Radiative Forcing and Ozone Depletion of a Decade of Satellite Megaconstellation Missions

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Environmental impacts of the space industry

Launches (0 km to orbit)

Hydrogen
Kerosene
Methane
Hypergolic
Solid
Bio-propellants?

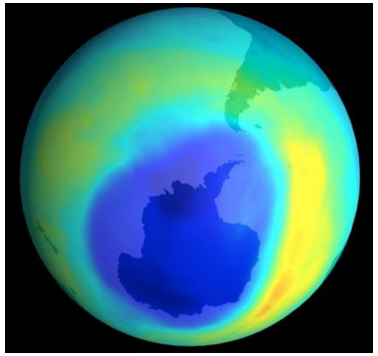
H_2O
CO_2
BC
NO_x
Chlorine
Al_2O_3

Reentries (60-80 km)

Payloads
Components
Capsules
Rocket Bodies
Debris

NO_x Al_2O_3 BC Cl_y

Stratospheric O_3 depletion



Driven by NO_x, BC, Cl_y, and Al_2O_3

Instantaneous Climate Forcing

BC | Al_2O_3 | Strat. Aerosol

The space industry (and our understanding of it) is rapidly changing

Onset of the satellite megaconstellation (SMC) era

SpaceX Starlink

9788

1313

Eutelsat OneWeb

660

6

Amazon Kuiper

104

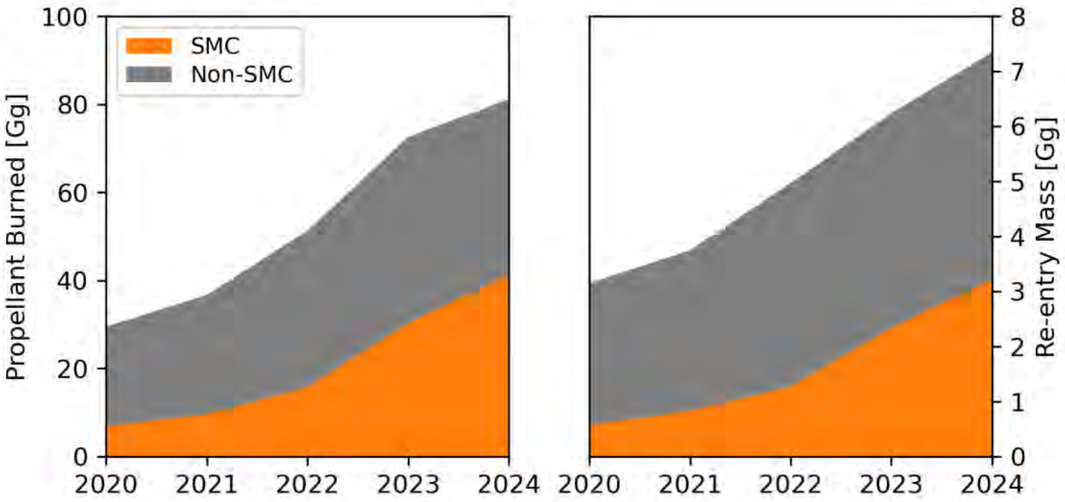
2

Thousand Sails

90

0

Propellant consumption and re-entry mass from the space industry



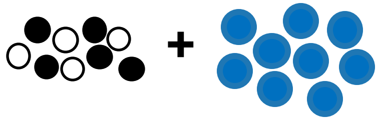
[JSR, 23/09/25]

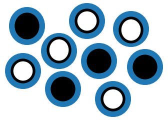
Understanding of emission chemistry has developed

Altitude-dependent emissions in the lower atmosphere

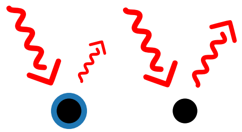
Uptake of aerosol emissions to sulfuric acid

BC/Al_2O_3 H_2SO_4





Complex re-entry ablation processes in the upper atmosphere



Lensing effect of coated stratospheric black carbon

Ablation products

- AlO, AlOH, Al^+
- Chlorine (resins)
- Cu, Li, Nb…
- Carbon

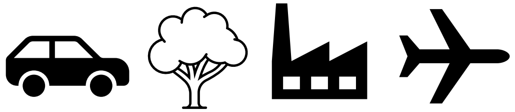
10% of the aerosol particles in the stratosphere contain metals from spacecraft re-entry

[Murphy *et al.*, 2023 and many others]

