Quantifying the emissions and modelling the environmental impacts of rapidly growing satellite megaconstellations

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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

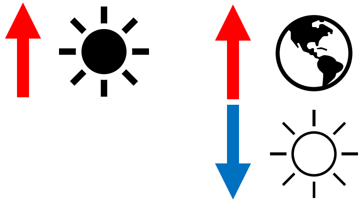
Thermal NO_x
Al_2O_3

Stratospheric O_3 depletion

Driven by **NOx, Cly, and Al_2O_3**

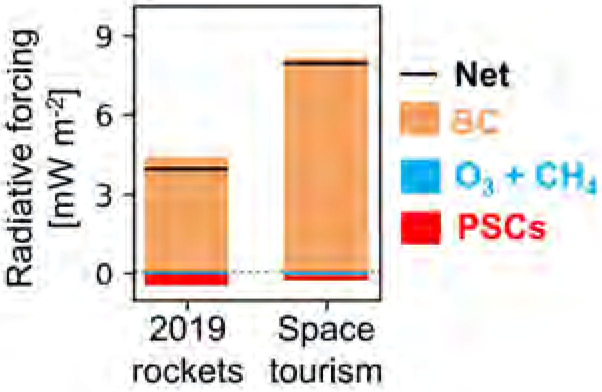
Climate forcing

BC Al_2O_3



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

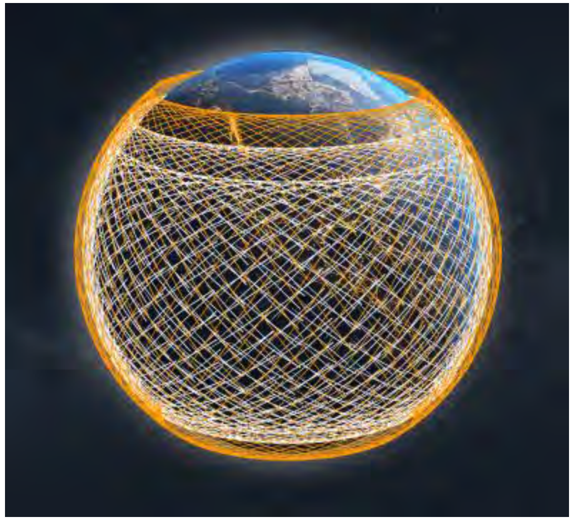
O_3 loss over 60-90°N is ~10% of recovery from Montreal Protocol.



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

[Ryan *et al.* 2022]

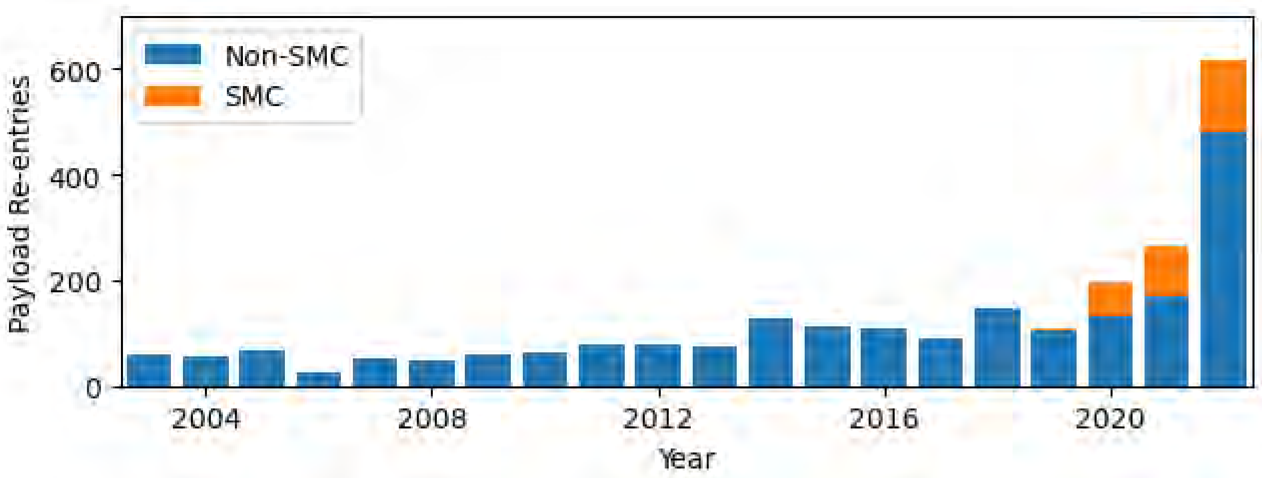
The onset of the satellite megaconstellation (SMC) era

