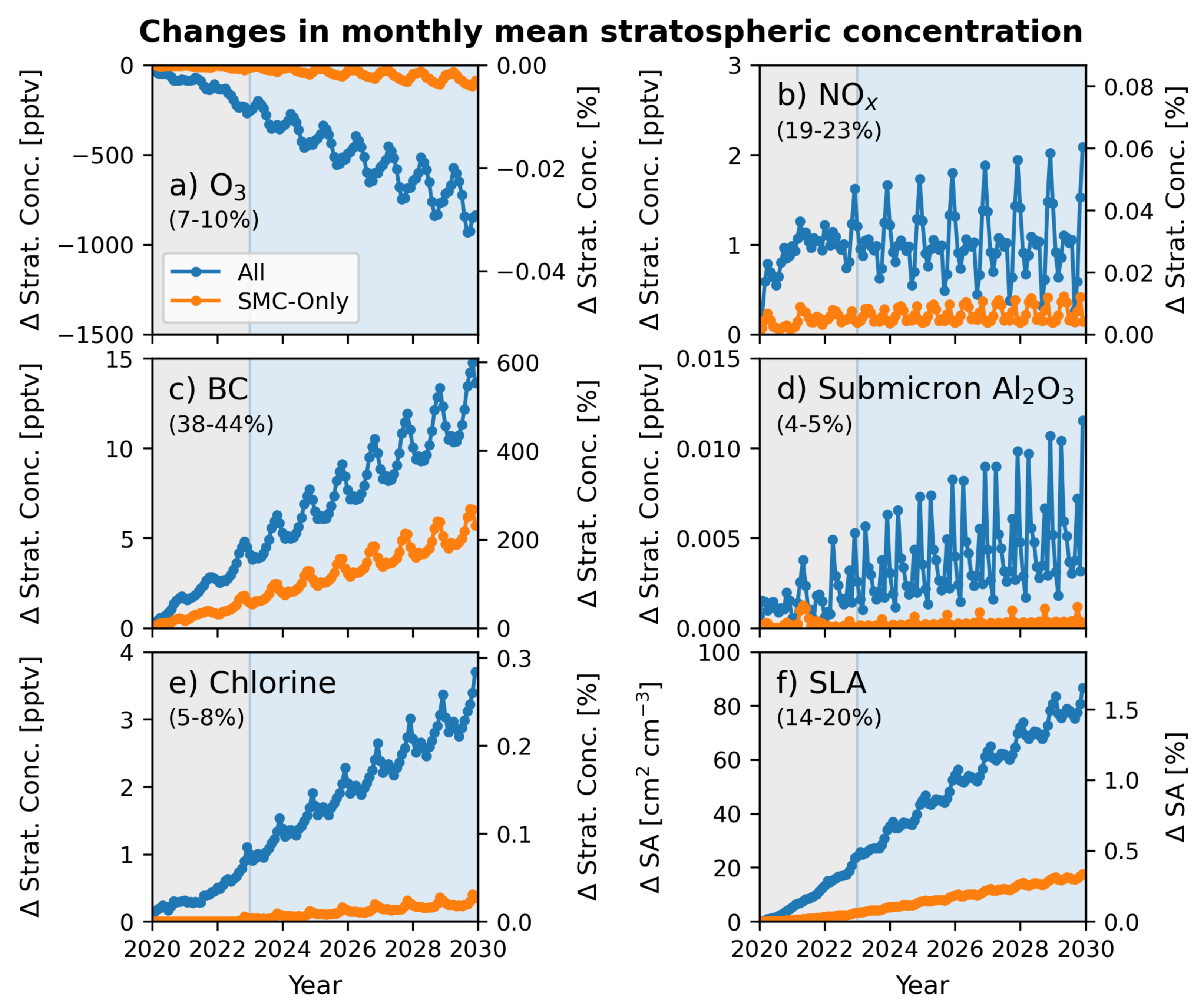
v14.3.0
2020-2029
4° x 5° x 47 layers

1. No missions
2. All missions
3. SMC missions only

Model Updates:
- New hygroscopic Al_2O_3 species with heterogenous chlorine activation.
- Gravitational settling of hydrophobic BC and Al_2O_3.
- Uptake of BC and Al_2O_3 to stratospheric sulfate.
- Lensing effect for sulfate-coated BC in stratosphere.