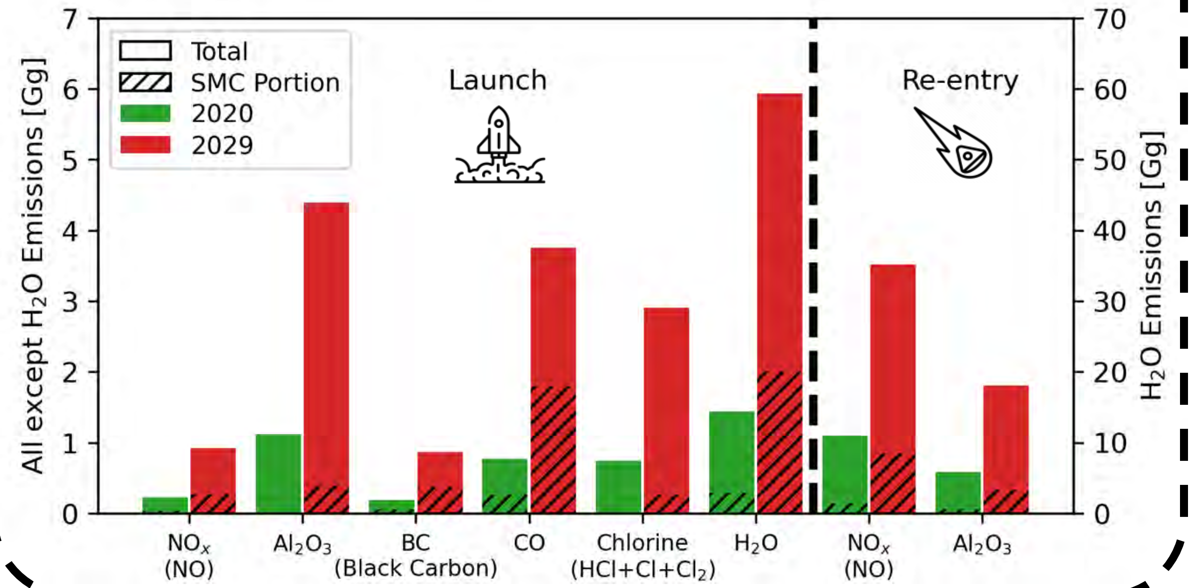
Implementing space activity emissions into a global model of atmospheric chemistry

Offline Meteorology

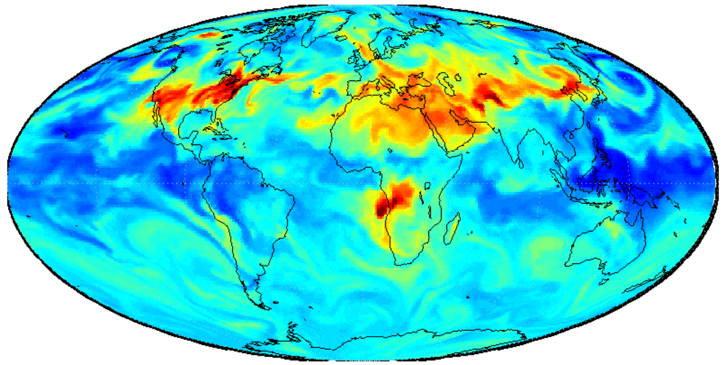
Biogenic / Anthropogenic Emissions



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



GEOS-Chem + RRTMG



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

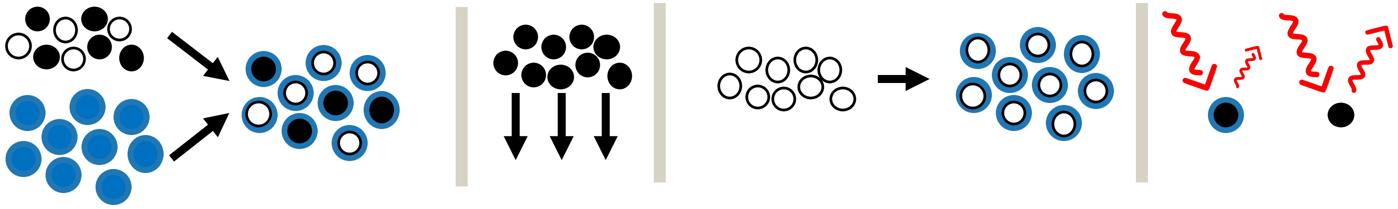
2020-2029
4° x 5° x 47 layers
0-80 km

Atmospheric Composition
Radiative Forcing

[Barker et al., submittted]

