Ozone Depletion from Satellite Megaconstellation Emissions

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Environmental impacts of the space industry

Launches (0-80 km)

Hydrogen	H_2O
Kerosene	CO
Methane	CO_2
Hypergolic	BC
Solid	Thermal NO_x
	Fuel NO_x
	Chlorine
	Al_2O_3

Reentries (60-80 km)

Payloads
Components
Capsules
Rocket Bodies
Debris

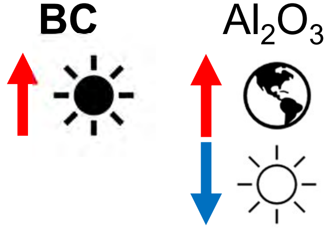
Thermal NO_x
Al_2O_3

Stratospheric O_3 depletion

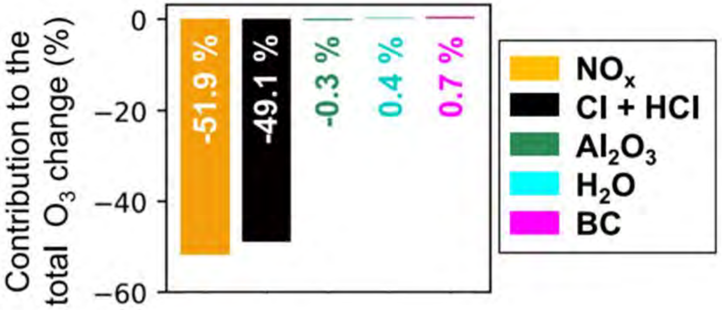
$$X + O_3 \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$
$$\overline{}$$
$$O_3 + O \rightarrow 2O_2$$

Driven by **NO_x, Cl_y, and Al_2O_3**

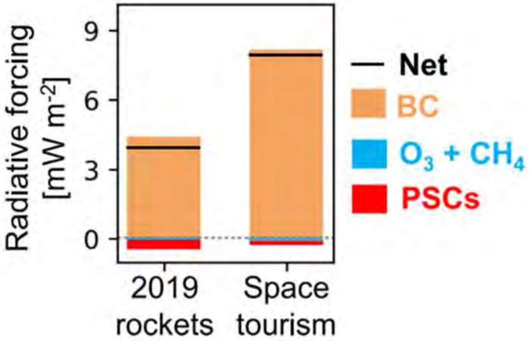
Climate forcing



Impact of a decade of increasing 2019 rocket launch and re-entry emissions



O_3 loss over 60-90°N is ~10% of recovery from Montreal Protocol.



BC emissions drive positive radiative forcing (375x more efficient than surface sources).

[Ryan *et al.* 2022]

Recent developments in the space industry

Onset of the satellite megaconstellation (SMC) era

SpaceX Starlink

↑ 8130

↓ 1008

Eutelsat OneWeb

↑ 660

↓ 6

SMCs are contributing to rapidly increasing launch rates and re-entry mass.

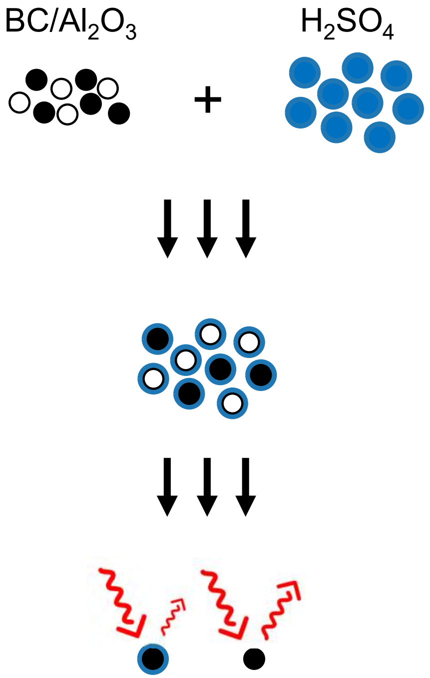
[JSR, 11/09/24]

Understanding of emission chemistry has developed

1° fuel burn emissions (altitude-independent)

2° afterburning emissions (altitude-dependent)