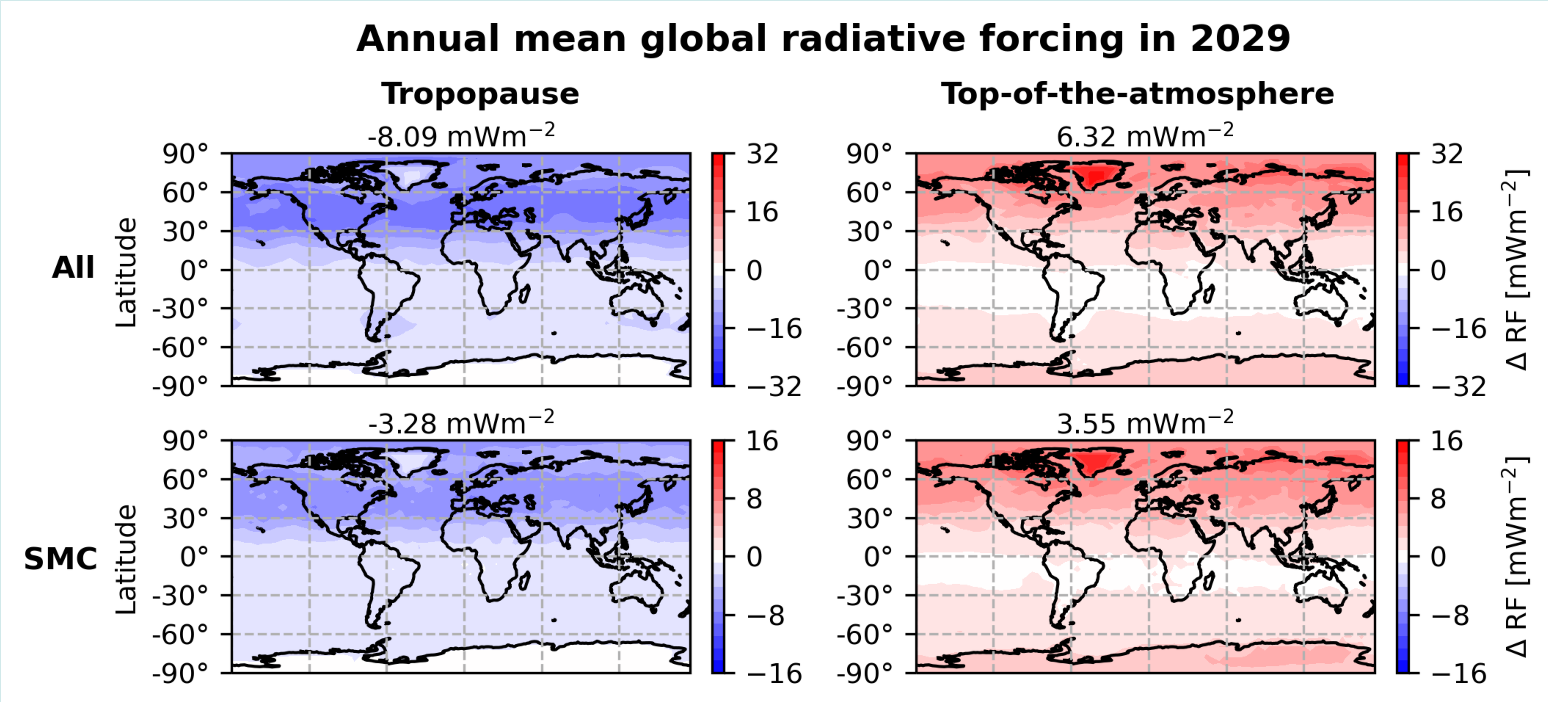
3. Stratospheric Composition in 2029

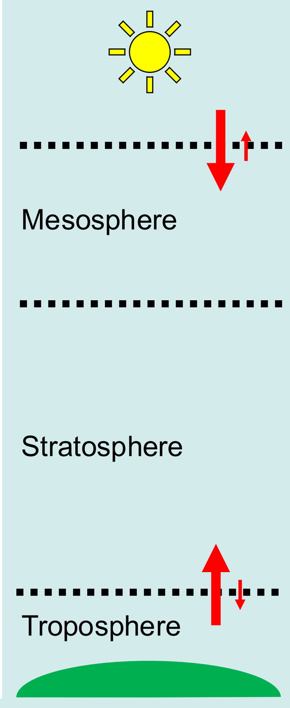
- Annual global mean stratospheric O_3 depletion is from the space industry is 0.03% in 2029, mainly due to NO_x and chlorine. BC and Al_2O_3 contribute minor ozone depletion.
- Only 10% of this O_3 depletion is from SMCs, due to kerosene fuel used for 98% of SMC launches. Kerosene fuel does not emit ozone-depleting Al_2O_3 and chlorine.