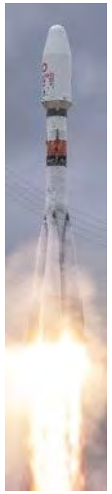


SpaceX Starlink

↑ 7001

↓ 607





Eutelsat OneWeb

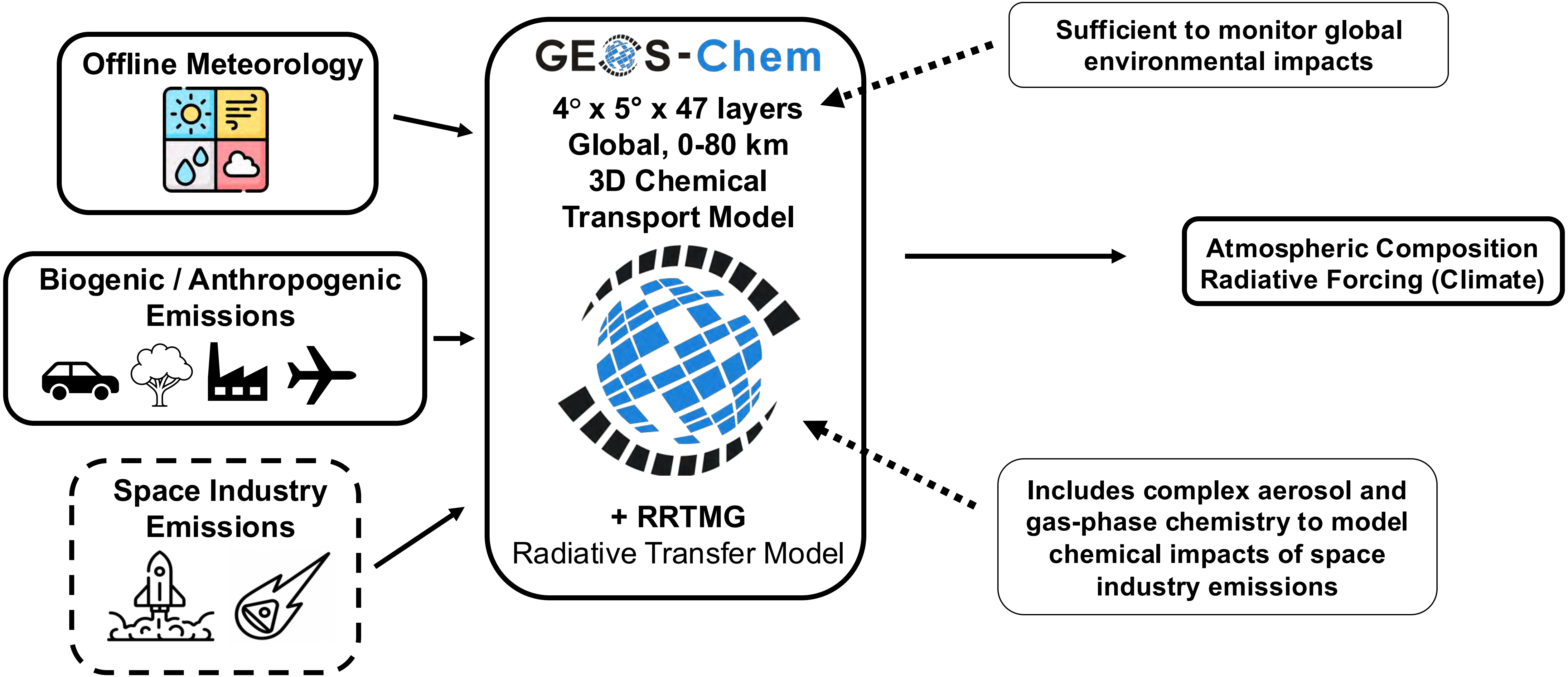
↑ 640

↓ 6

>1 million megaconstellation satellites filed, 60-100k expected to be launched.
New sustainability and debris guidelines will contribute to rapidly increasing launch rates and re-entry mass.

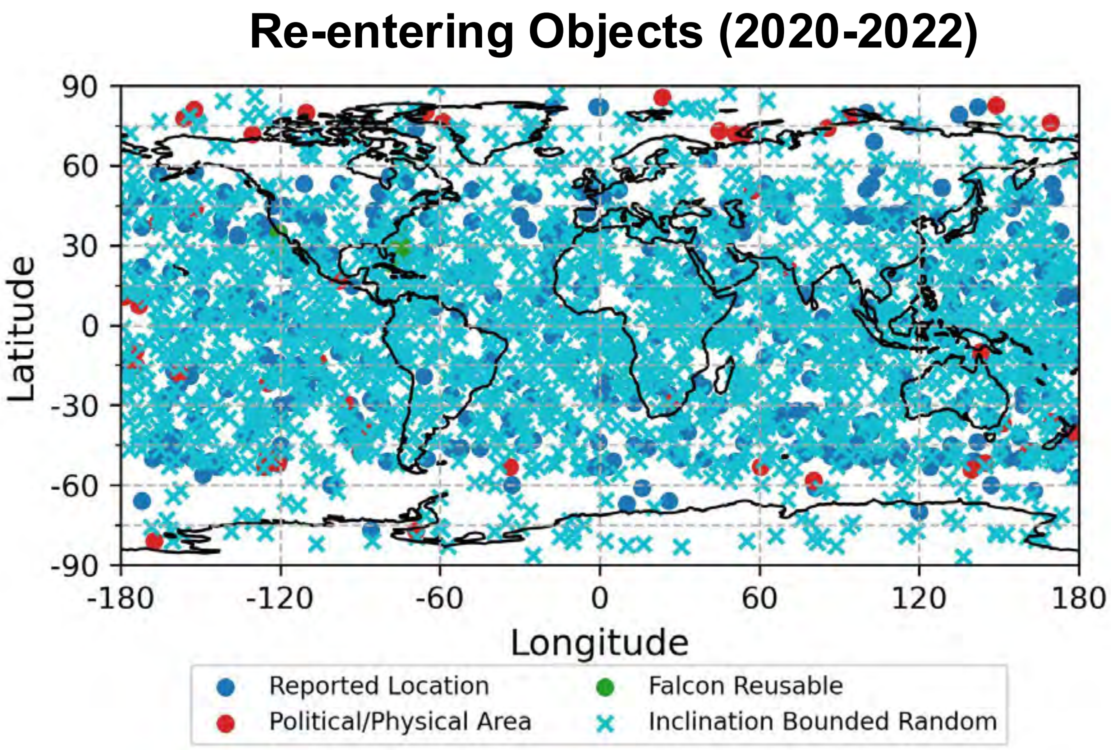
[JSR, 11/09/24]

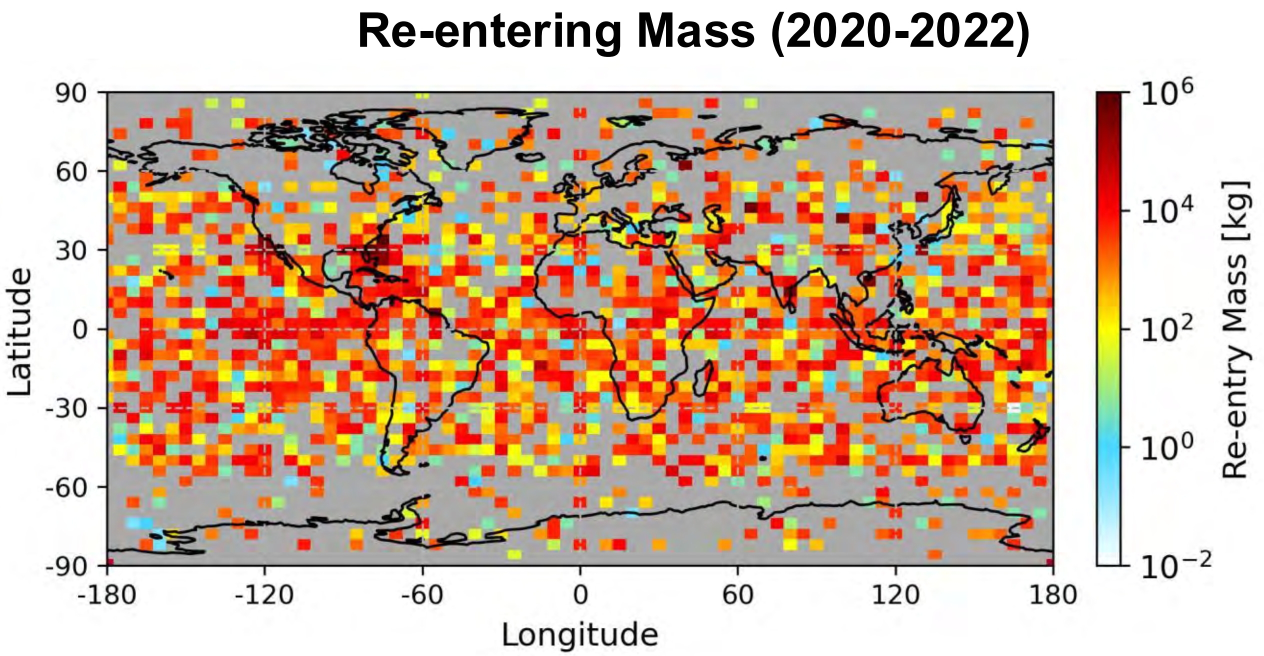
Modelling space industry emissions in a 3D atmospheric chemistry model



[IPCC 2007]

Global 3D mapping of re-entry mass





Annual re-entry mass (5 Gg) is now ~40% of natural influx.