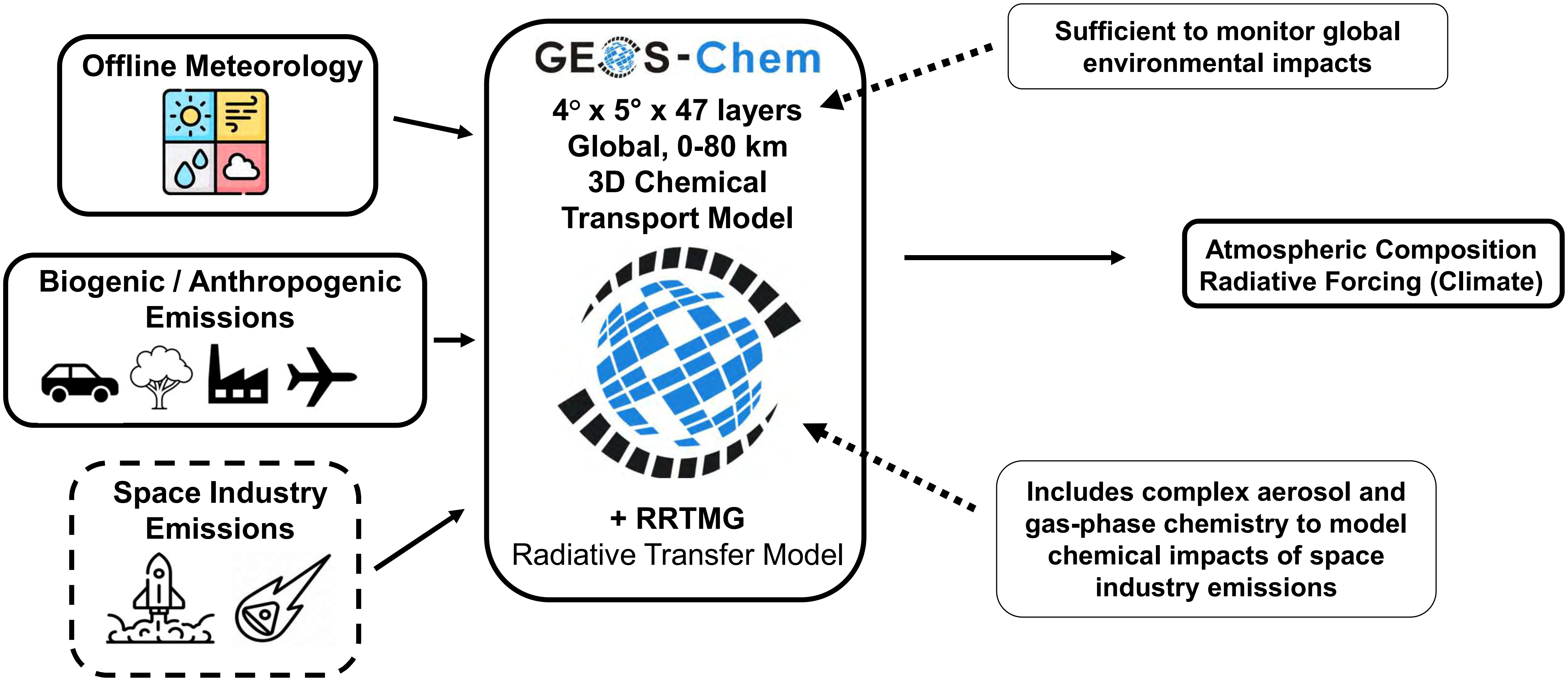
Launch emissions change with altitude depending on oxygen availability



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

[Murphy *et al.*, 2023]

Modelling space industry emissions in a 3D atmospheric chemistry model



Offline Meteorology

Biogenic / Anthropogenic Emissions

Space Industry Emissions

GEOS-Chem

4° x 5° x 47 layers
Global, 0-80 km
3D Chemical Transport Model

+ RRTMG
Radiative Transfer Model

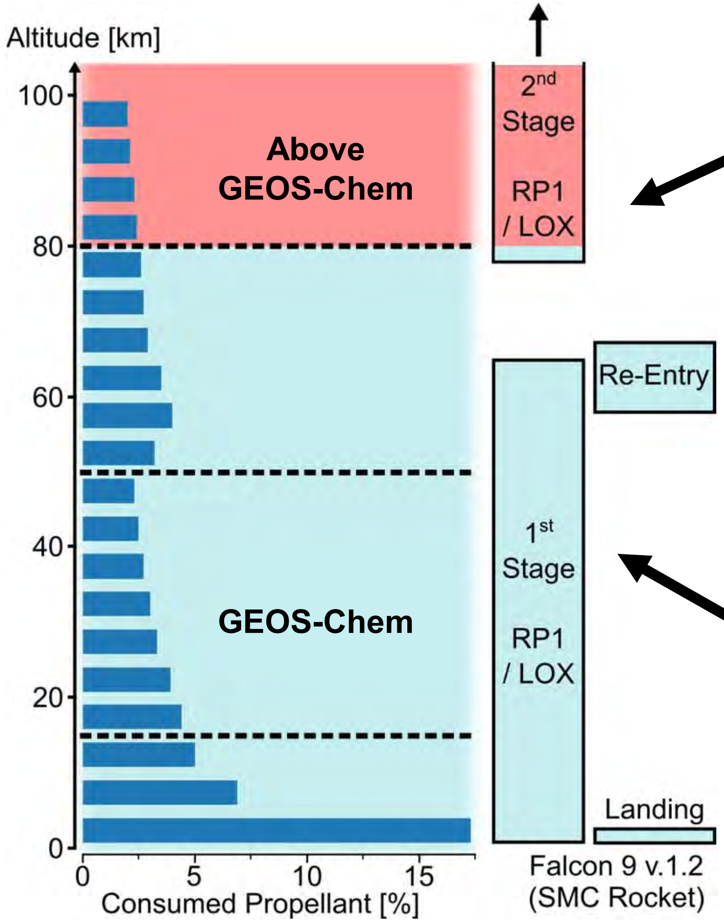
Sufficient to monitor global environmental impacts

Atmospheric Composition
Radiative Forcing (Climate)

Includes complex aerosol and gas-phase chemistry to model chemical impacts of space industry emissions

Developing 3D emission inventories of rocket launches and re-entries

Launch emissions (all atmospheric layers)



Within model range:
- **79% propellant burn**
- **33-98% emissions**

Altitude-dependent emission factors included.