- SMCs inject a large proportion of the total BC (44%), which absorbs solar radiation.
- Uptake of BC and Al_2O_3 to stratospheric sulfate results in an increase in stratospheric liquid aerosol (SLA) surface area (1.5%), increasing reflectivity.

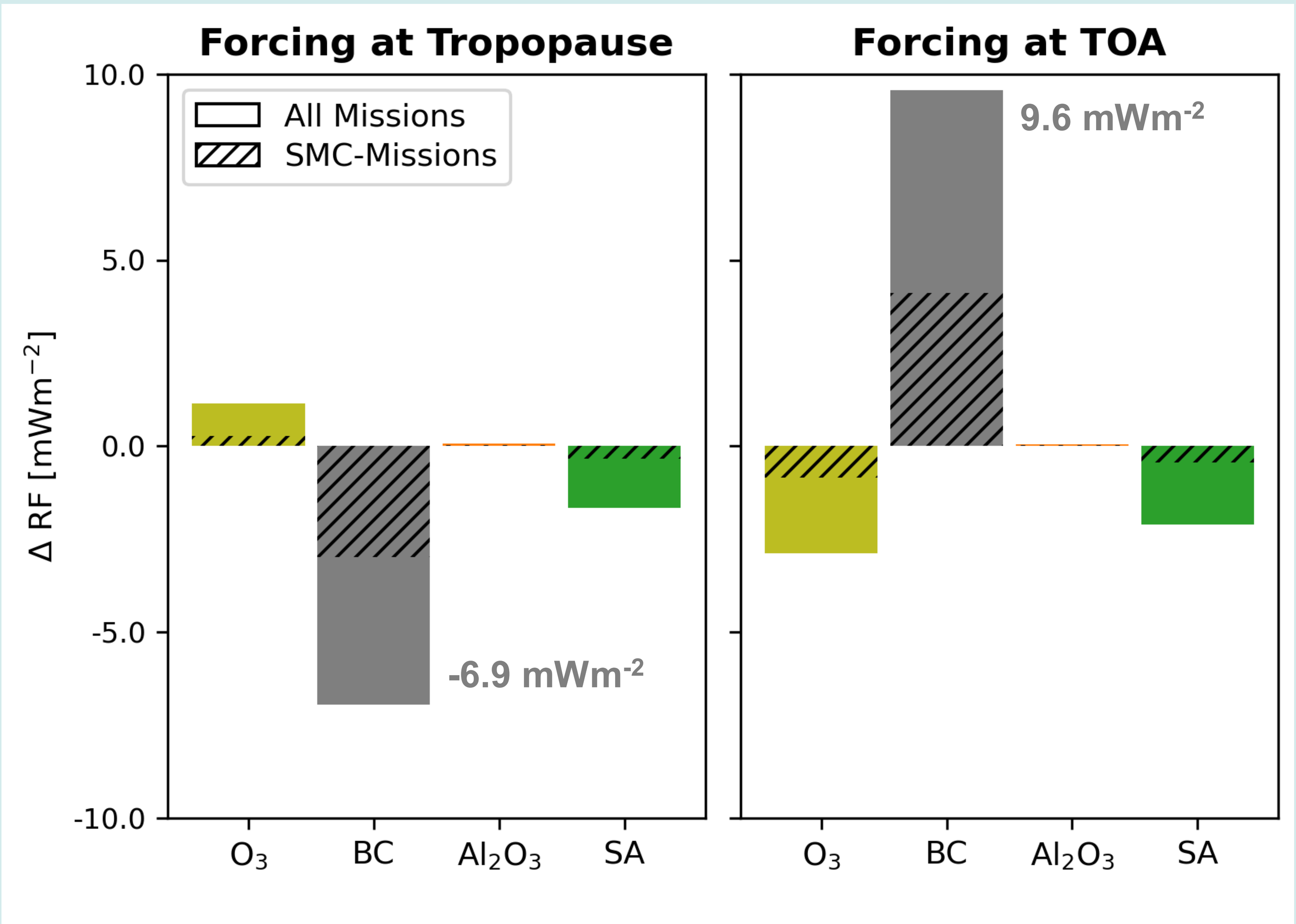
4. Global Radiative Forcing in 2029



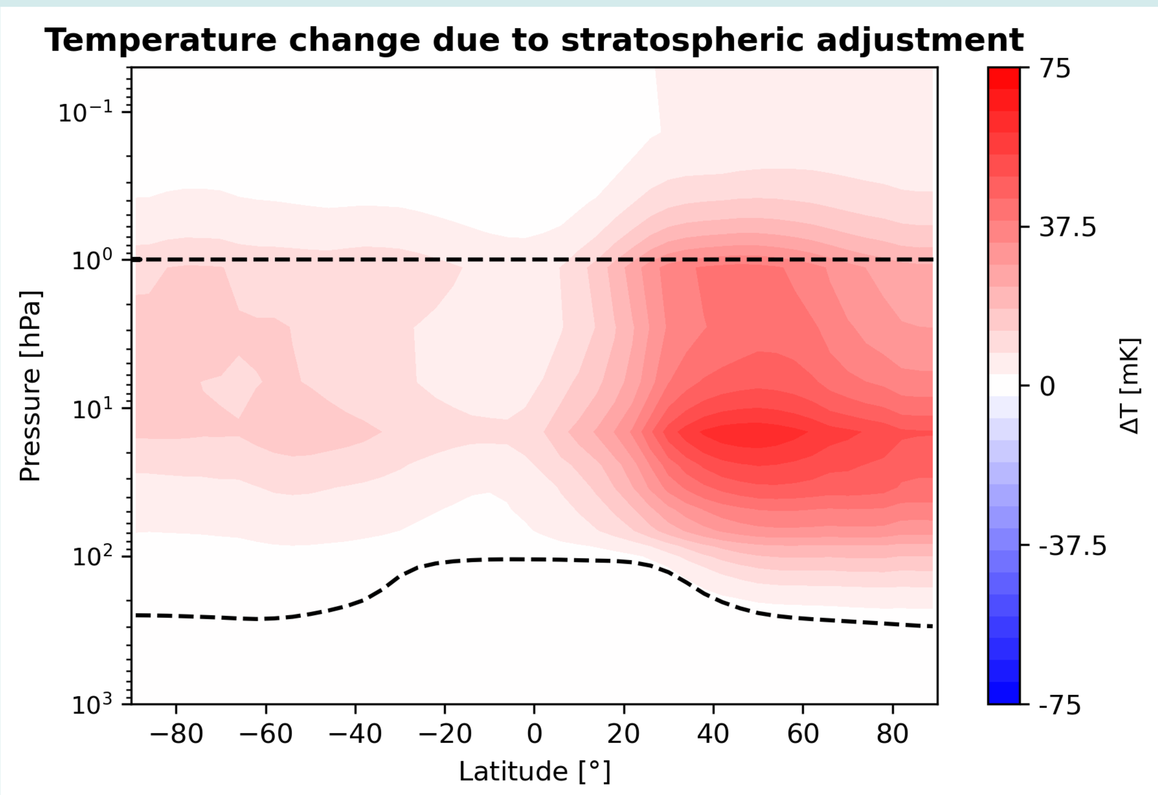


- SMCs contribute 42% and 56% of global mean forcing at the tropopause and TOA.
- Hotspot over Greenland where less solar radiation now reaches the high albedo surface.

- Radiative forcing is driven by absorption of SW radiation by BC above the tropopause.
- Removal of UV-absorbing ozone works to reverse forcing by BC.
- Small ozone depletion by SMCs has less of a mitigating effect, leading to increased forcing efficiency by SMCs.