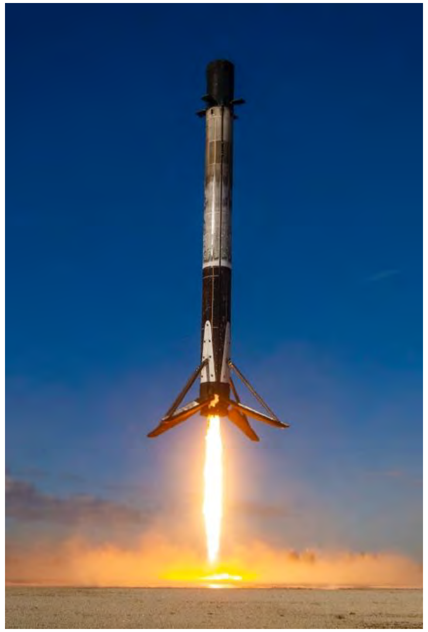
2020 – 3.15 Gg - 878 objects – 18% SMC
2021 – 3.75 Gg - 1095 objects – 22% SMC
2022 – 4.97 Gg - 1649 objects – 26% SMC

Increasing re-entry mass driven by satellite megaconstellations

[Barker *et al*., accepted]

Conversion of re-entry mass to upper atmosphere emissions

Reusable Objects



17.5% → NO_x

0% → Al_2O_3

Expendable Objects

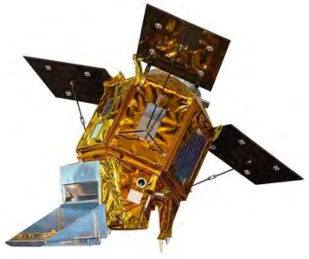
Composition:

Rocket Stages
70% Al

Survivability:

70% Core
35% Upper

Payloads
40% Al



0% SMC
20% Non-SMC

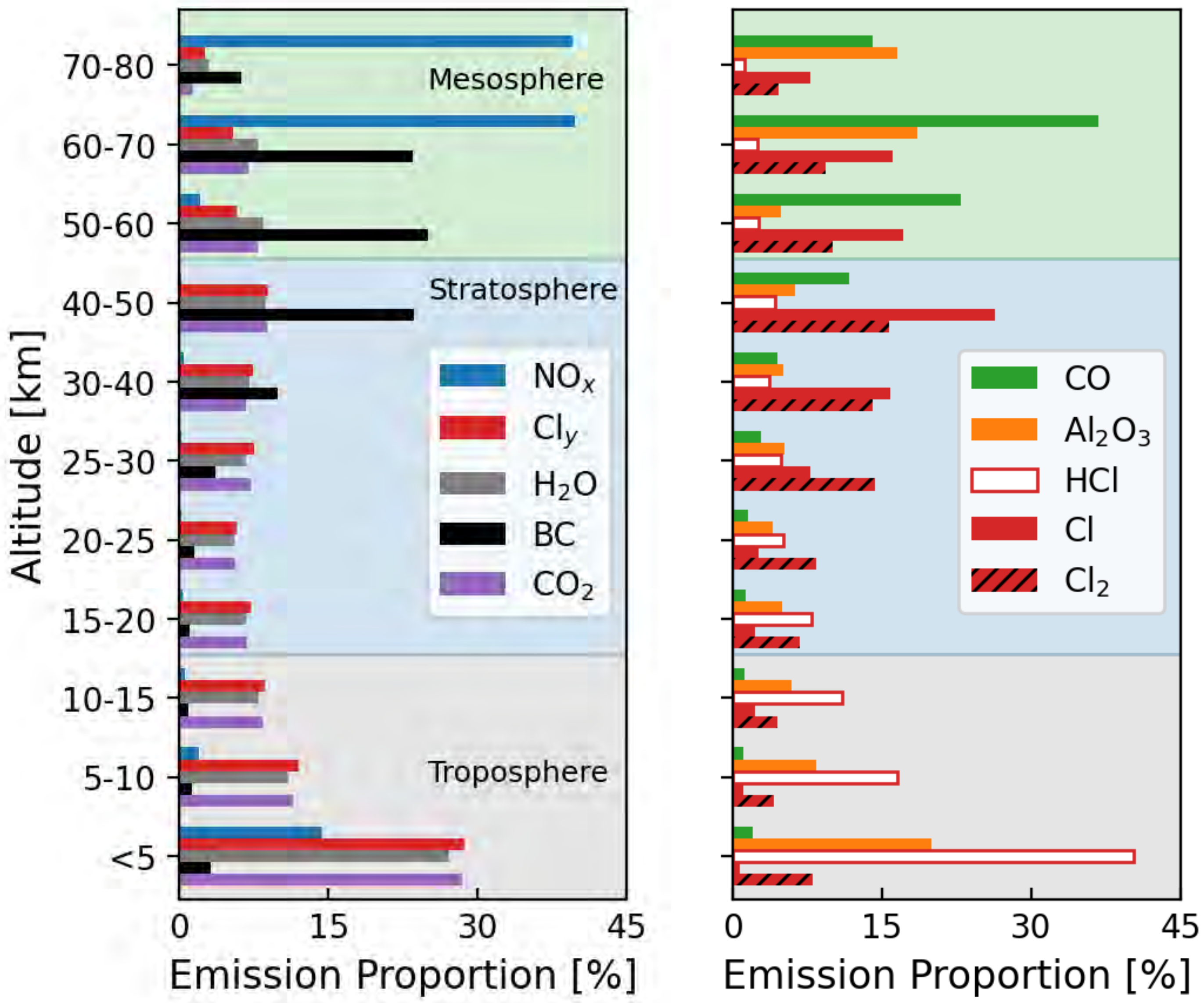
40% → NO_x

Variable % → Al_2O_3

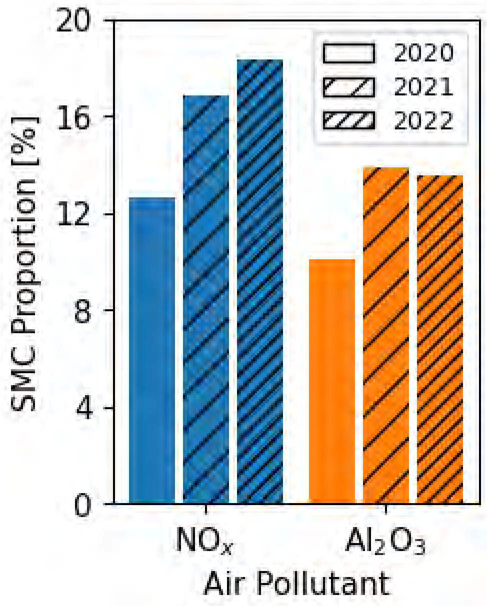
Our results imply 2 kilotonnes of unablated mass return to Earth annually, with potential risk to life.