We model the specific altitude range of each rocket stage burn.

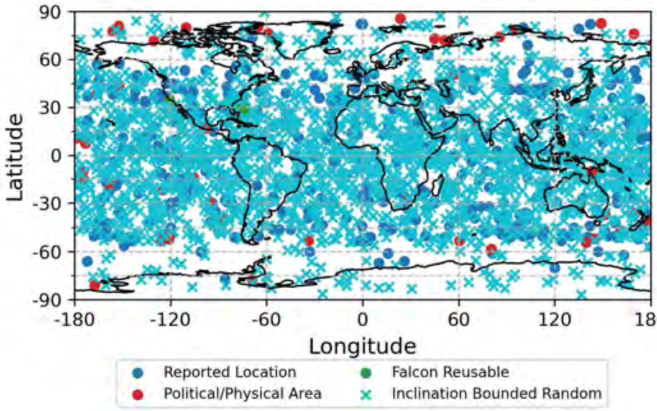
Annual propellant consumption increased from 36-63 Gg in 2020-2022.

Re-entry emissions (60-80 km)

Reusable

Expendable

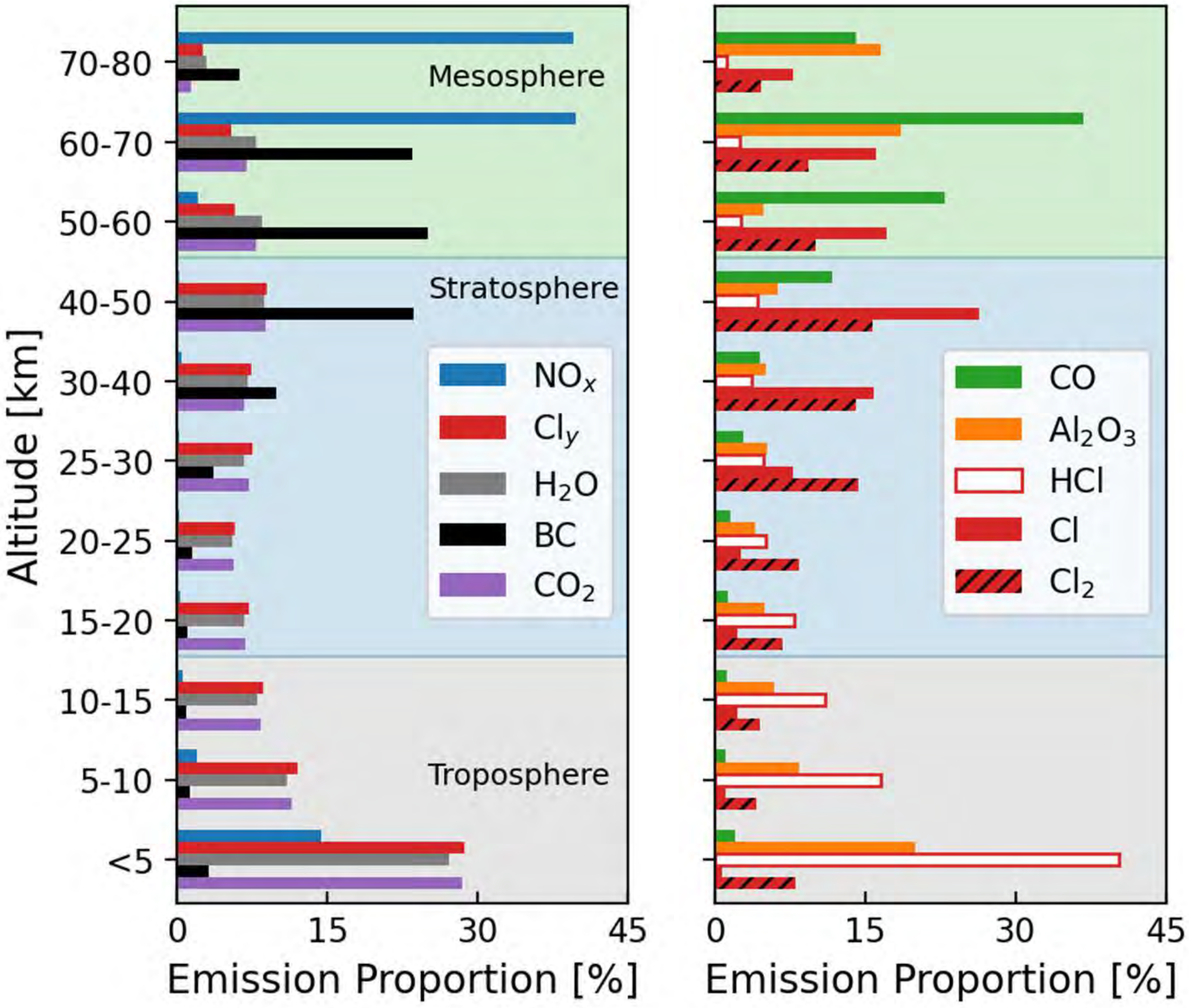
Re-entering Objects (2020-2022)



