A Global, 3D Inventory of Satellite Megaconstellation Emissions from Rocket Launches and Satellite Re-Entries: Impacts on Stratospheric Ozone and Climate

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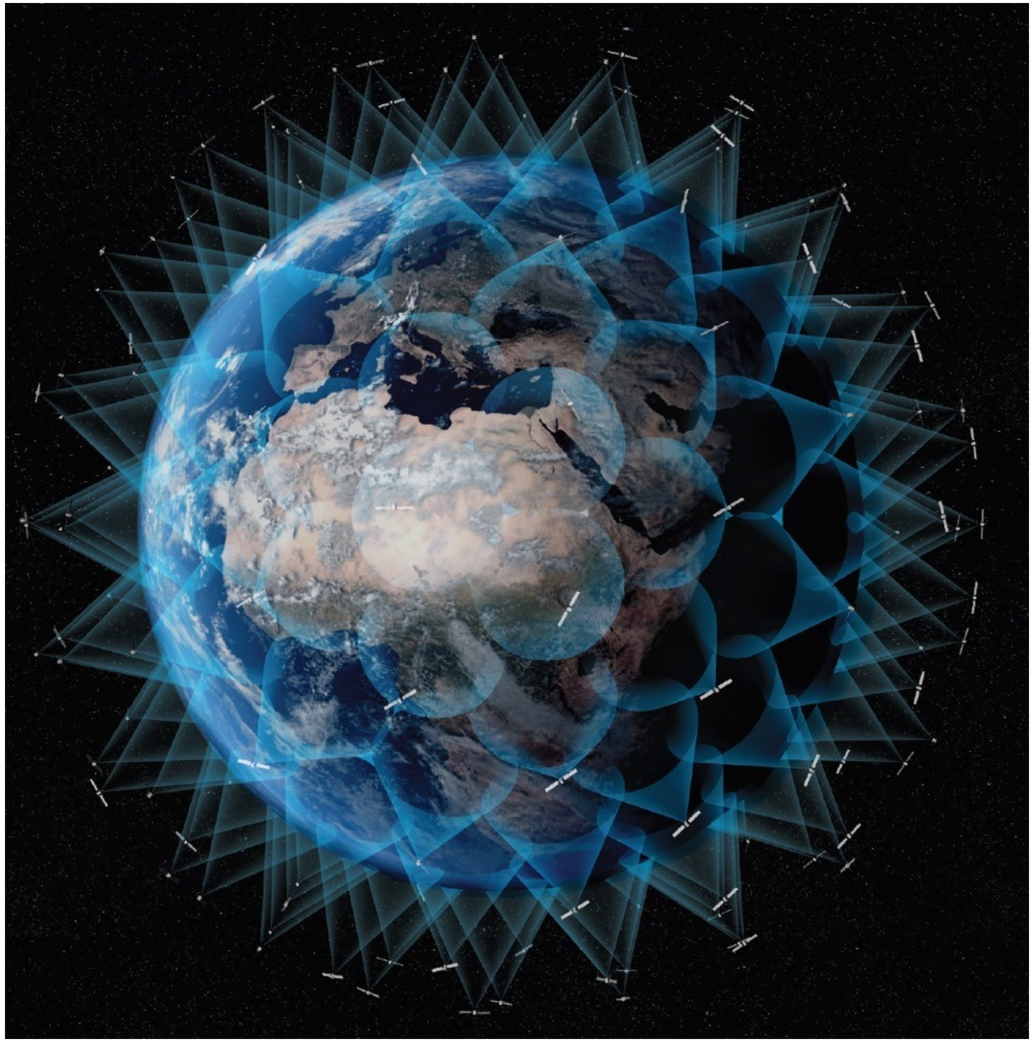
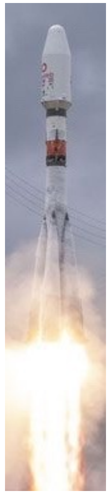
The rise of satellite megaconstellations (SMCs)



SpaceX Starlink

6528

450



Eutelsat OneWeb

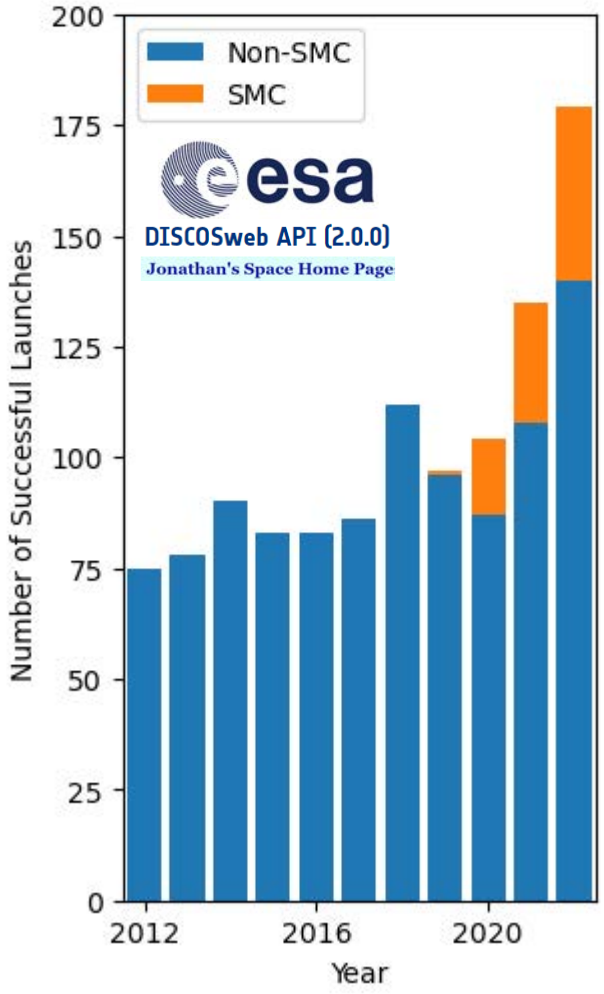
640

6

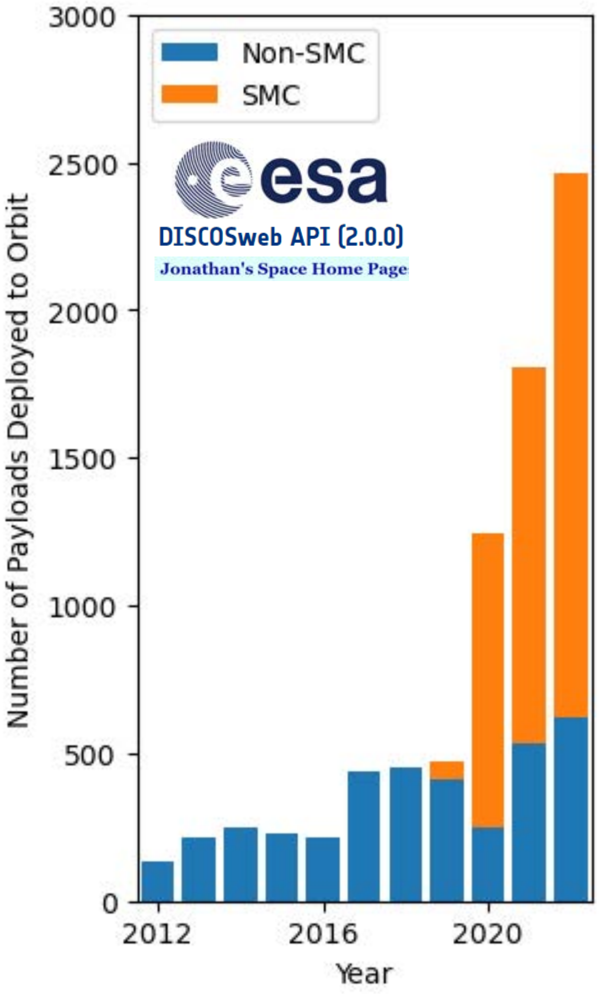
~ 540,000 extra SMC satellites planned for Low Earth Orbit. New sustainability and debris guidelines will contribute to rapidly increasing launch rates and re-entry mass.