[Schulz, L. & Glassmeier, K. H. 2021, Jain 2023]

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



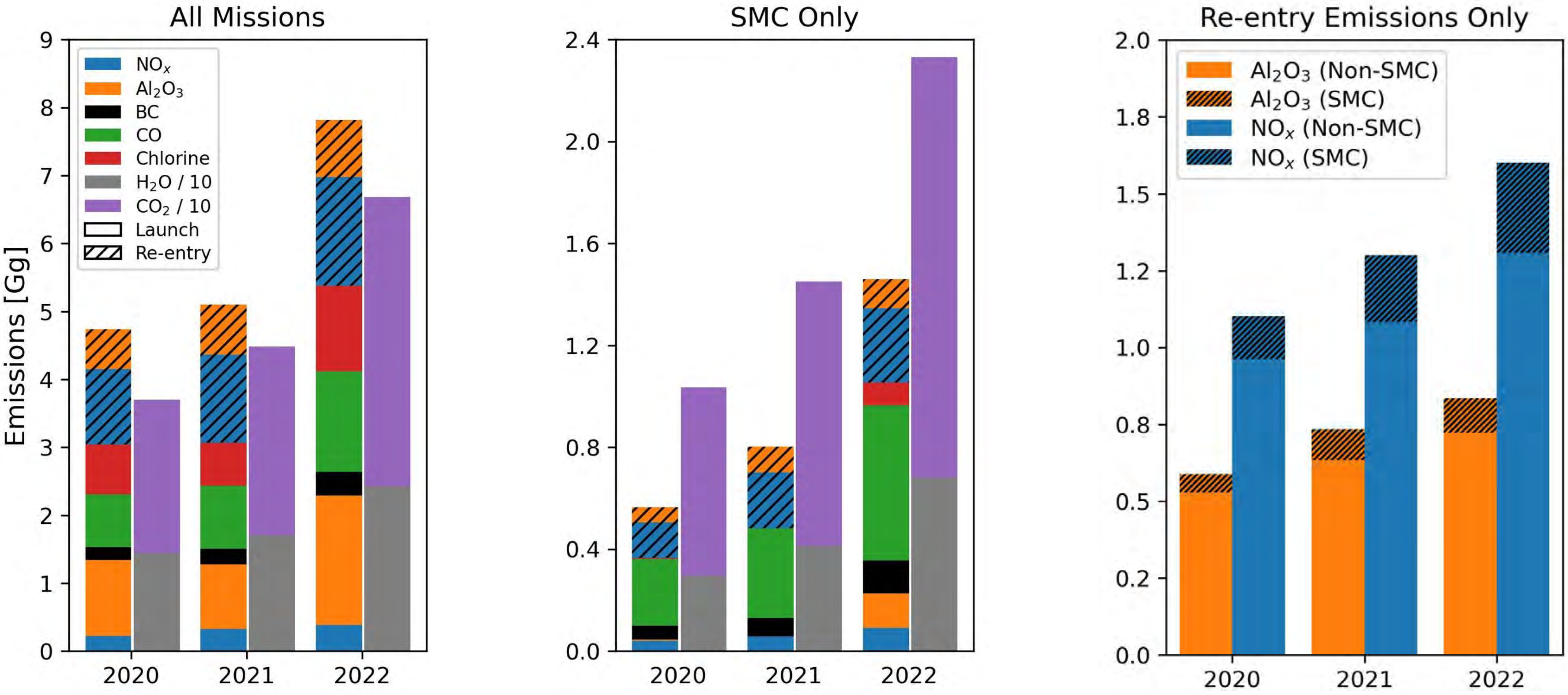
Re-entry dominates NO_x and Al_2O_3 emissions in the mesosphere.



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

[Barker *et al*., accepted]

Growth in rocket launch and re-entry emissions (2020-2022)



Re-entry emissions of Al_2O_3 and NO_x are approaching the natural influx.

Doubling of annual re-entry emissions from SMCs.

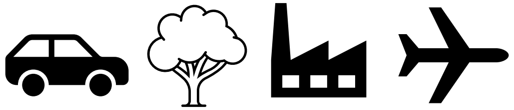
Emission Inventory
DOI: 10.5522/04/26325382
Barker and Marais 2024

[Barker *et al*., accepted]

Modelling space industry emissions in a 3D atmospheric chemistry model

Offline Meteorology

Biogenic / Anthropogenic Emissions



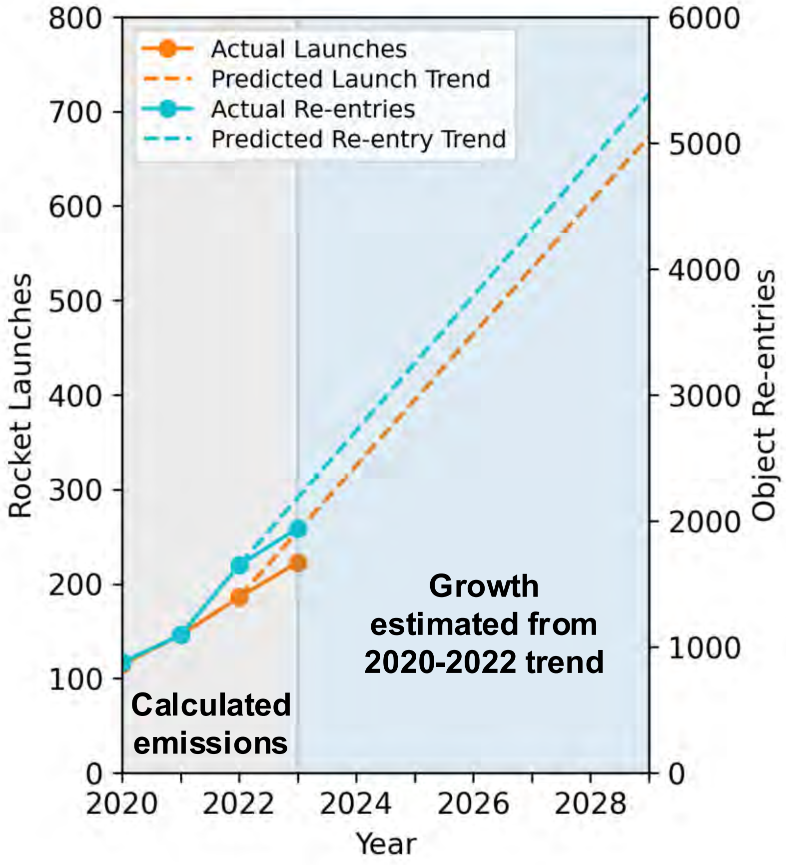
Space Industry Emissions

GEOS-Chem + RRTMG

Three Simulations (2020-2029)