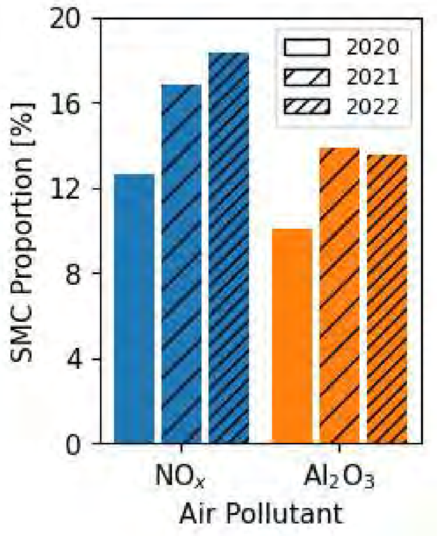
Annual re-entry mass (5 Gg) is now ~40% of natural influx (18-26% SMC). 2 kt unablated mass returns to Earth.

[Ross *et al.* 2014, Barker *et al.*, 2024]

Vertical distribution of emissions for all rocket launches and re-entries (2022)



Re-entry dominates NO_x and Al_2O_3 emissions in the mesosphere.

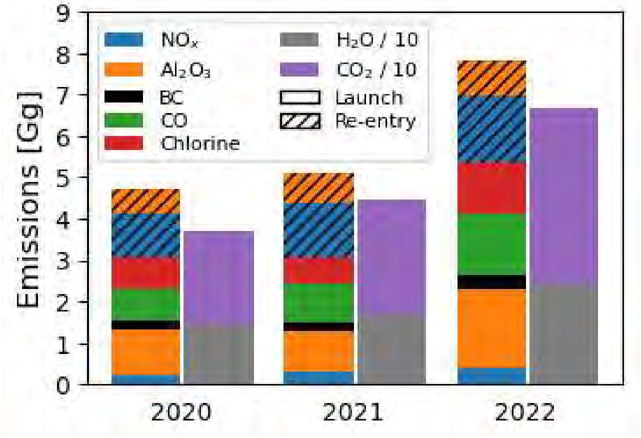


SMC contribution to re-entry emissions is increasing (12-15% in 2022).

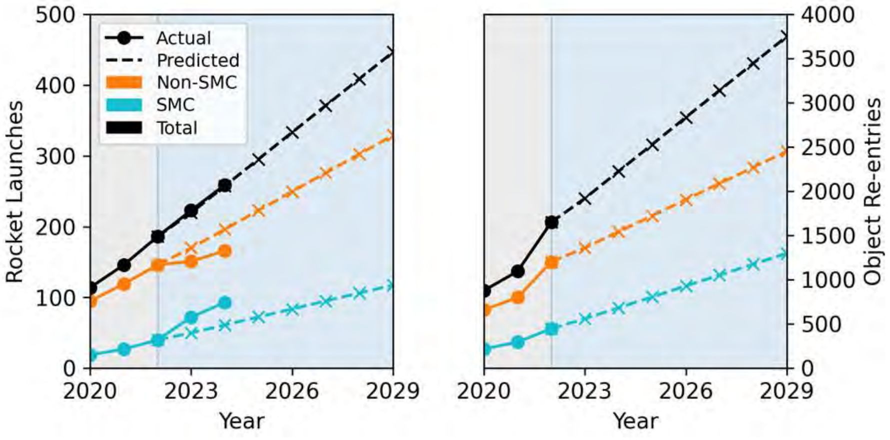
[Barker *et al.*, 2024]