Updating GEOS-Chem to represent stratospheric aerosol injection

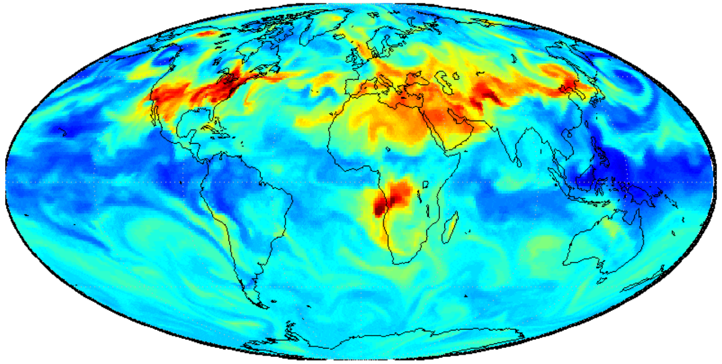
Updated aerosol treatment



Updated radiative forcing

GEOS-Chem

+ RRTMG



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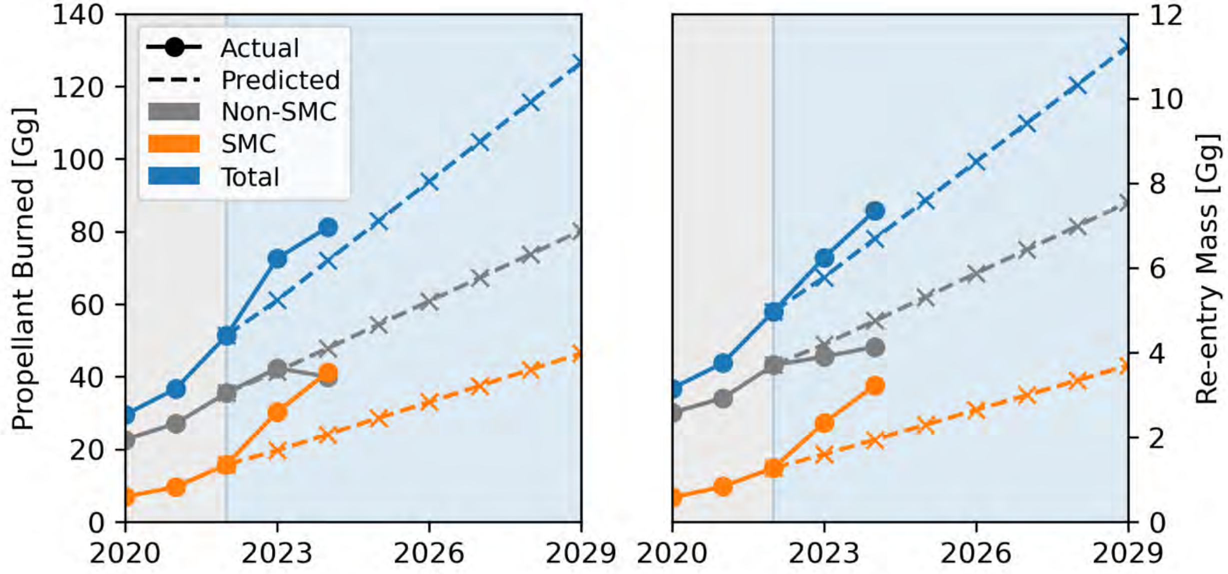
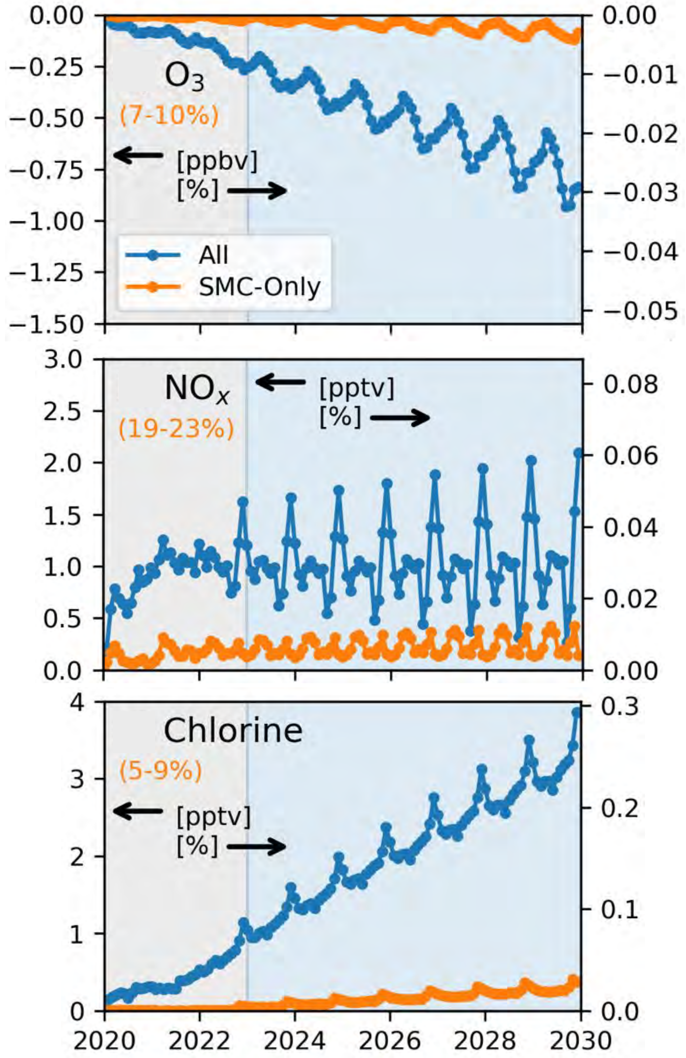


Atmospheric Composition
Radiative Forcing

[Barker et al., submitted, IPCC 2007]

Impact of space industry emissions on stratospheric composition – Ozone Depletion