1. No rocket/re-entry emissions
2. All rocket/re-entry emissions
3. SMC rocket/re-entry emissions only

Projected Space Industry Growth

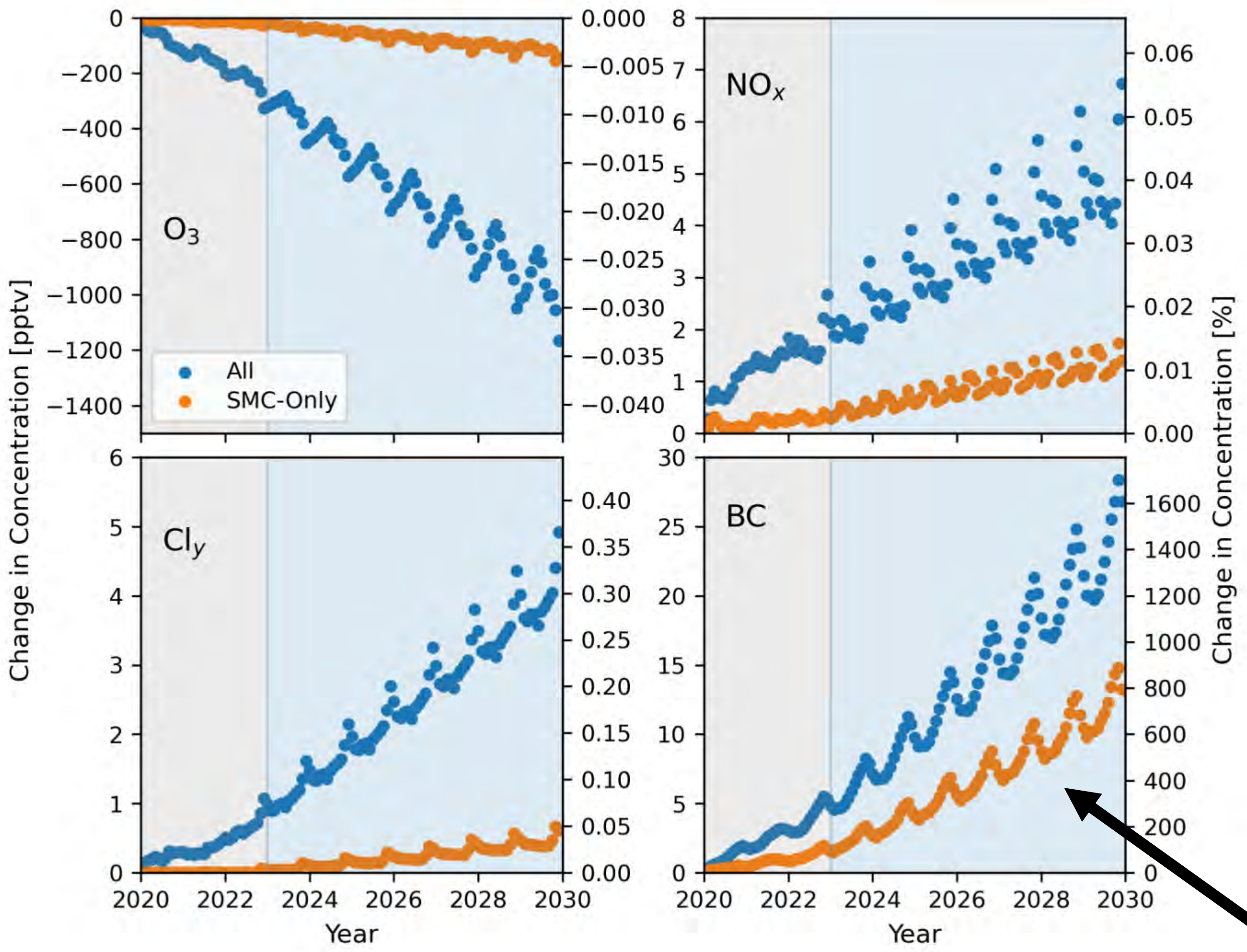


Specific growth rates applied to SMCs and non-SMCs, but large uncertainties remain.

[IPCC 2007]