Modelling space industry emissions in a 3D atmospheric chemistry model

42-91% increase in annual emissions in 2020-2022



Emissions projected to 2029



GEOS-Chem

+ RRTMG

2020-2029

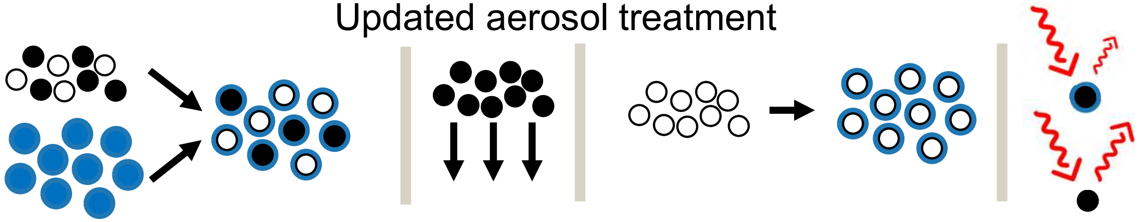
4° x 5° x 47 layers

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

Atmospheric Composition
Radiative Forcing

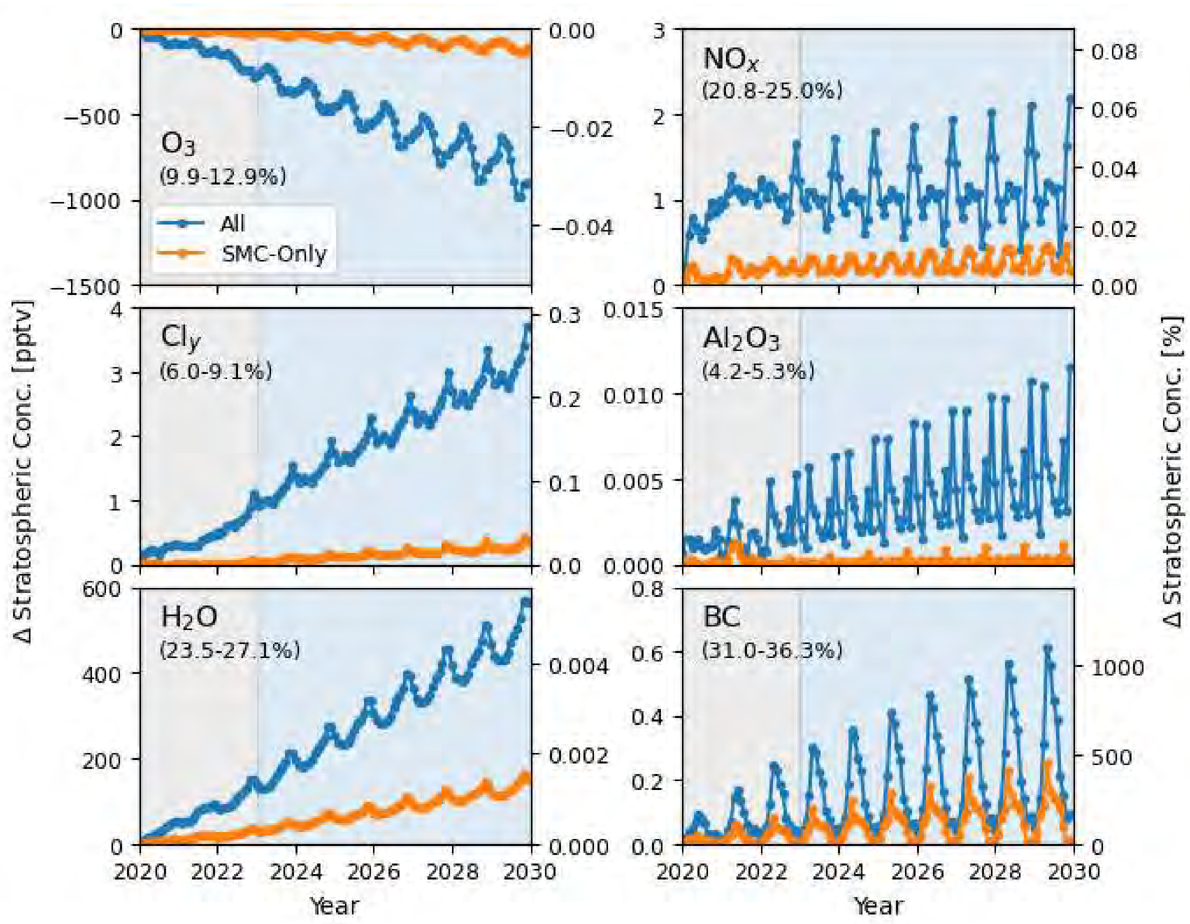
Updated radiative forcing

Updated aerosol treatment



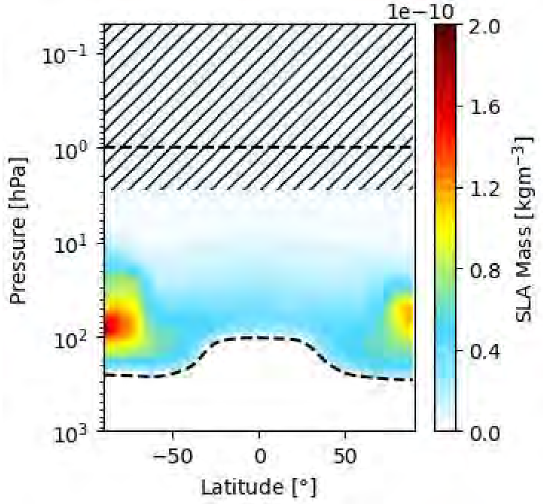
[Barker *et al.*, 2024, *in draft*, IPCC 2007]

Impact of space industry emissions on stratospheric composition



Minimal O_3 loss or increases in ozone depleting emissions (Cl_y, NO_x) from SMCs.

Mean Stratospheric Liquid Aerosol Concentration



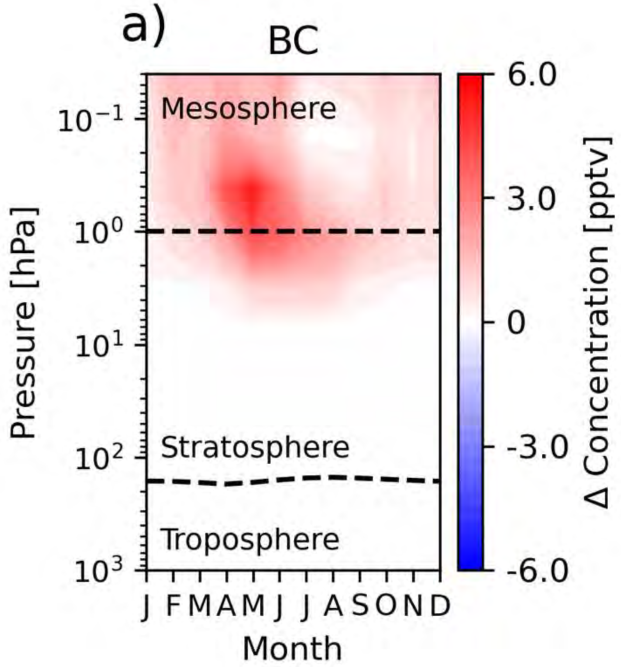
[SLA] < 2 ng m^{-3}

Stratospheric ozone depletion remains low (0.03%) at the end of the decade compared to surface sources (~2% in 2022).