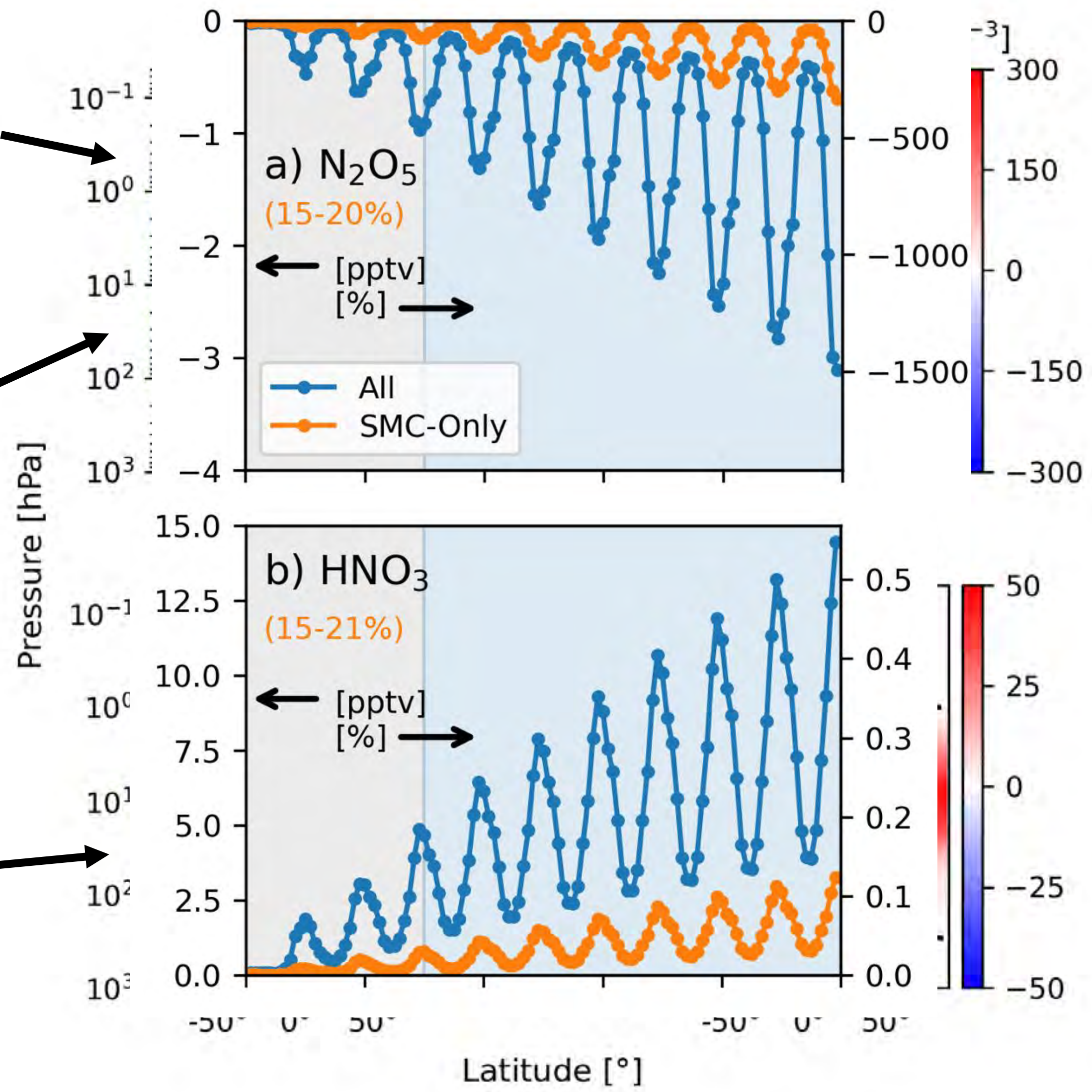
Monthly Mean Change in Stratospheric Concentration