Accelerating payload launch and re-entry rates

Orbital Launches

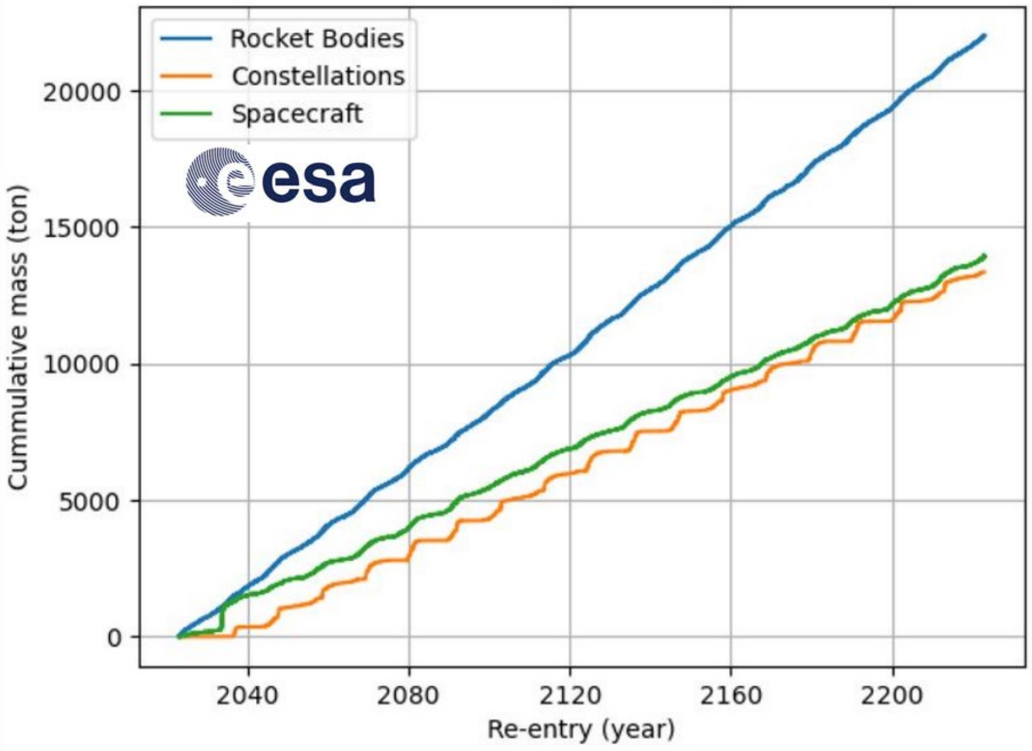


Payloads Deployed



Most payloads deployed to orbit are for SMCs, and SMC launch rates are increasing.

Future Re-entry Projections



ESA predict increasing atmospheric re-entries from constellations.

Air pollutant emissions from SMCs

Launches (all atmospheric layers)

Hydrogen
Delta IV Heavy
LOX / LH_2
H_2O
Thermal NO_x

Kerosene
Falcon 9
LOX / RP1
H_2O
CO
CO_2
BC
Thermal NO_x

Methane
Zhuque-2
LOX / CH_4
H_2O
CO
CO_2
BC
Thermal NO_x

Hypergolic
Proton-M
N_2O_4 / UDMH
H_2O
CO
CO_2
BC
Thermal NO_x
Fuel NO_x

Solid
Long March 11
Al / NH_4ClO_4 / HTPB
H_2O
CO
CO_2
BC
Thermal NO_x
Fuel NO_x
Chlorine
Al_2O_3

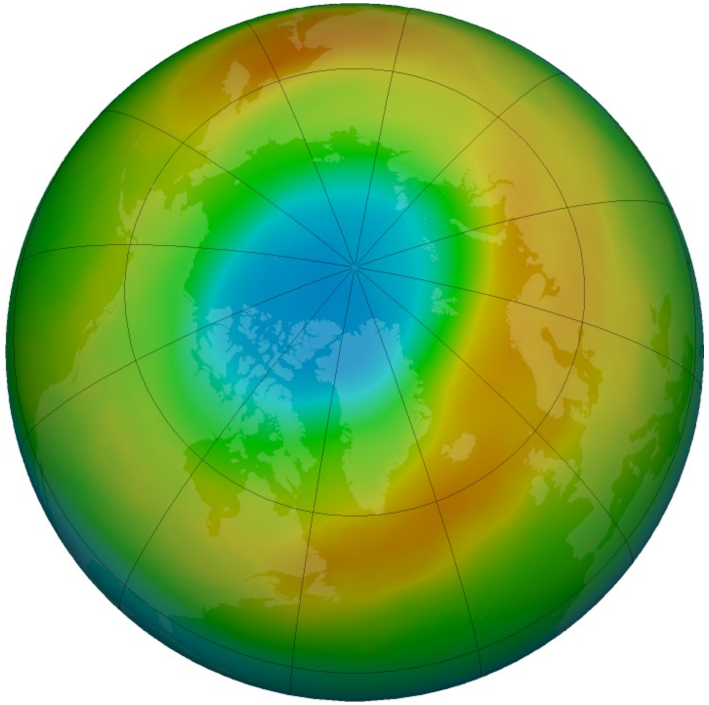
Reentries (upper atmosphere)

Payload/Rocket
Thermal NO_x
Al_2O_3

Unlike surface sources, pollutants are injected directly into all atmospheric layers. ~10% of stratospheric aerosol particles contain elements from satellite and rocket re-entries.

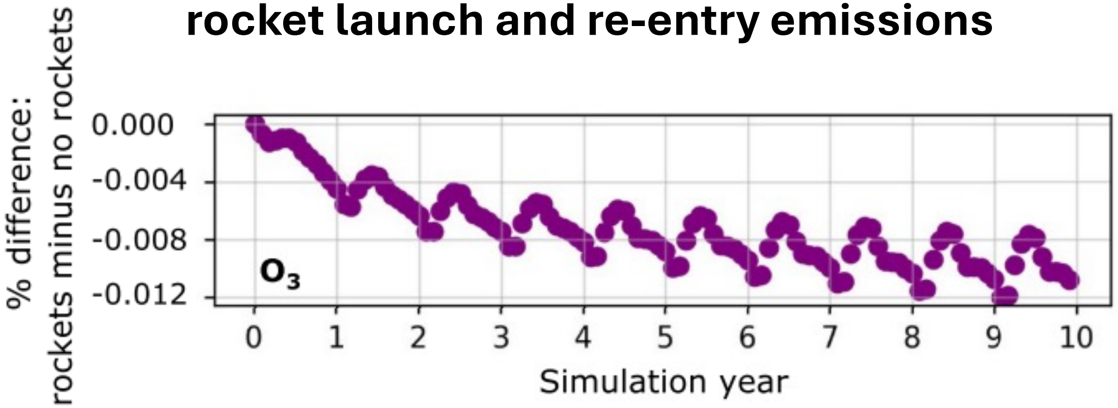
Stratospheric ozone depletion from rocket launches and re-entries