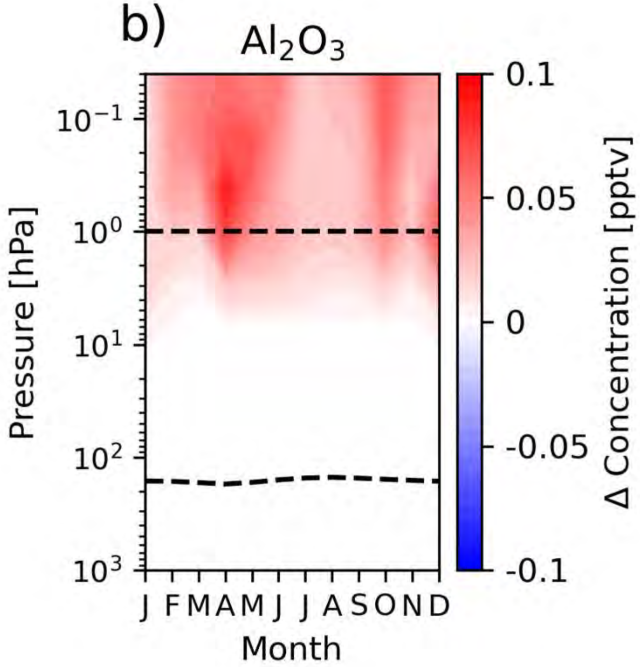
[Barker *et al.*, *in draft*]

Uptake of particulate emissions by stratospheric sulfate

Annual mean aerosol concentration (2020-2029)

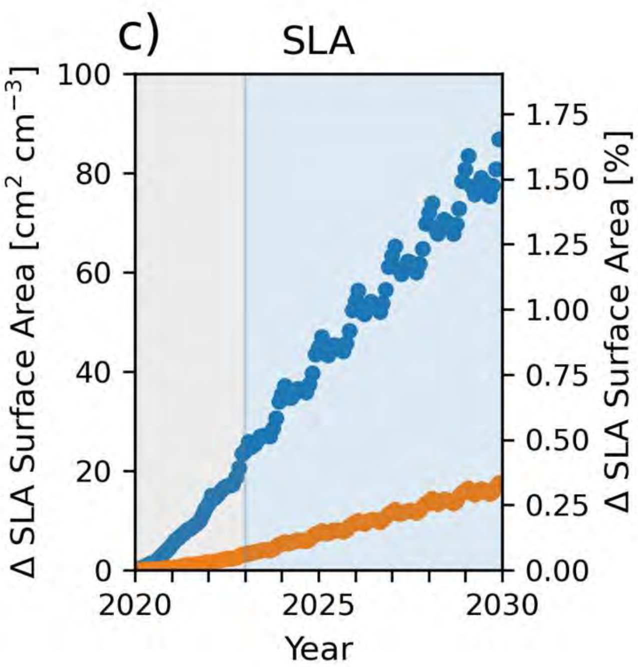


BC ($r = 0.035$ μm) particles slowly settle, and mesospheric concentration increases in spring-summer.



Larger Al_2O_3 particles ($r = 0.14$-4.5 μm) rapidly settle, but concentration increases are still limited to the mesosphere and upper stratosphere.

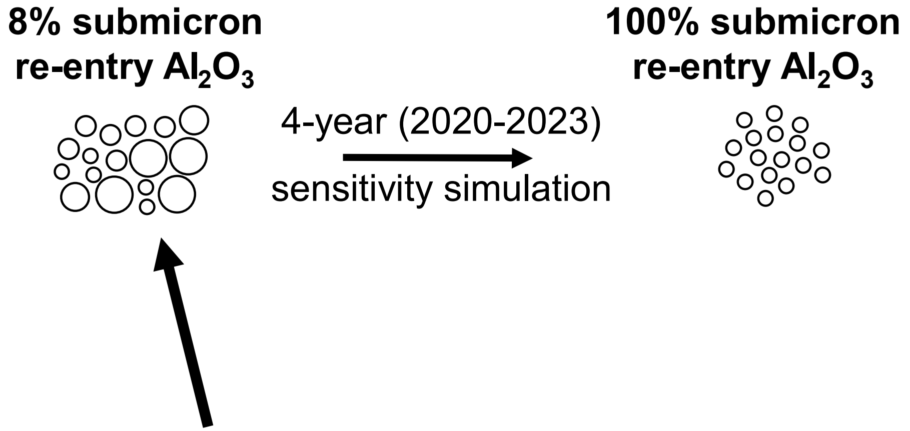
Monthly mean stratospheric liquid aerosol surface area



Uptake to sulfate removes BC and Al_2O_3 below the upper stratosphere, reducing potential to deplete ozone but increasing SLA surface area.