Maximum ozone depletion in the upper stratosphere northern hemisphere

Maximum ozone production in middle stratosphere

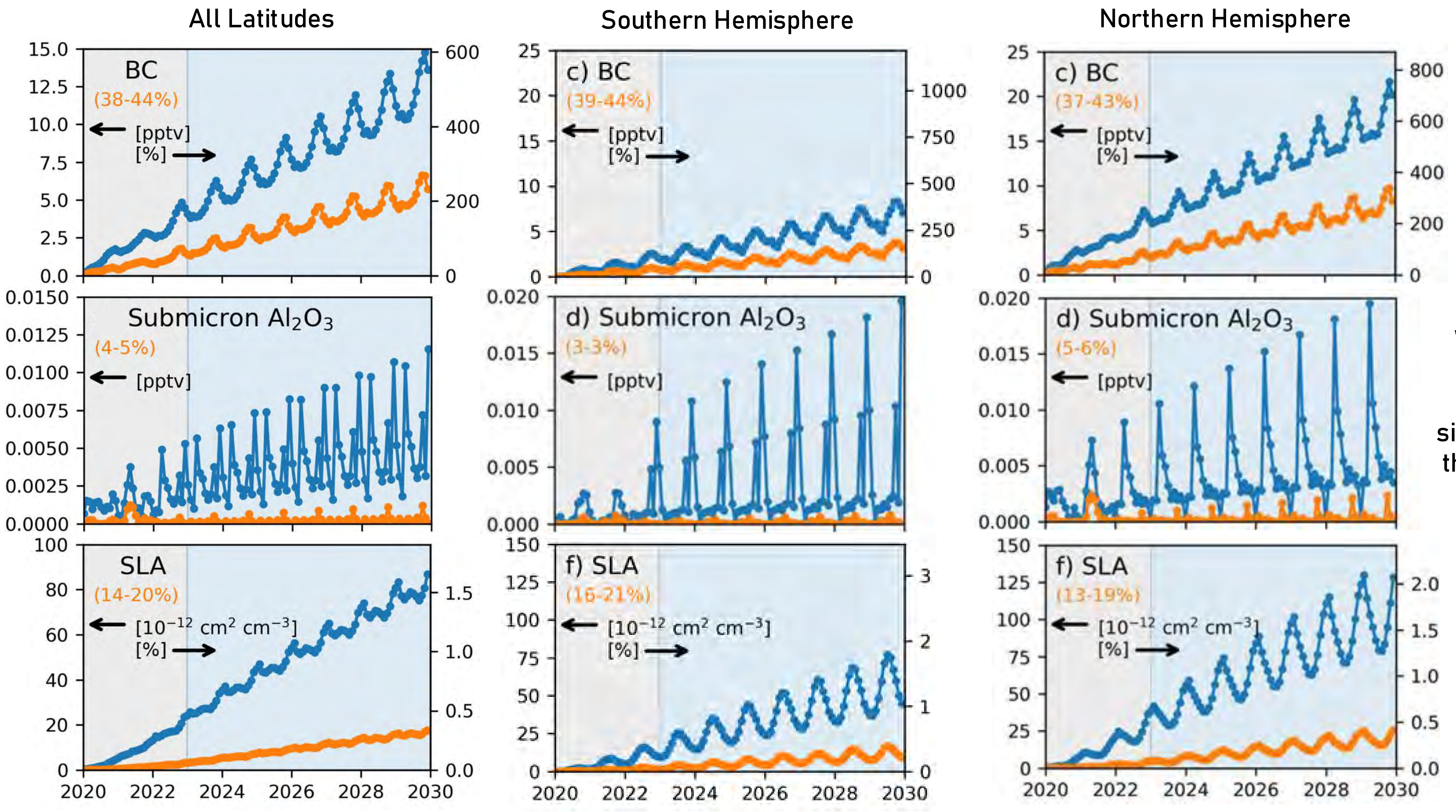
Increase in surface area of stratospheric sulfuric acid increases rate of hydrolysis of N_2O_5 to form HNO_3



Global stratospheric ozone depletion by the space industry is low (0.03%) at the end of the decade compared to surface sources (~2% in 2022). Depletion by megaconstellations is negligible.

[Barker et al., submitted]

Impact of space industry emissions on stratospheric composition – Aerosols



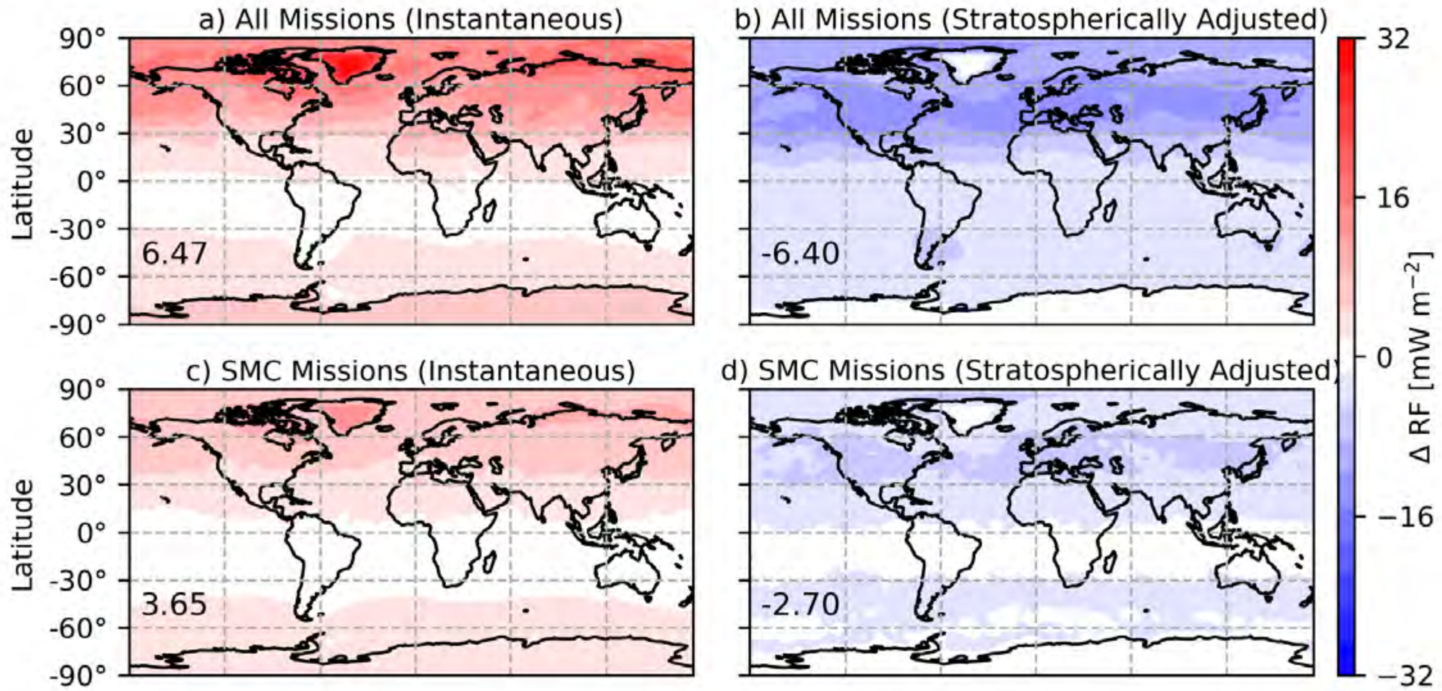
We test sensitivity of our simulations to aluminium re-entry size distribution, finding that is has no effect on ozone depletion.