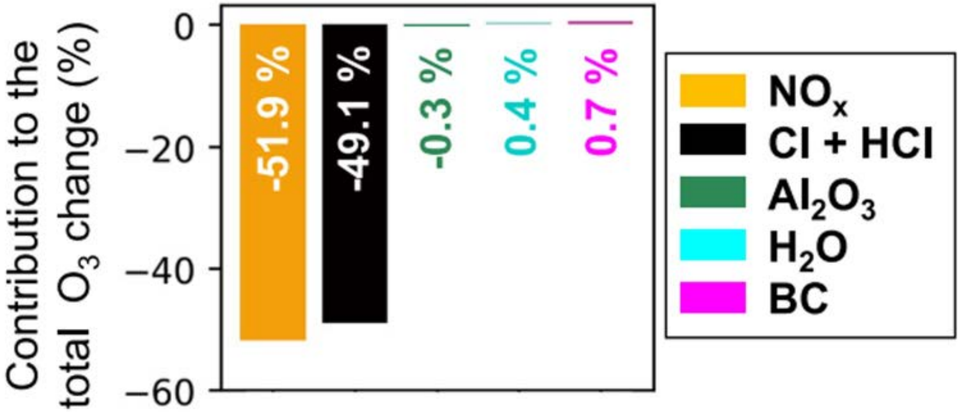
Total Ozone – Nov 2023



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

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



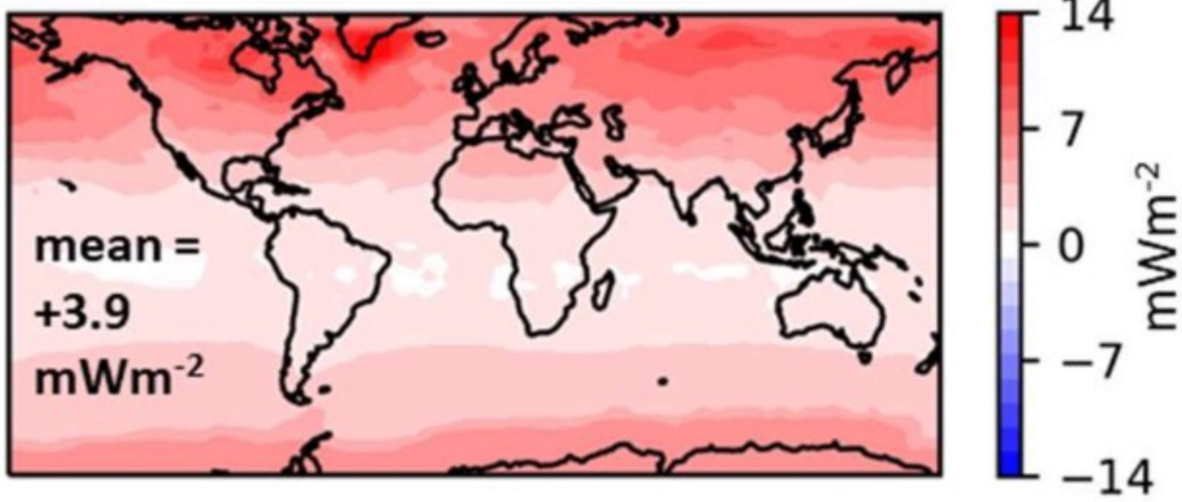


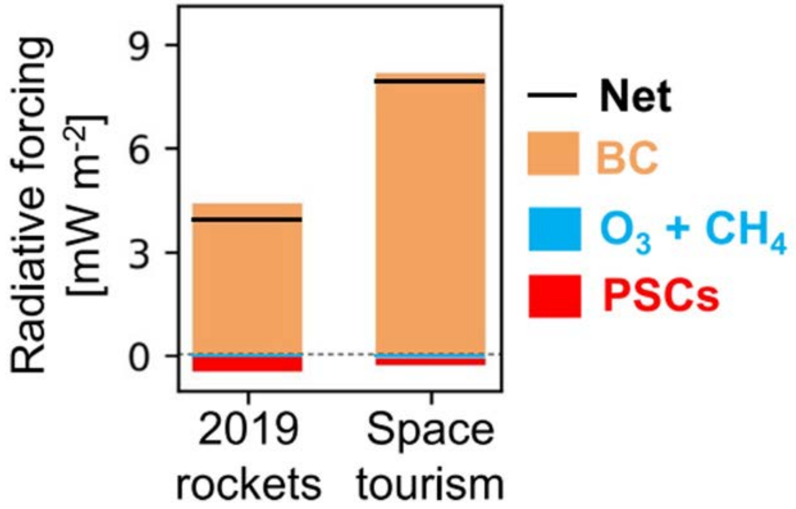
Driven by Cl_y and NO_x emissions.

[Nasa Goddard Space Flight Center, Ryan *et al.* 2022]

Radiative forcing from rocket launches and re-entries

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





BC emissions drive warming and are 375x more efficient than surface sources.

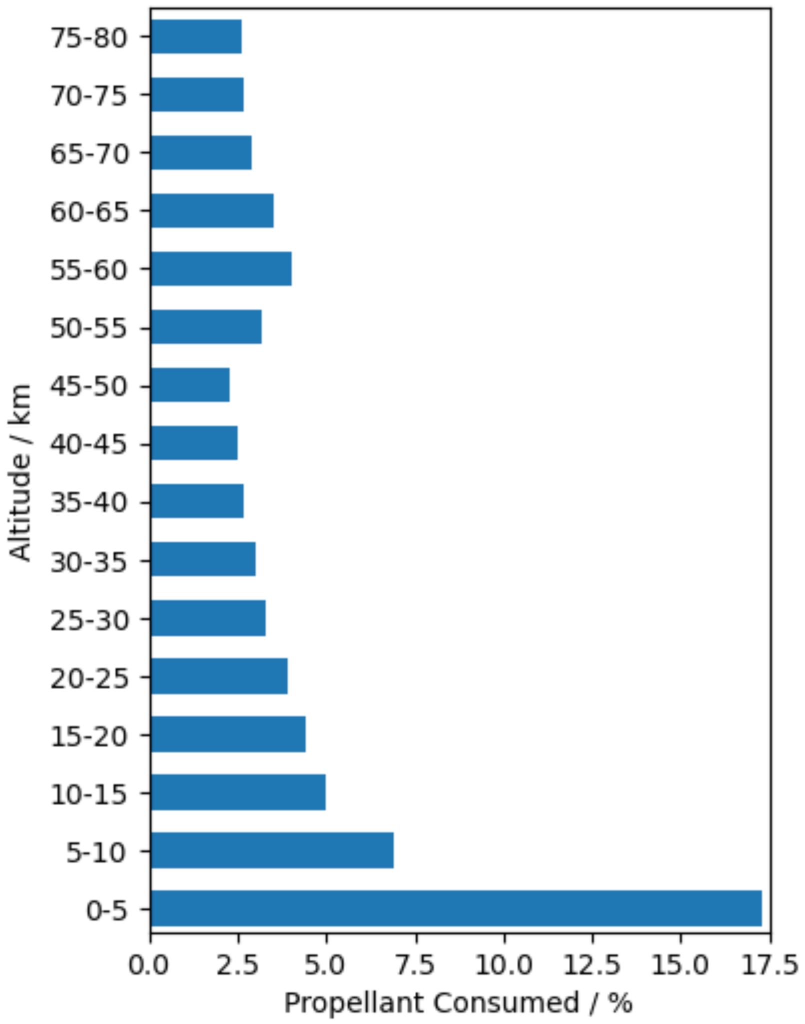
BC	Al_2O_3
↑ Absorbs solar	↑ Absorbs terrestrial
	↓ Reflects solar

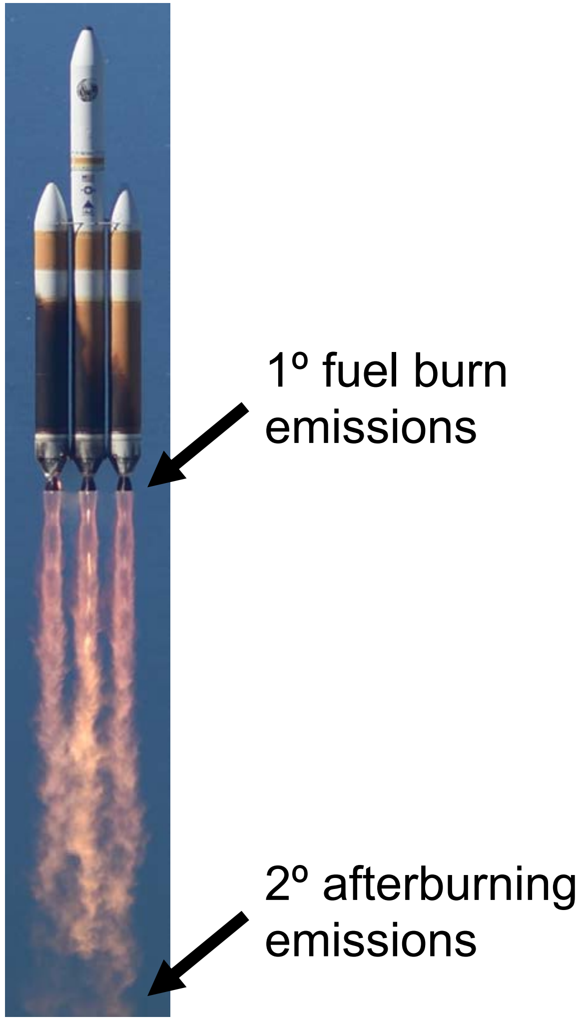
How does introduction of SMCs and rise in launch and re-entry rates affect ozone and climate?