Impact of space industry emissions on stratospheric composition

Effect of air pollution on the stratosphere



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

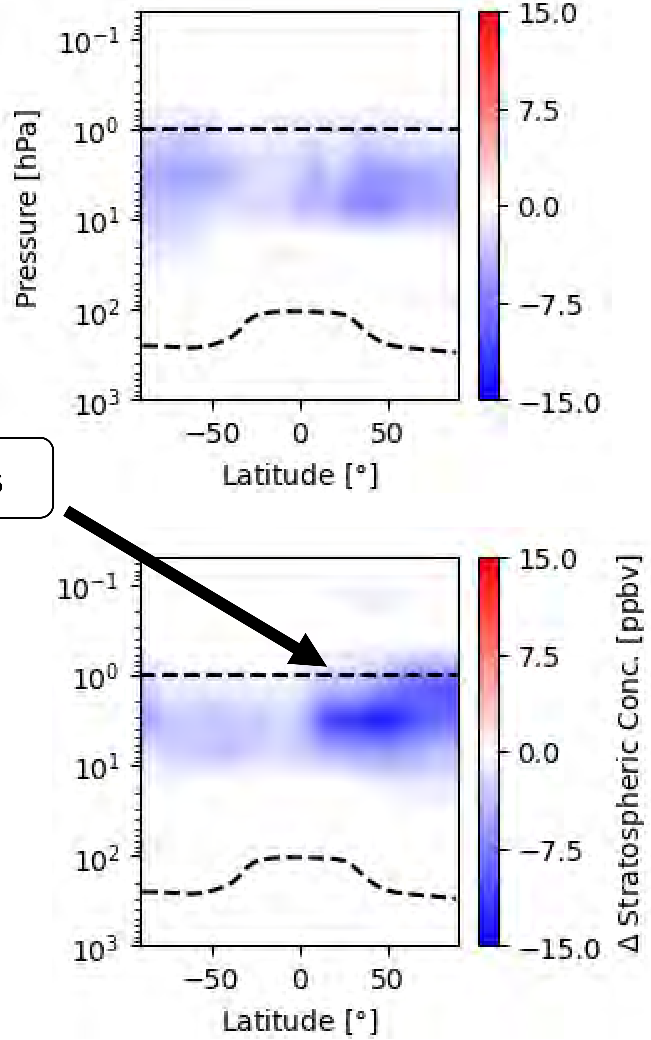
>50% of BC is from SMCs

Ozone depletion in 2029 from all missions

July

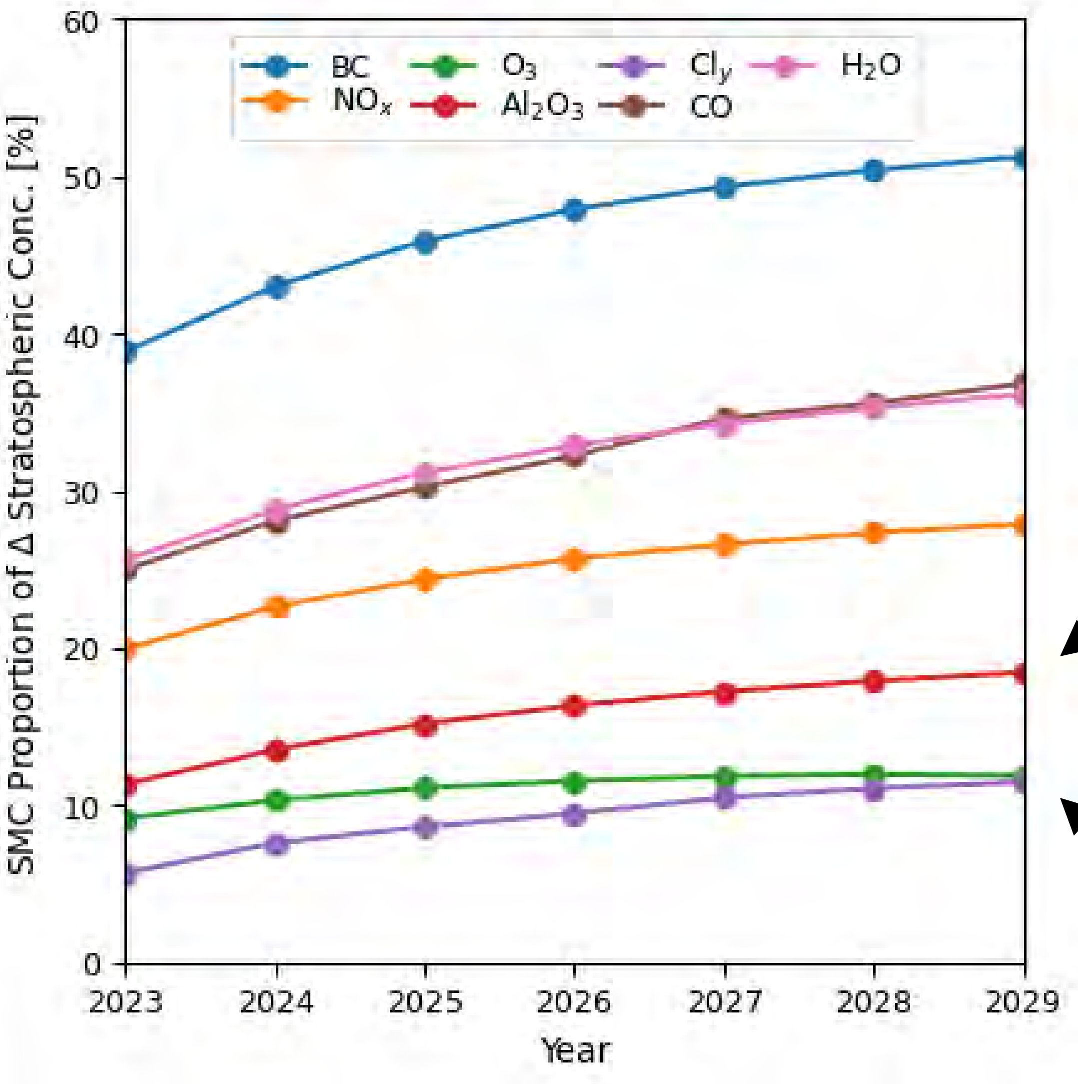
December

Peak O_3 loss



Annual contribution of SMCs to stratospheric concentration changes

Increasing impact of SMCs on stratospheric concentration.

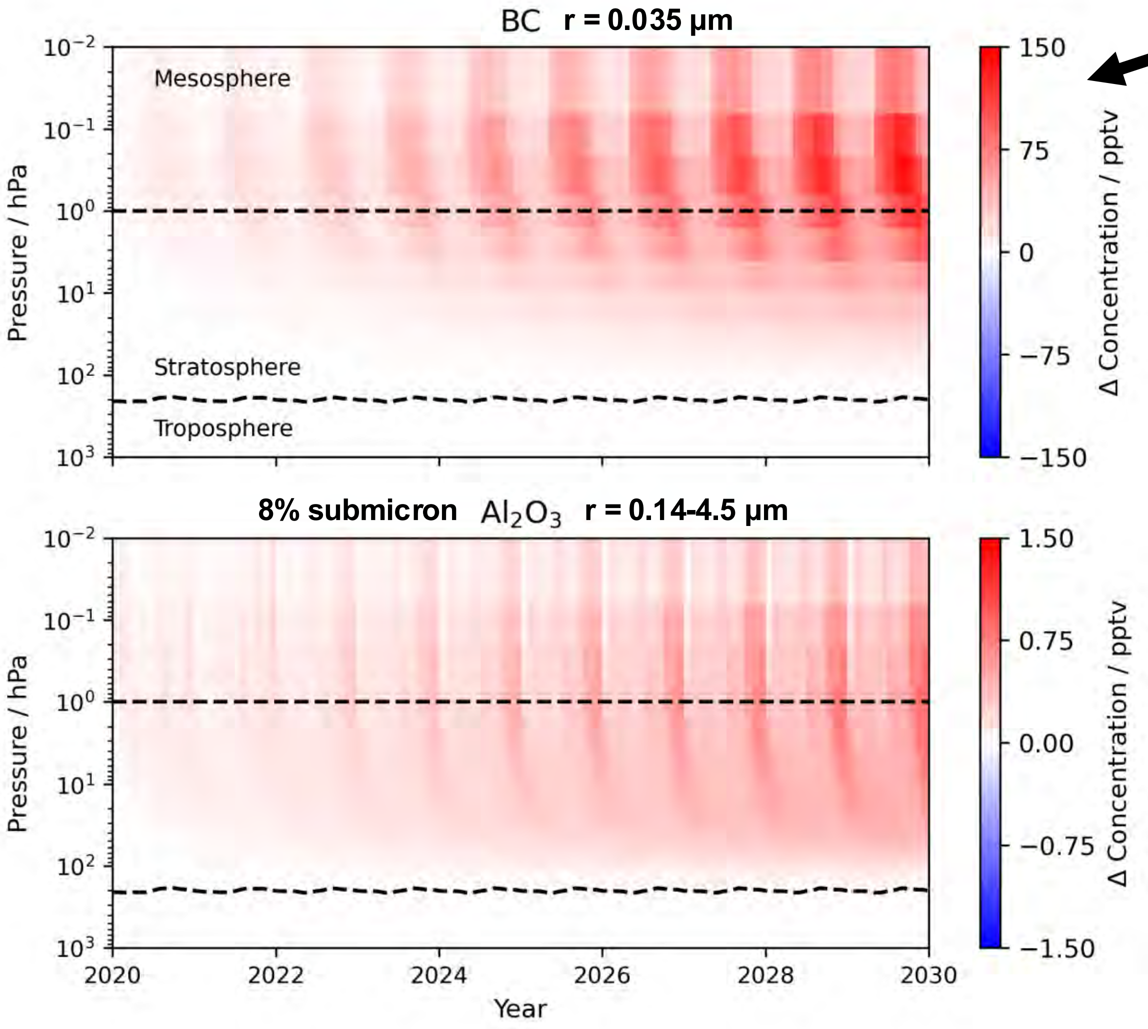


SMCs contribute 18% of Al_2O_3, ~half from re-entry.

SMCs are responsible for ~12% of O_3 depletion.