BC seasonality is governed by northern hemisphere launches, with 44% from SMCs.
Al_2O_3 has peaks in each hemisphere winter, with almost none (3%) from SMCs.

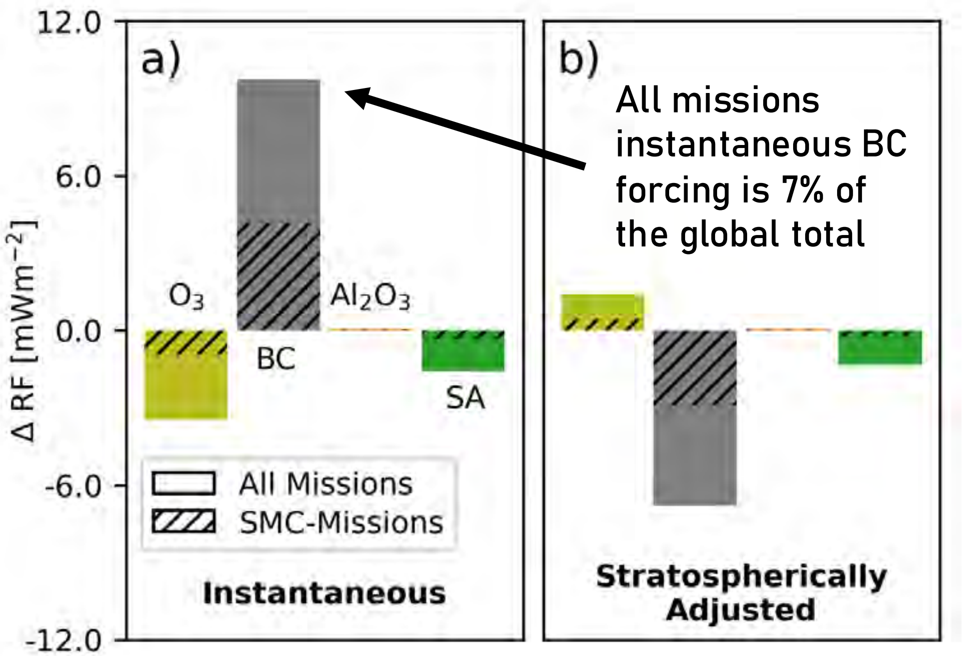
[Barker et al., submitted]

Impact of space industry emissions on radiative forcing

Annual Mean Radiative Forcing in 2029



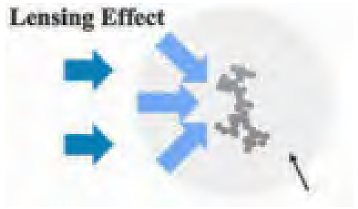
Annual Mean Speciated Radiative Forcing in 2029



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. SMCs inject 44% of BC, so result in 42-56% of BC forcing from SMCs.