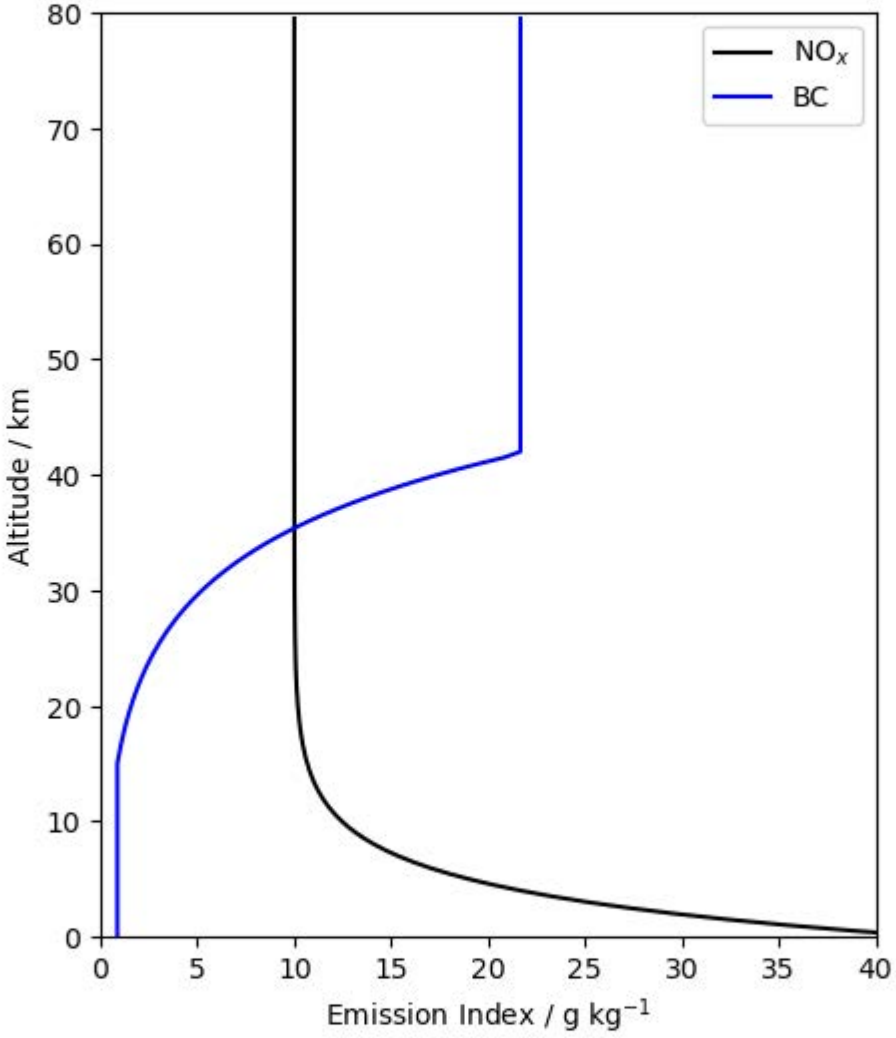
[Ryan *et al.* 2022]

Constructing vertical launch emission profiles

$$Mass\ Emissions(g) = Propellant\ consumed\ (kg) \times Emission\ Index\ (g\ kg^{-1})$$







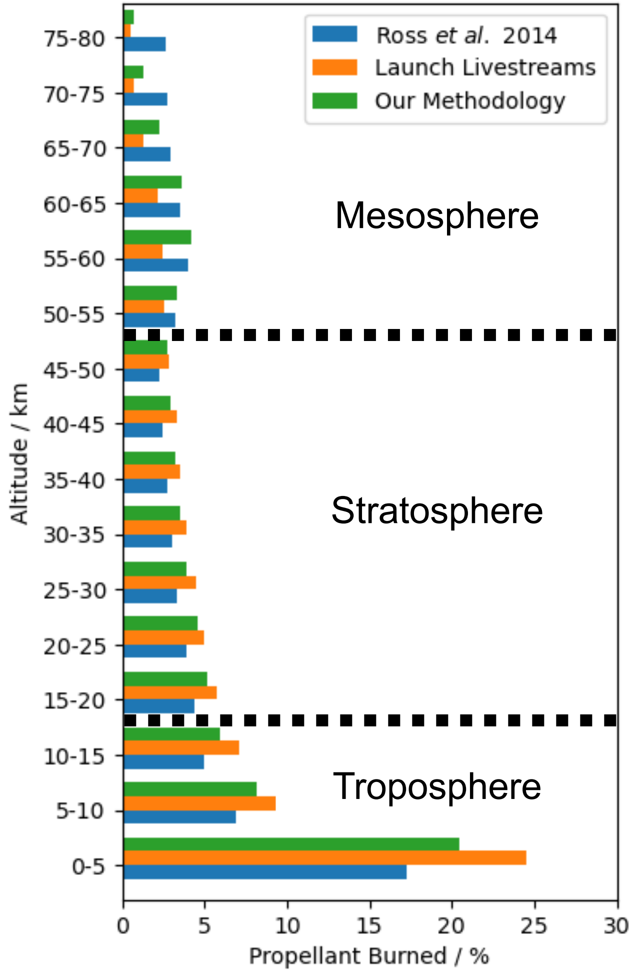
Emissions are a combination of propellant combustion and afterburning reactions in the hot rocket plume.

Source: Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate, https://doi.org/10.1029/2021EF002612

Validating our emission profiles with existing launch data

Collating data from launch livestreams

Comparing Propellant Consumption Profiles



Our methodology is 17% higher than the livestream method, diverging most in the mesosphere.

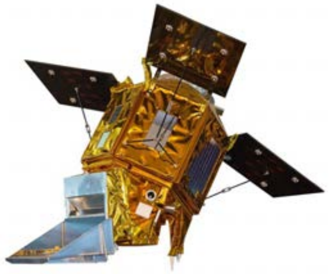
Converting re-entry mass to upper atmosphere emissions

Reusable Objects

17.5% → NO_x

0% → Al_2O_3

Expendable Objects



40% → NO_x

Variable % based on object type → Al_2O_3

Conversion to emissions requires broad assumptions on ablation, chemical composition, and aerosol properties.

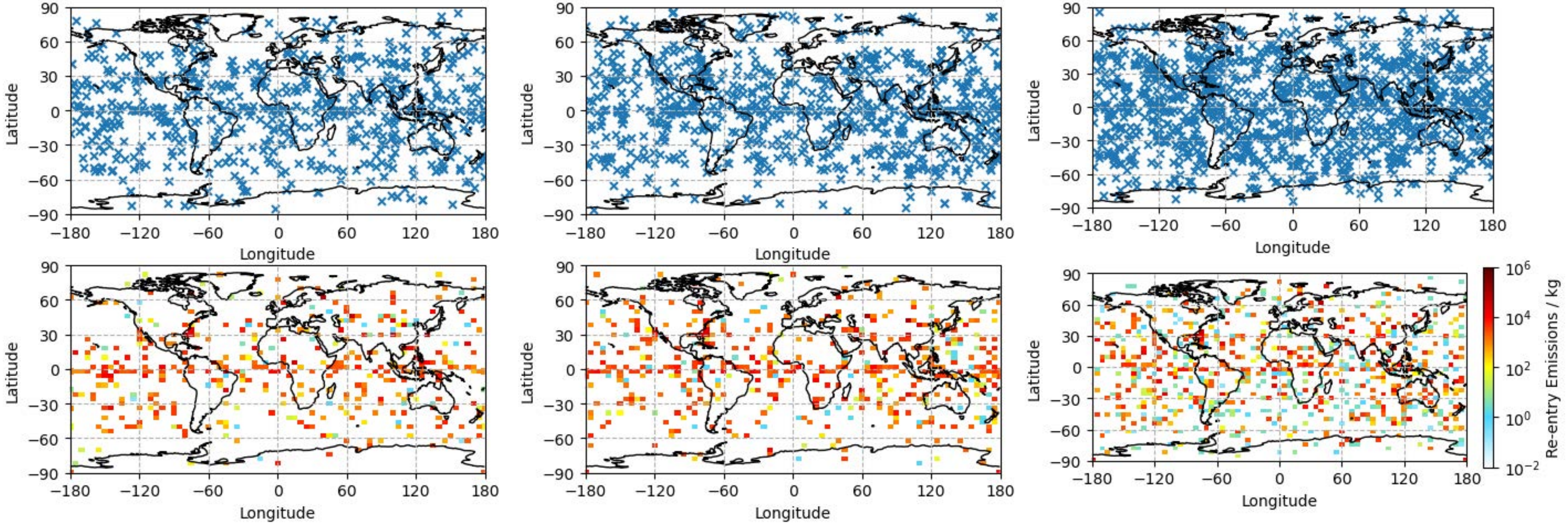
[Schulz, L. & Glassmeier, K. H. 2021, Jain 2023]