[Barker *et al.*, *in draft*]

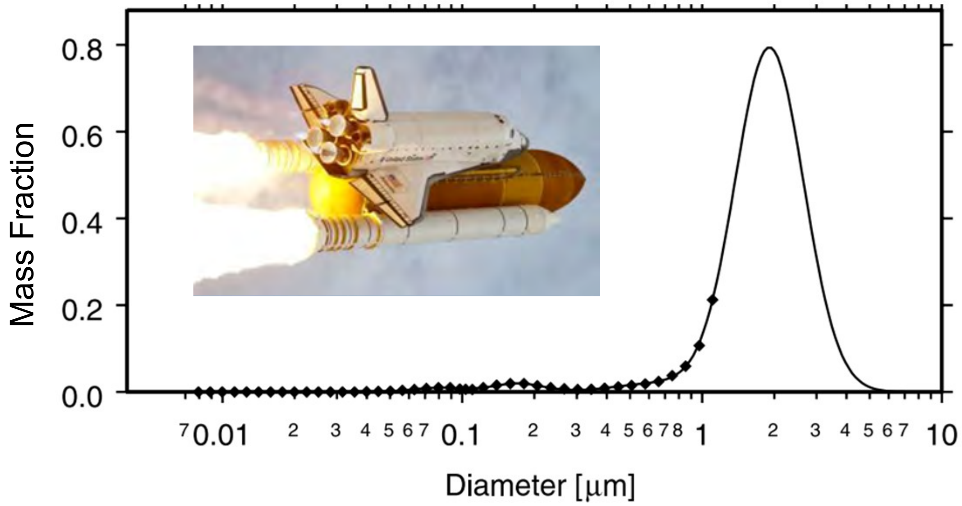
Alumina size distribution affects ozone depletion