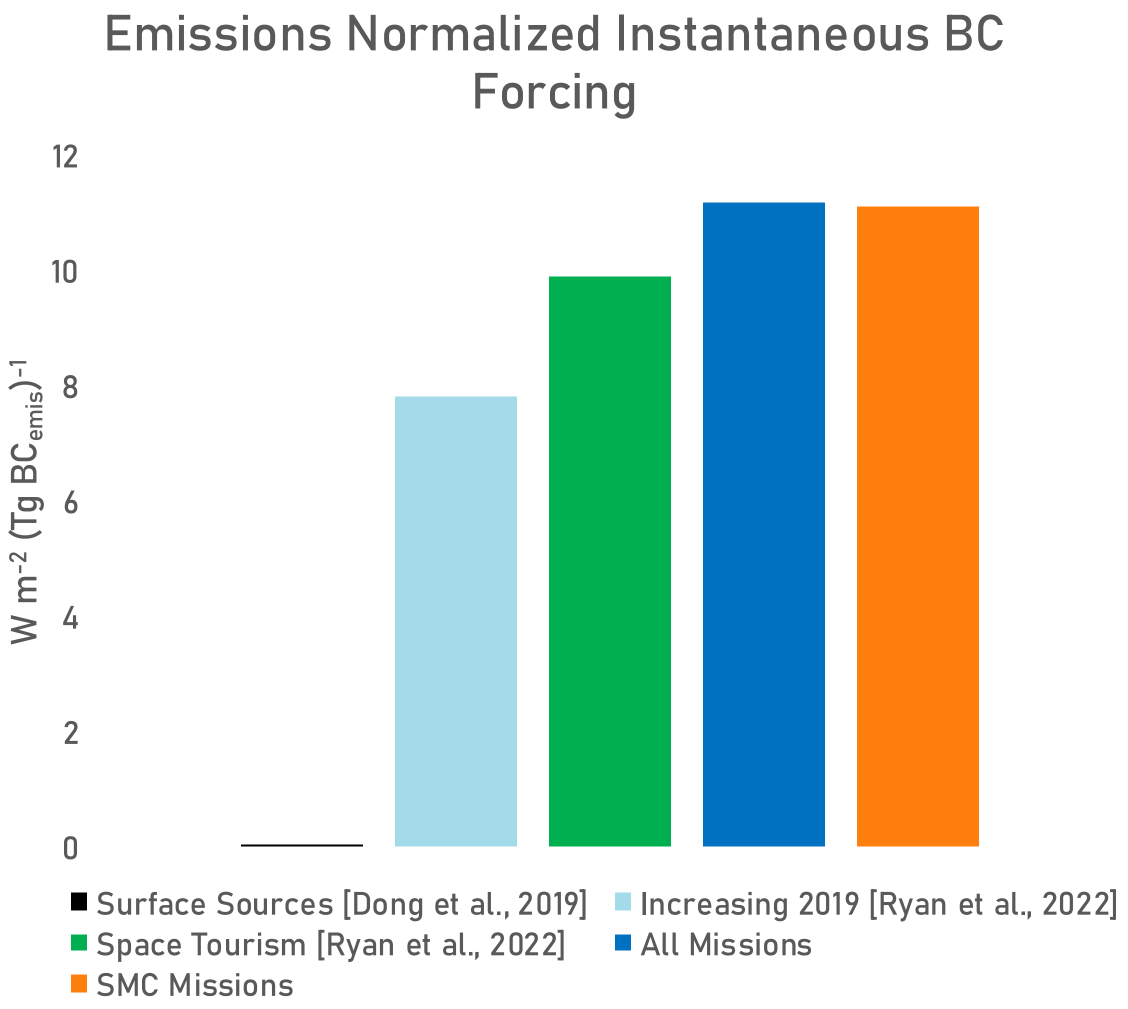
Overall effect is like geoengineering strategies to cool the troposphere, but uncontrolled and untested.