Mapped re-entry mass and emissions

2020
878 objects

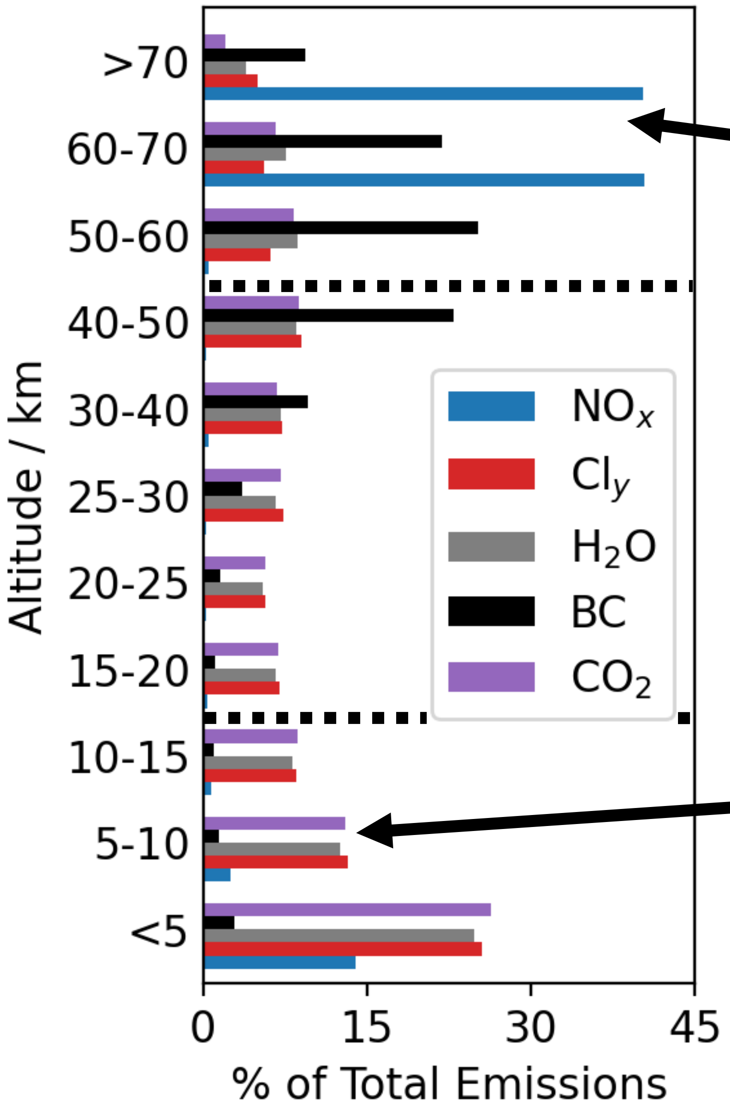
2021
1095 objects

2022
1650 objects

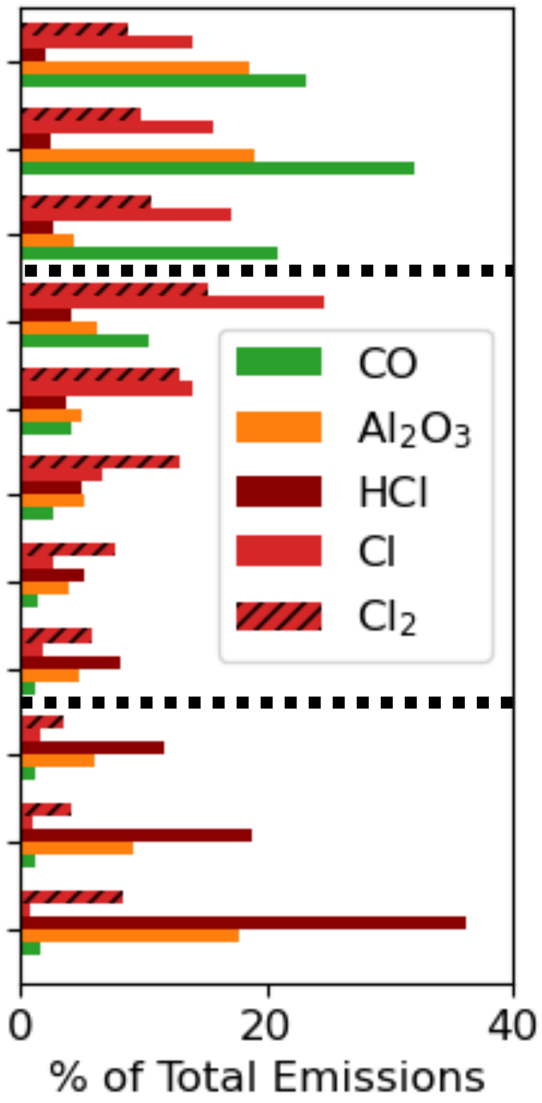


Increasing re-entry mass and emissions (3.15-4.97 Gg) now roughly 40% of natural influx, partly driven by satellite megaconstellations (18-25%).

Vertical distribution of rocket launch and re-entry emissions



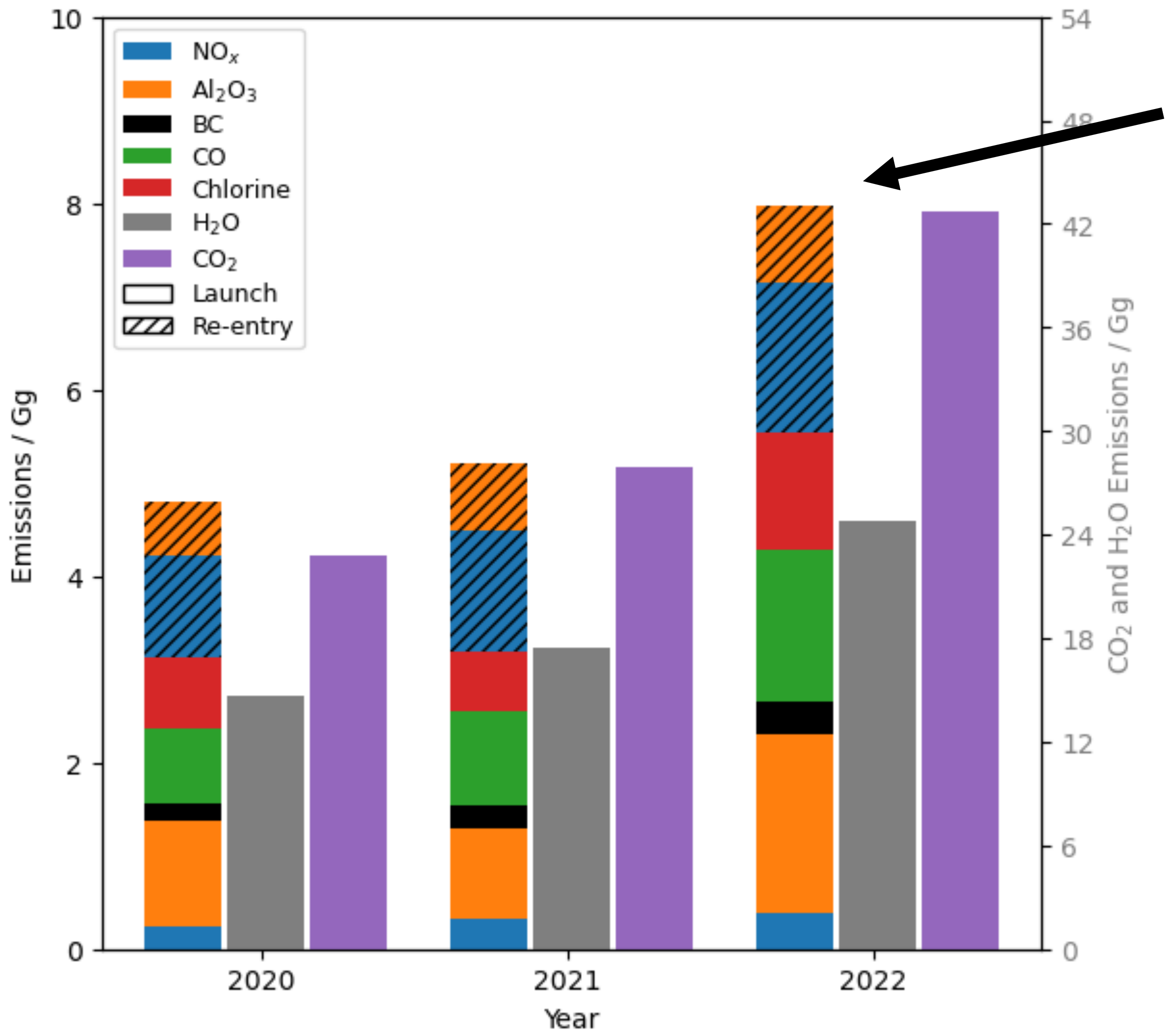
Large emissions of NO_x and Al_2O_3 (re-entry) and CO and BC (incomplete combustion) above stratopause.



Emissions with no (H_2O) or a weak (CO_2) altitude dependence follow the propellant consumption profile.

Much lower emissions than surface sources, however most BC, NO_x, H_2O, CO, Cl_y, and Al_2O_3 emissions were injected above the tropopause in 2022.