Particle-phase emissions from rocket launches and re-entries

Particle-phase concentrations from all mission types



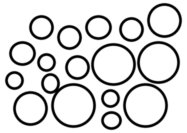
BC remains in mesosphere with seasonal settling.

Al_2O_3 rapidly sediments upon release, reducing atmospheric lifetime.

The size distribution of re-entry Al_2O_3 directly affects environmental impacts and needs further study.

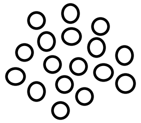
Using the model to assess the impact of uncertainties

8% submicron re-entry Al_2O_3

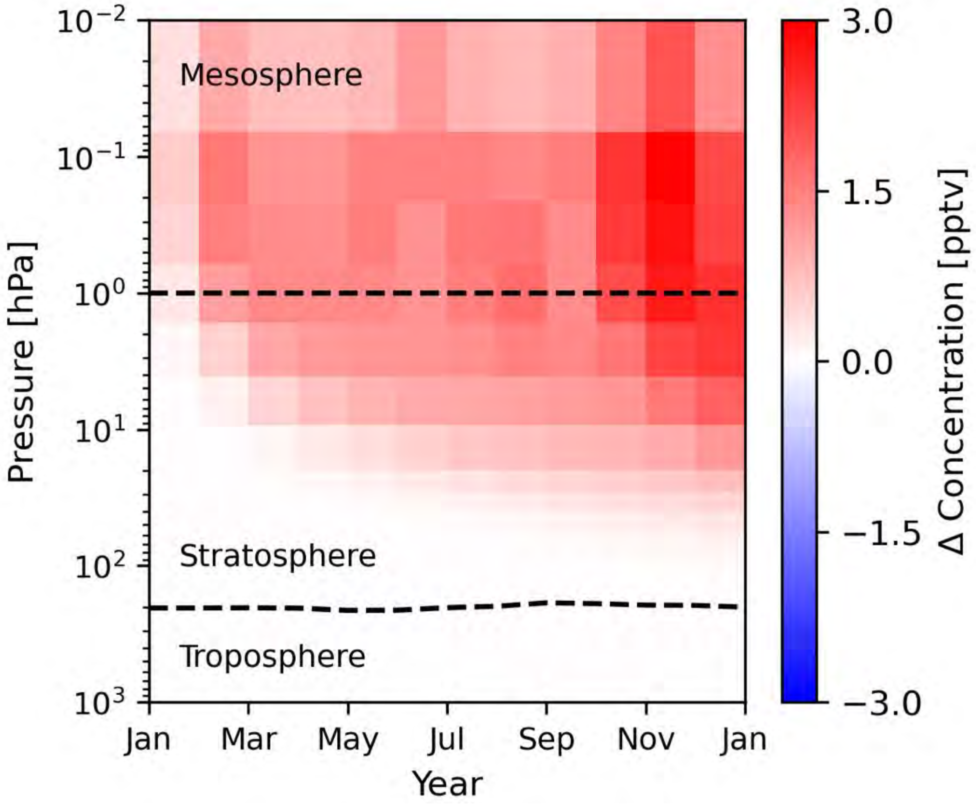


1-year (2023)
sensitivity simulation

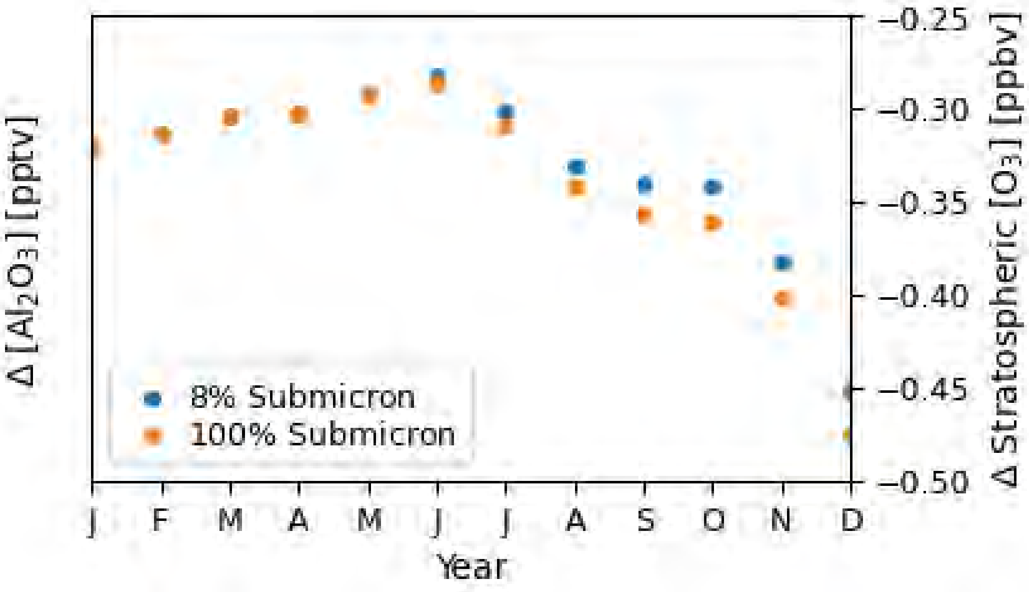
100% submicron re-entry Al_2O_3



Effect on concentration

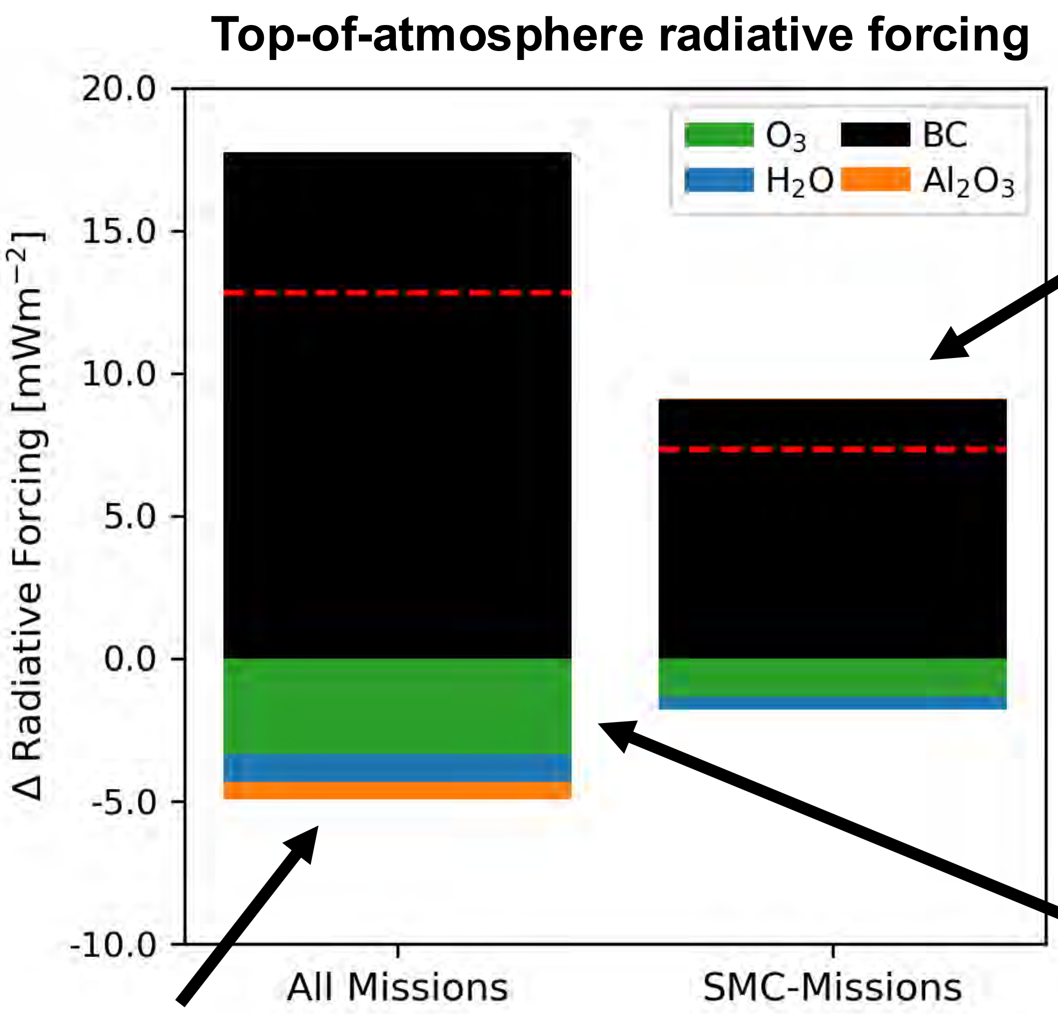


Effect on O_3 depletion



Our results show that decreasing uncertainties in re-entry Al_2O_3 size distribution will constrain O_3 depletion estimates.

Instantaneous radiative forcing from each emission species



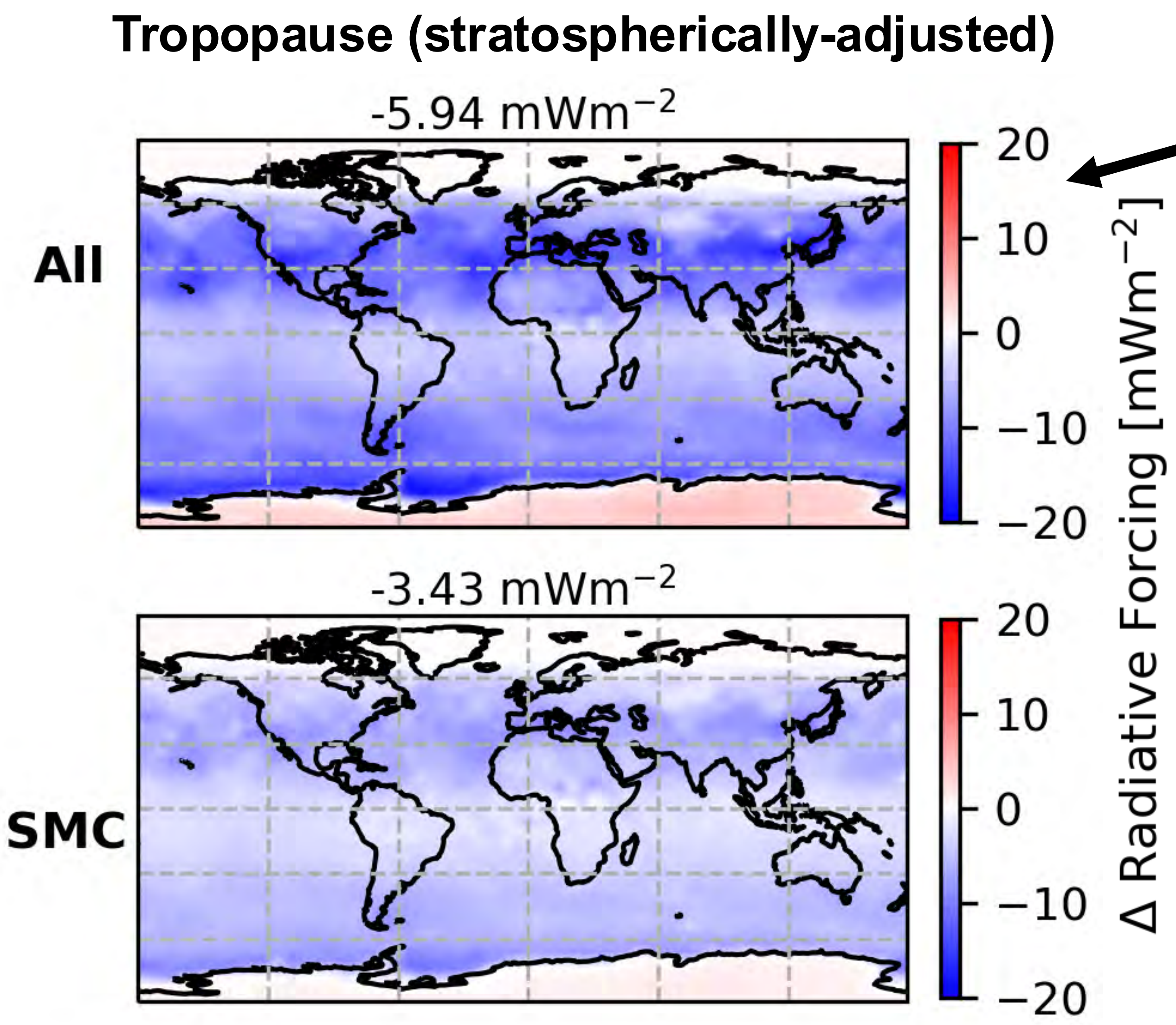
BC dominates warming through absorption of shortwave radiation

Greater understanding of the optical, chemical, and physical properties of particle-phase re-entry emissions will help to constrain the radiative impacts

NO_x emissions deplete O_3 leading to negative forcing

Al_2O_3 emissions only result in a very small negative forcing

Impact of space industry emissions on radiative forcing



Negative flux at tropopause due to BC absorption above the tropopause.

SMCs again contribute >50% of the radiative flux

Rocket launch and re-entry emissions affect radiative forcing throughout the atmosphere.

Summary

- **Re-entry mass and emissions quantified and geolocated for 2020-2022 (accepted).**
- **Simulations demonstrate immediate impacts on ozone and climate (in draft).**
  - SMCs cause negligible O_3 depletion (~12% of total) but lead to large changes in radiative forcing (>50% of total).
  - Increasing rocket launch and re-entry emissions cause cooling at tropopause flux and warming at top-of-atmosphere.
- **Sensitivity simulations highlight need to reduce uncertainties:**
  - **Our simulations show that increasing the submicron fraction of re-entry derived Al_2O_3 increases ozone depletion by 5% after 1 year.**
- **Upcoming sensitivity simulations:**
  - **Model resolution.**
  - **Ageing of aerosol above the tropopause.**
  - **Separating launch and re-entry impacts.**

Our rocket launch and re-entry emission inventory is available for download here:

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