BC absorption is enhanced through the lensing effect

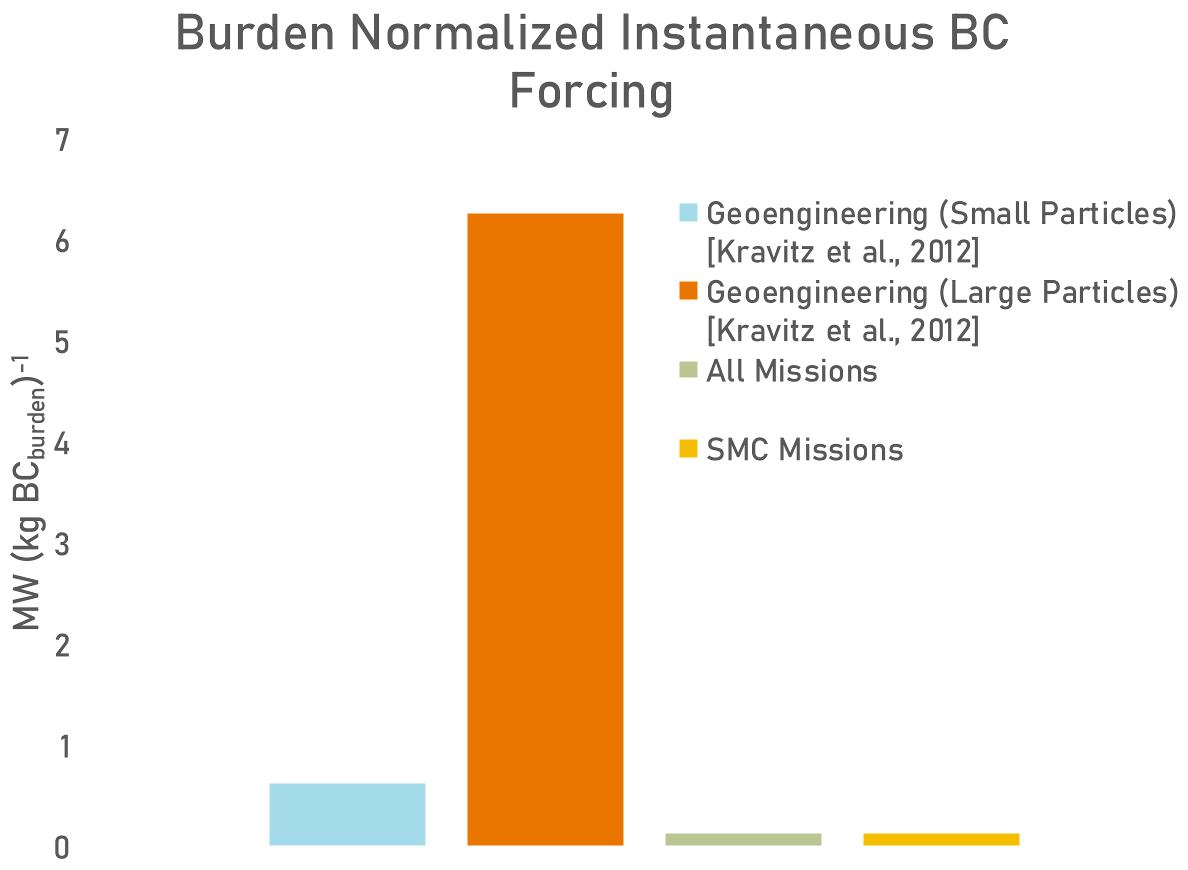


[Barker et al., submitted, Feng *et al.*, 2021]

Impact of space industry emissions on radiative forcing



Normalized BC IRF is ~540 times greater than all Earth-bound sources (Dong et al., 2019)



Normalized BC IRF acts like a geoengineering experiment with small particles (r=0.08µm)

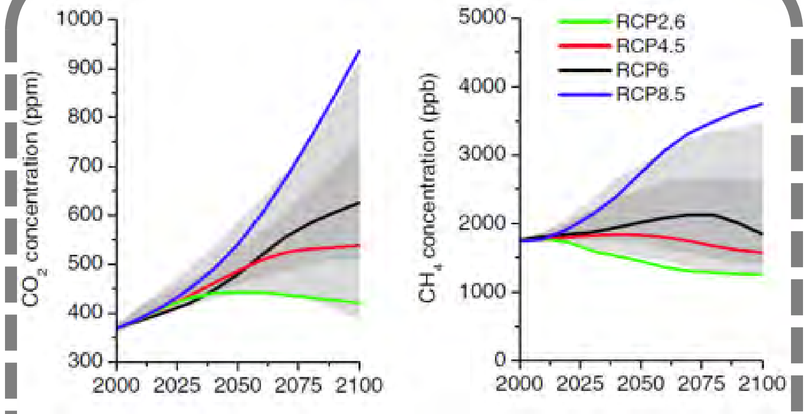
Paths forward for atmospheric modelling and inventory development

1. Emission Inventories → 2. Growth Scenarios → 3. Modelling

Intercomparison of launch and re-entry inventories

- Connor Barker (UCL)
- Leonard Schulz (TUB)
- Jan-Steffan Fischer (Stuttgart)
- Jose Ferreira (USC)
- Laura Revell (Canterbury)

If you are also developing an emission inventory, let me know! (connor.barker@ucl.ac.uk)



Common RCP-like pathways of space sector growth

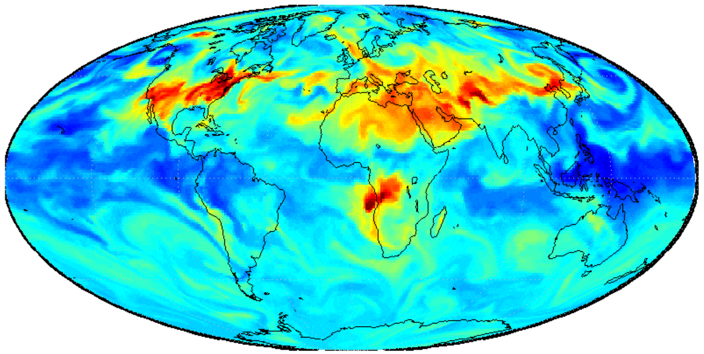
Updated chemistry and climate schemes informed by measurements and observations

Summary

- Implemented an emission inventory for all rocket launches and re-entry mass into a chemistry transport model.
- Global ozone depletion is 0.03% from all mission types, and 0.003% from SMCs, compared to 2% from surface sources.
- SMC launches mostly (98%) use kerosene fuel, emitting large amounts of black carbon but no ozone-depleting Al_2O_3 and chlorine, limiting SMC ozone depletion to 10% of the total.
- 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.
- The space industry is like a geoengineering experiment, but untested and uncontrolled.

GEOS-Chem

+ RRTMG



Check out our space activity emissions trackers!

Contact: Connor Barker
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