Annual emission totals for all rocket launches and re-entries

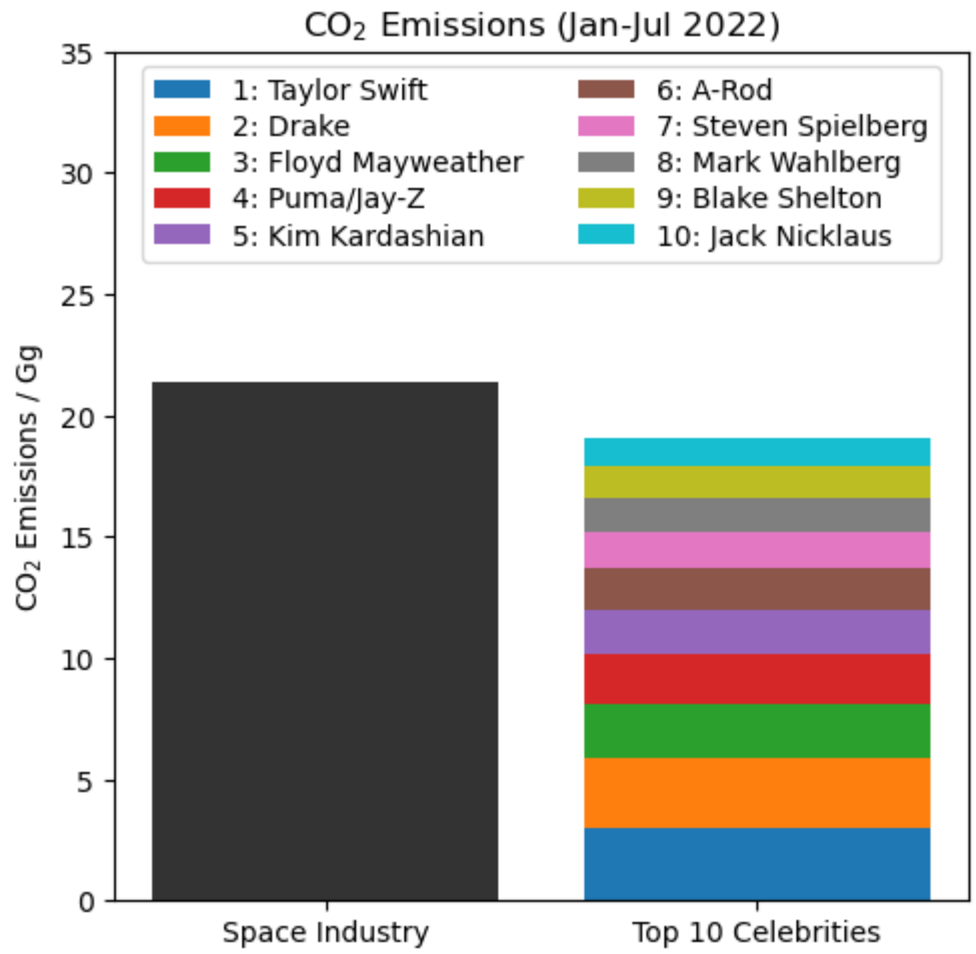


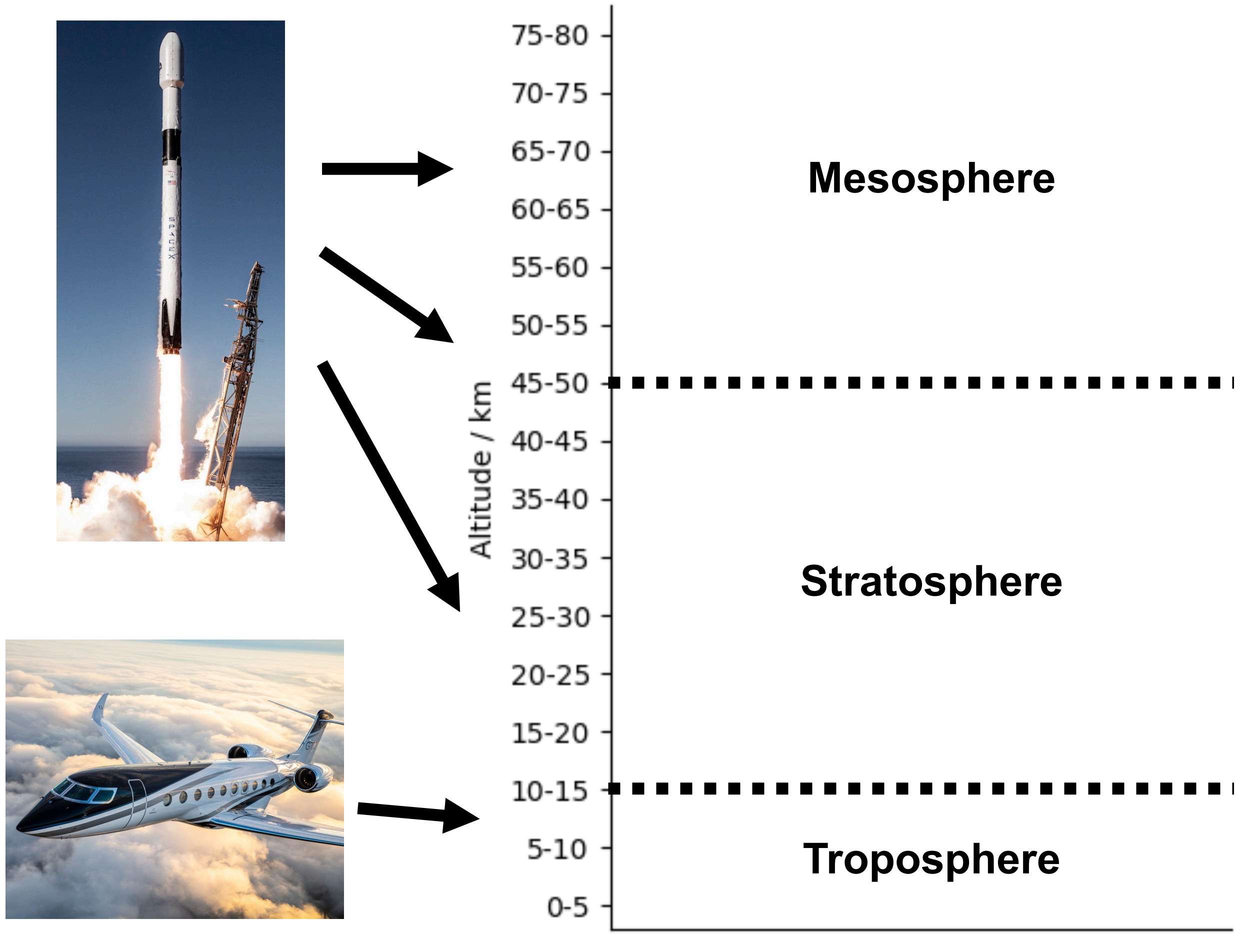
Re-entry Al_2O_3 and NO_x have exceeded and are approaching natural levels.

H_2O and CO_2 are the dominant pollutants.

Annual emissions are rapidly increasing as propellant consumption grows.
Continued emissions of ozone depleting substances.

Putting rocket launch CO_2 emissions in context



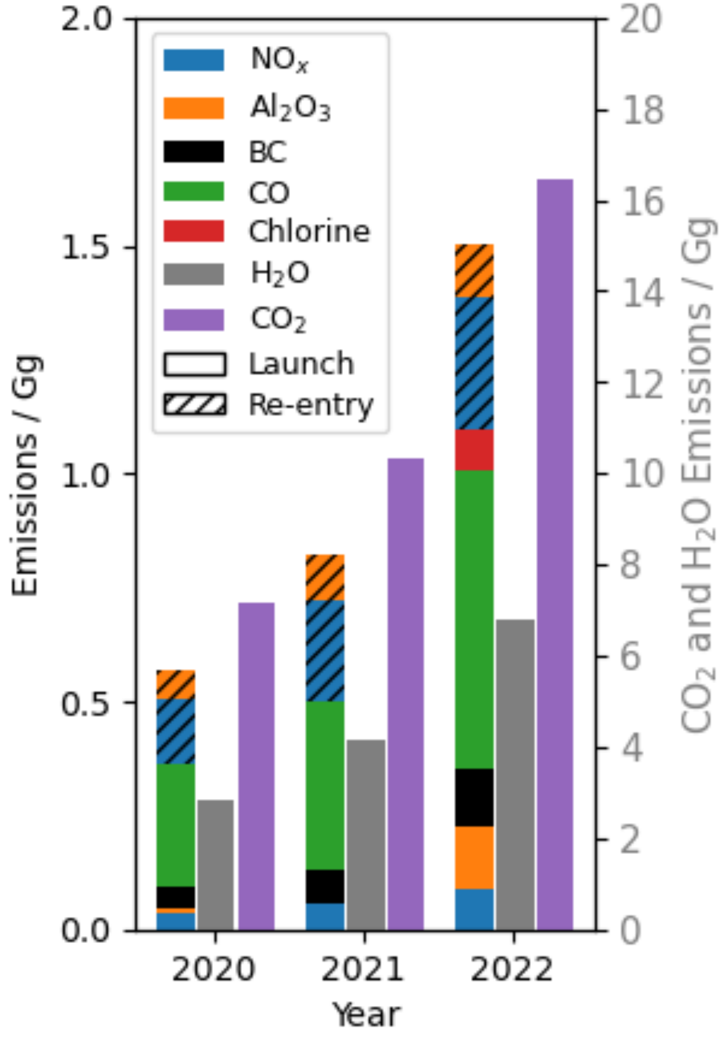


Space industry CO_2 emissions in early 2022 were similar to the celebrities with the highest private jet emissions.