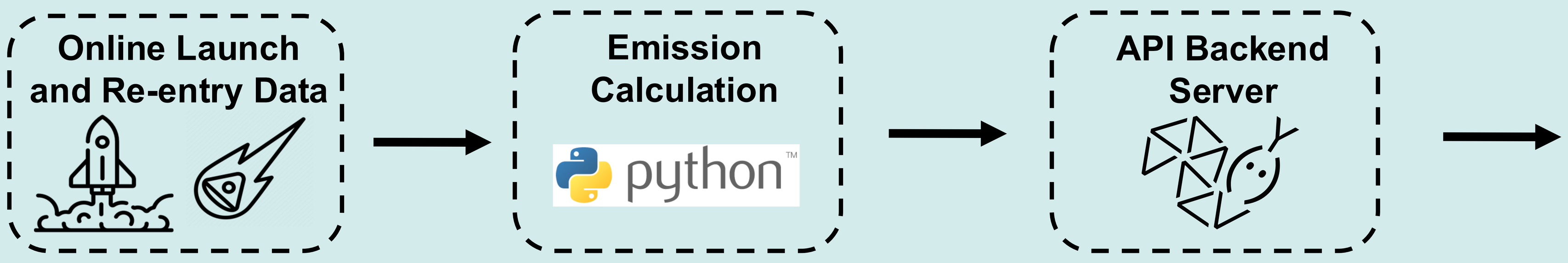
5. Stratospheric Warming

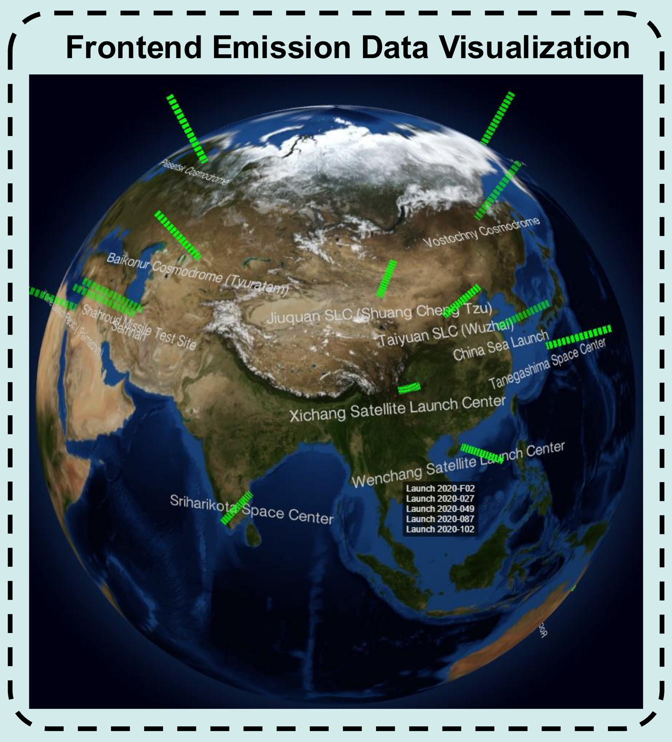


- The change in annual mean stratospheric temperature is 22 mK in the northern hemisphere in 2029.
- Warming of the stratosphere may offset stratospheric contraction caused by surface-based greenhouse gas emissions.

6. Online Emissions Tracker

- Visualisation tool for our global, 3D emission inventory [1].
- Data is available for all rocket launches [2] and re-entries [3] in 2020-2022.
- Updates to 2024 coming soon, with real-time emissions estimates planned.
- Freely available tool for use by the public, media, and policymakers.





Conclusions

- Global ozone depletion is 0.03% from all mission types, and 0.003% from SMCs, compared to 2% from surface sources [4].
- Black carbon absorbs shortwave radiation above the tropopause, leading to tropospheric cooling and top-of-atmosphere warming.
- SMCs contribute 10% of the ozone depletion and half of the warming.

References

1. Barker, C.R., Marais, E.A. & McDowell, J.C. *Sci Data* **11**, 1079 (2024). https://doi.org/10.1038/s41597-024-03910-z
2. https://maraisresearchgroup.co.uk/launch_emis.html.
3. https://maraisresearchgroup.co.uk/reentry_emis.html.
4. World Meteorological Organization (WMO) (2022).

[1]University College London, Department of Geography, London, United Kingdom (connor.barker@ucl.ac.uk)
[2]Imperial College London, Department of Aeronautics, London, United Kingdom