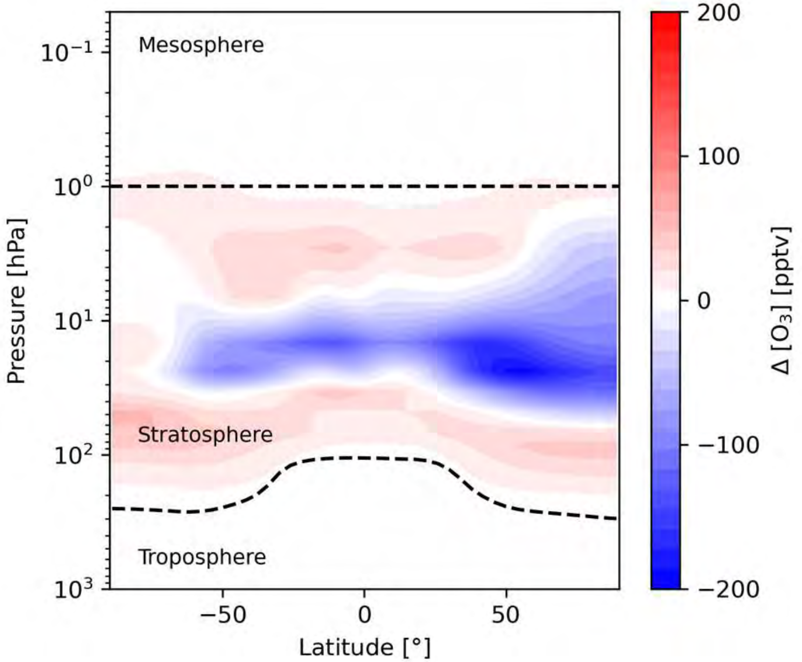
8% submicron re-entry Al_2O_3

4-year (2020-2023)
sensitivity simulation

100% submicron re-entry Al_2O_3



Annual mean change in O_3 concentration in 2023

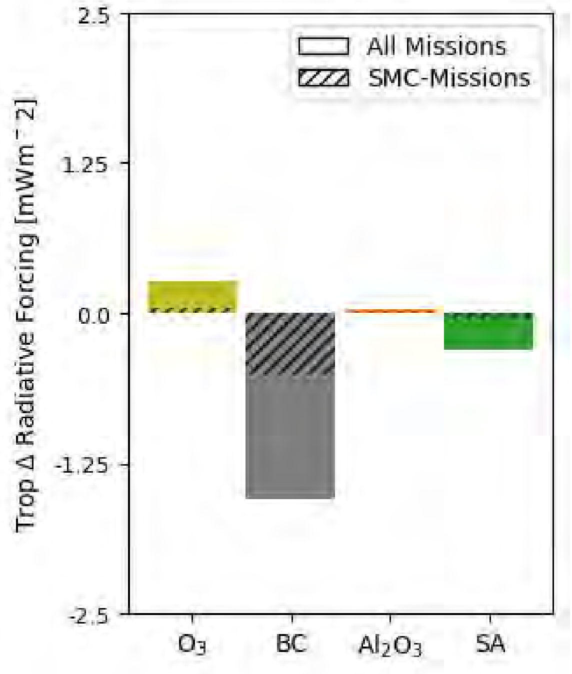


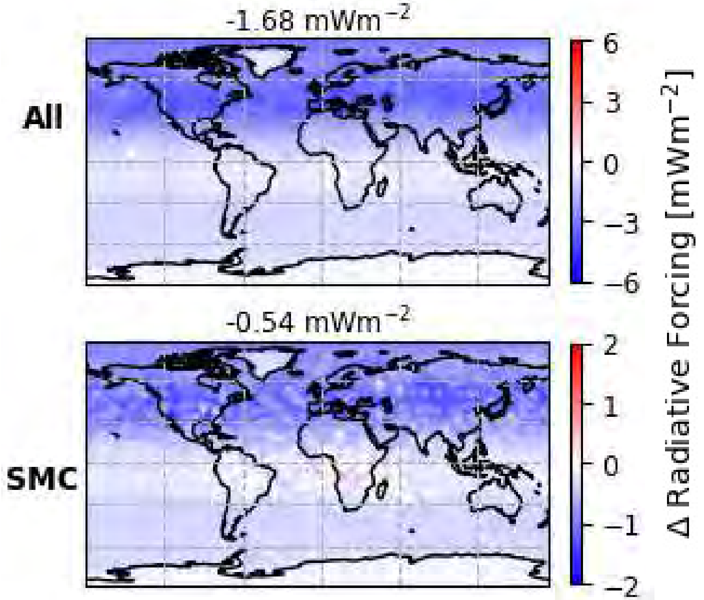
Negligible (0.0002%) global change in ozone, but ozone depletion shifts towards the mid-stratosphere

[Barker *et al.*, *in draft*]

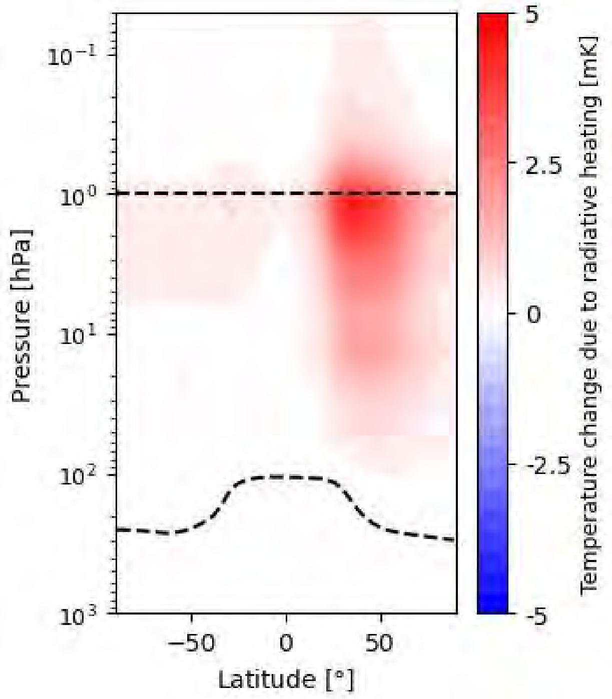
Impact of space industry emissions on radiative forcing

Annual Mean Radiative Forcing in 2022 at Tropopause

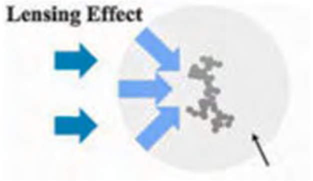




Temperature Change in 2022



SW absorption of SW by black carbon dominates, enhanced by sulfate coating



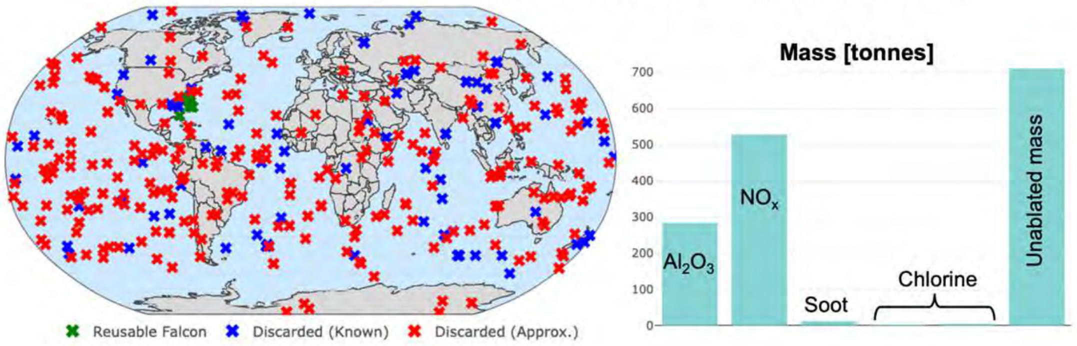
Overall effect is warming of the stratosphere and a negative flux at the tropopause.

[Barker *et al.*, *in draft*, Feng *et al.*, 2021]

Summary

- **Developed an emission inventory for all rocket launches and re-entry mass for 2020-2022.**
- **Modelling shows that SMCs cause negligible O_3 depletion compared to other mission types (~13% of total), due to kerosene fuel.**
- **Rocket launch and re-entry emissions cause stratospheric warming and tropospheric cooling.**
- **Sensitivity simulations demonstrate that the size distribution of re-entry derived Al_2O_3 affects the location of ozone depletion.**

Object re-entry events and emissions for January-June 2021



Emission Inventory published
in Nature Scientific Data

Rocket Launch and Re-entry
Emission Trackers

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[Images from SpaceX, OneWeb, ULA, and media reports]