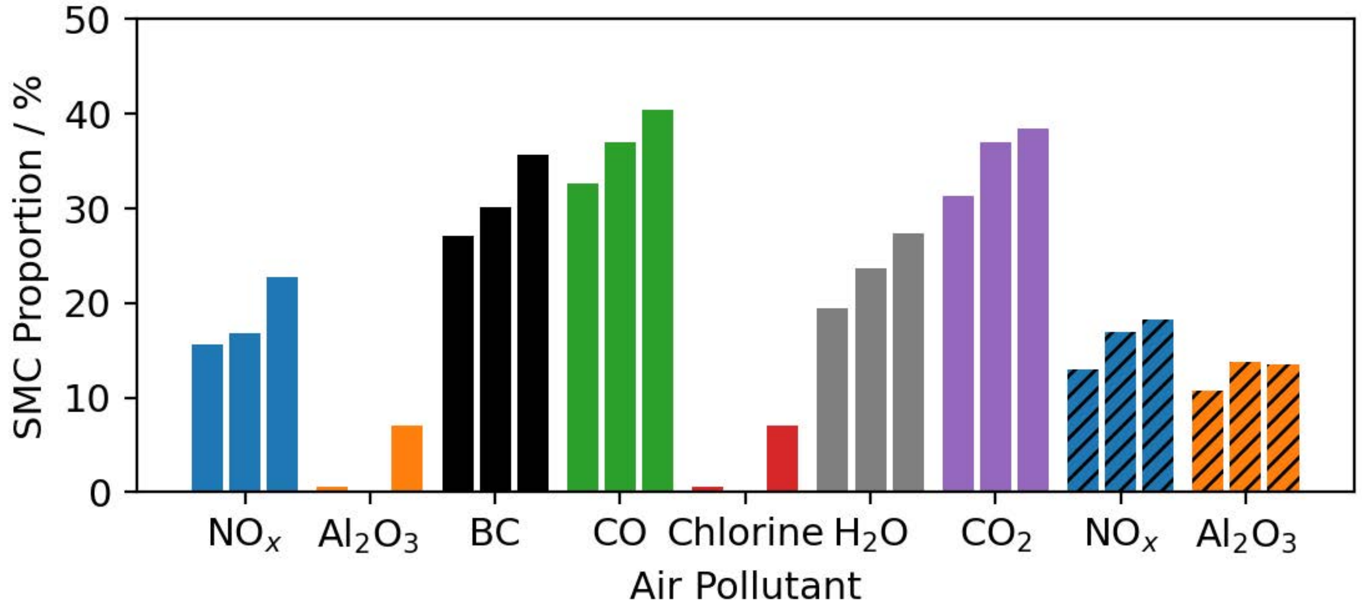
Just Plane Wrong: Celebs with the Worst Private Jet Co2 Emissions, Yard, 2022, https://weareyard.com/insights/worst-celebrity-private-jet-co2-emission-offenders

SMCs present a growing contribution to total emissions

Megaconstellation rocket launches and re-entries

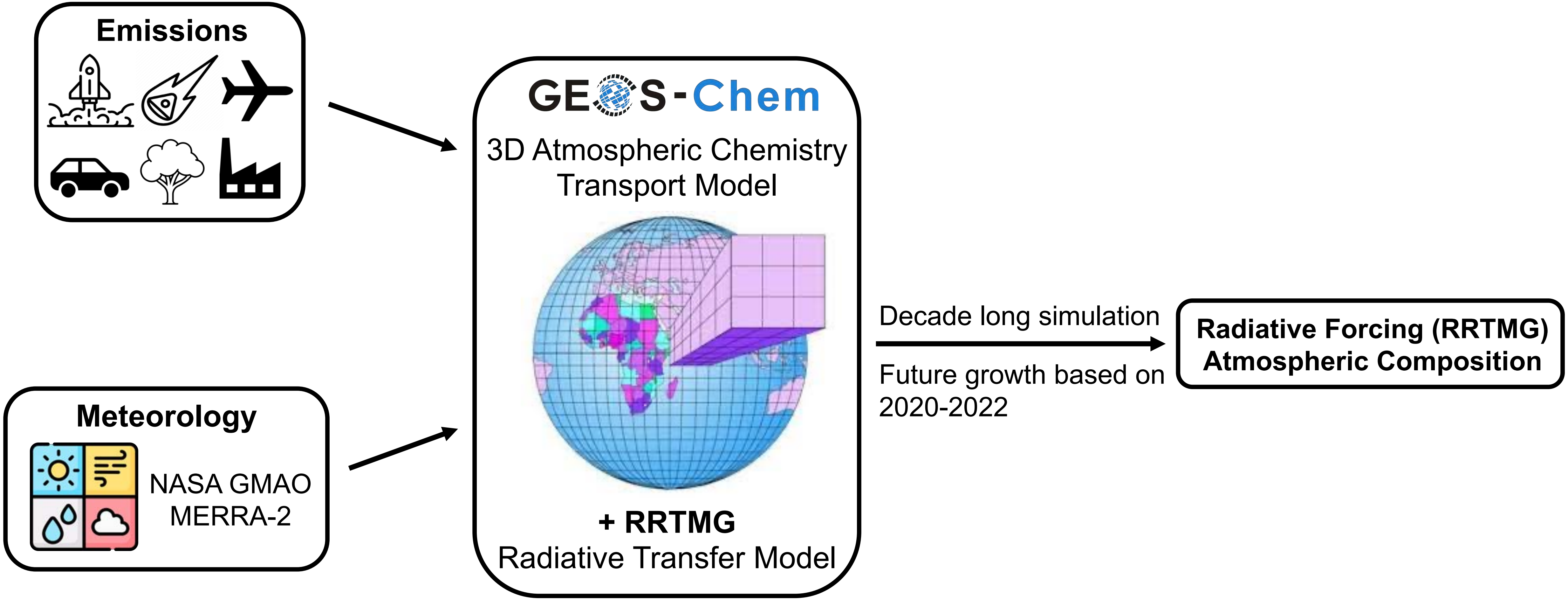


Proportion of annual emissions from SMCs



SMC proportion is increasing annually, highest proportions for carbon emissions (BC, CO, CO_2).

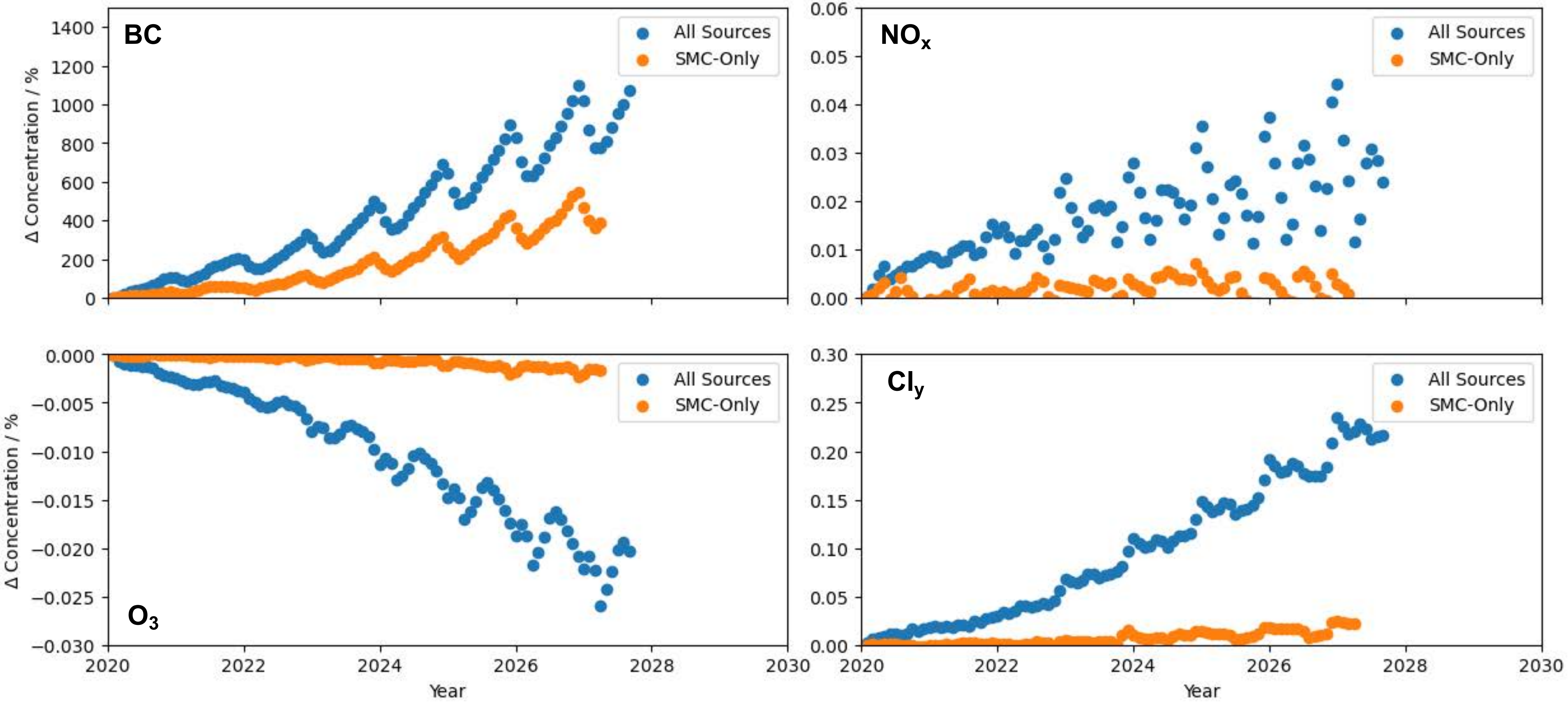
Implementation of space industry emissions in GEOS-Chem



Chemical transport model is limited by resolution and altitude (0-80km) but can monitor the impact of rocket launch / re-entry emissions on global atmospheric composition and climate.

SMCs cause minimal O_3 loss

GEOS-Chem + RRTMG

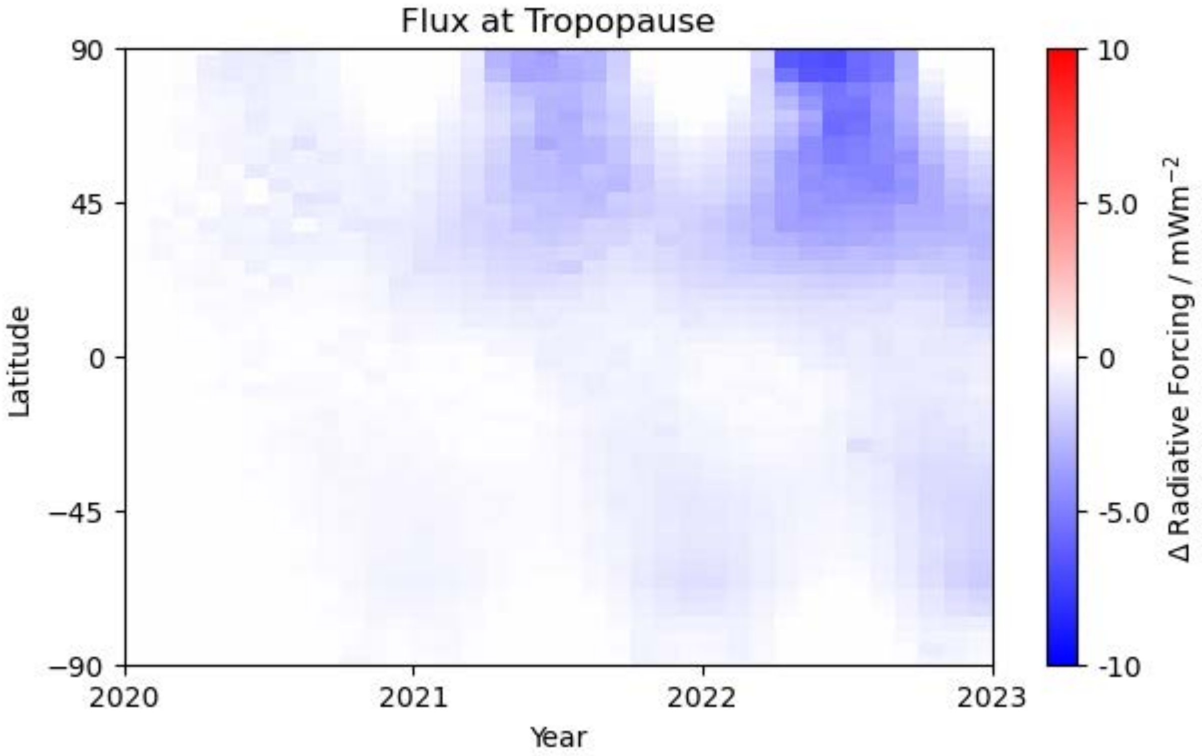


Minimal O_3 loss from SMCs but significant BC emissions. O_3 loss after 8 years is ~9% of Montreal recovery.

Cl_y peak and O_3 loss occur simultaneously, much lower ozone depleting emissions for SMCs.

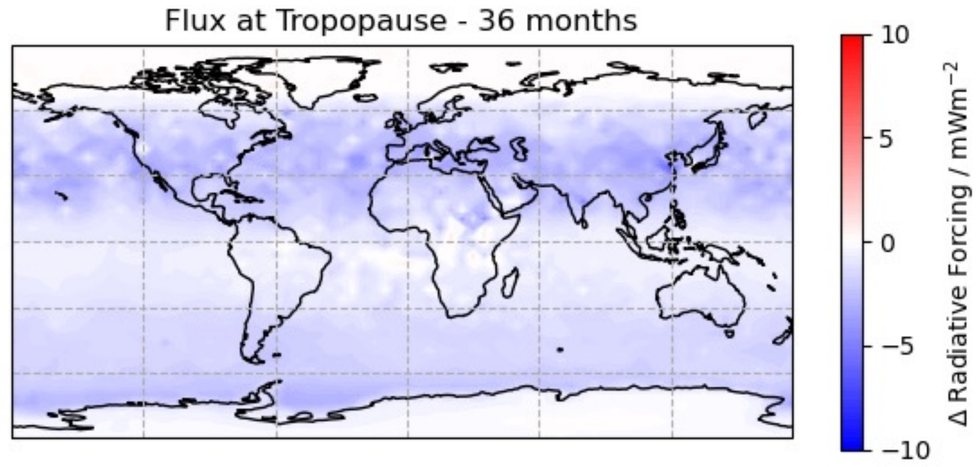
The space industry decreases radiative flux at the tropopause

All rocket launches and re-entries

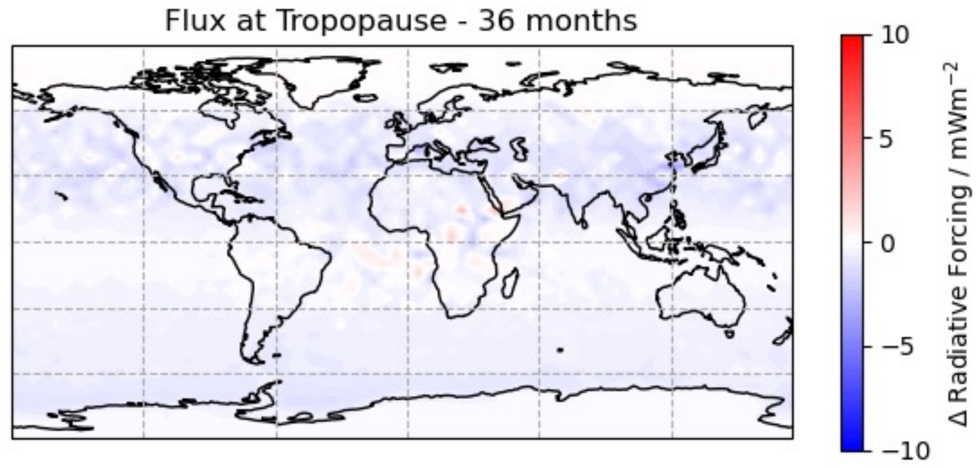


Increased stratospheric BC burden results in a decrease in net radiative flux at the tropopause, dominated by SW.

All rocket launches and re-entries



SMC rocket launches and re-entries



~30% of BC emissions are from SMCs, resulting in a small tropospheric cooling effect from SMCs.

GEOS-Chem + RRTMG

Preliminary Results

Conclusions and next steps

- **Developed emission inventories for 2020-2022 SMC and non-SMC emissions.**
  - Increasing propellant consumption and re-entry mass from 2020-2022, partly from SMCs.
  - Increasing contribution of SMCs to emissions, especially carbon-based.
- **Preliminary results demonstrate immediate environmental impacts.**
  - 8-years of increasing rocket launch and re-entry emissions reverse 9% of Montreal Protocol gains.
  - SMCs cause negligible O_3 depletion but lead to large increases in stratospheric BC of +400%.
  - Increasing rocket launch and re-entry emissions cause decrease in net radiative flux at tropopause.
- **Next steps:**
  - Finish simulating the impacts of a decade of launch and re-entry emissions on stratospheric ozone and climate.
  - Run sensitivity simulations.

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