Radiative forcing and ozone depletion due to pollution from launch and demise of satellite megaconstellations

Led by Connor Barker (UCL postdoc)

With Eric Tan, Jonathan McDowell, Sebastian Eastham, NOAA SABRE campaign team,

University of Reading seminar, 10 November 2025

Eloise Marais, e.marais@ucl.ac.uk, https://maraisresearchgroup.co.uk/

Starting Grant

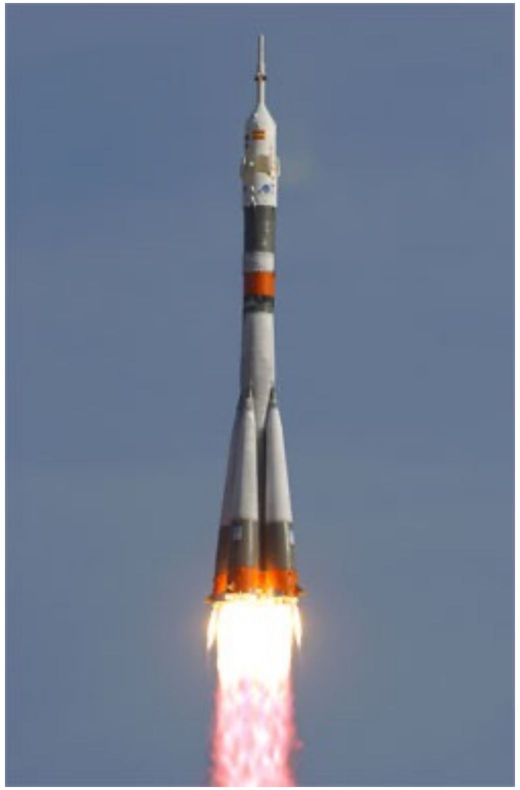
Air Pollutant Emissions from Rocket Launches

Mix of pollutants depends on propellant type

Solid

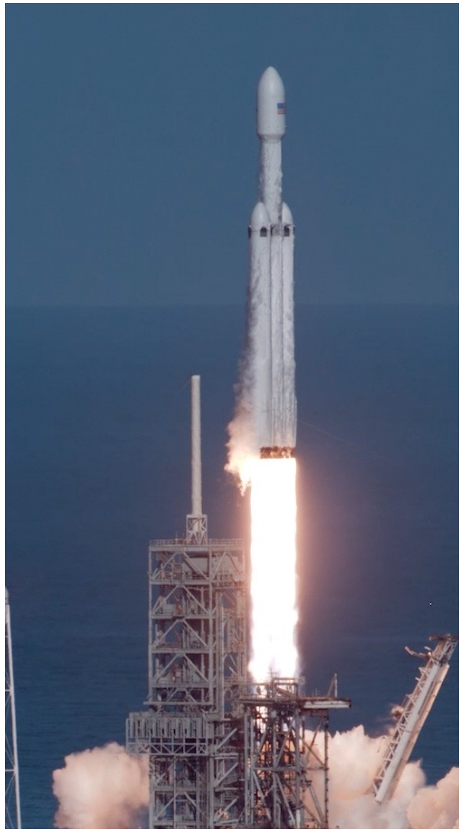
NO_x
$HCl+Cl+Cl_2$
Al_2O_3
H_2O
BC

Hypergolic



NO_x
H_2O
BC

Kerosene or Methane



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

BC: Black Carbon
Al_2O_3: Alumina

Air Pollutant Emissions from Rocket Launches

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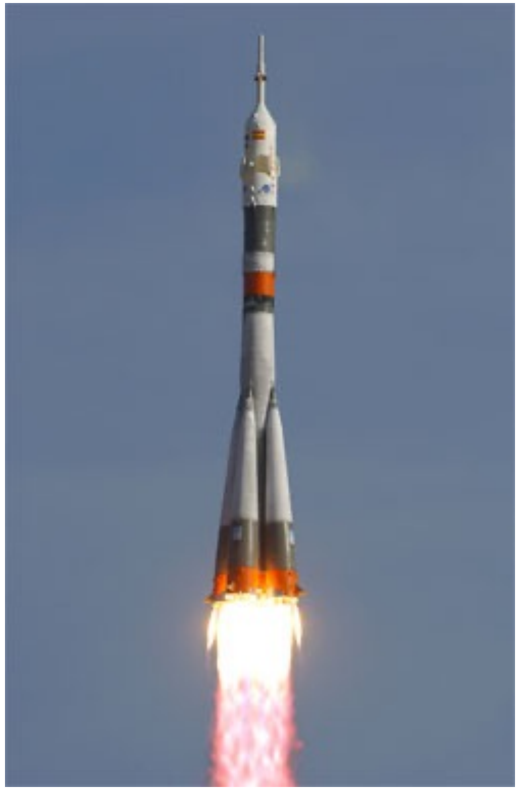
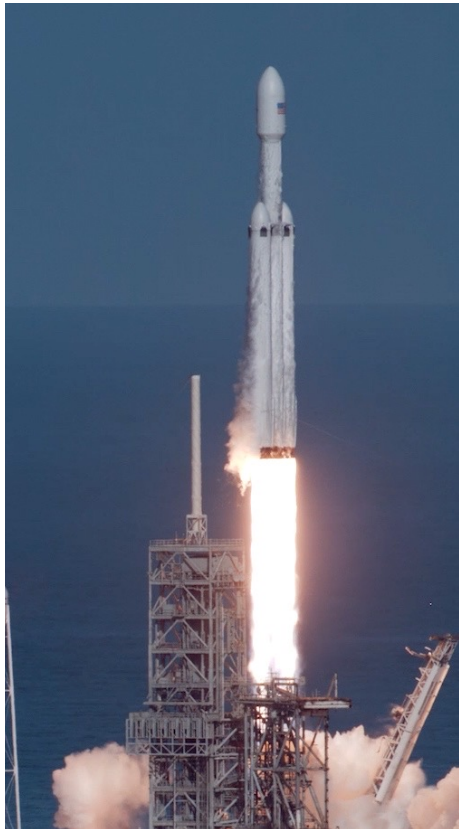


NO_x
H_2O
BC

Kerosene or Methane



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

Climate concern

Air Pollutant Emissions from Rocket Launches

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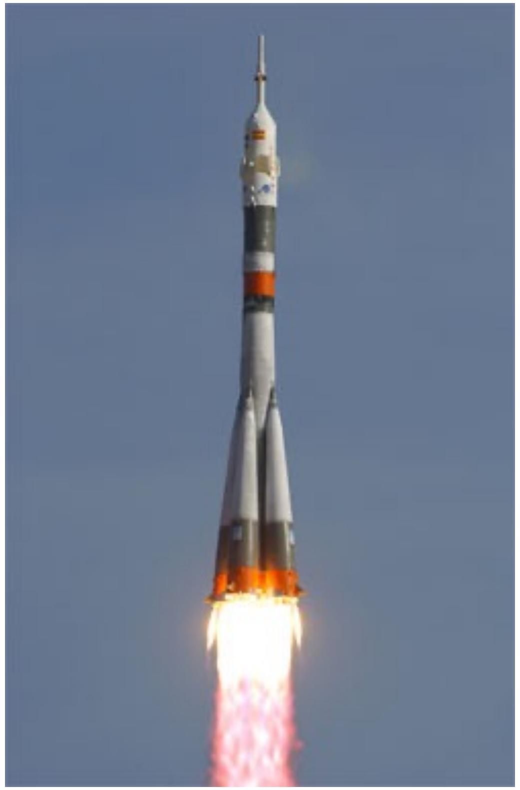
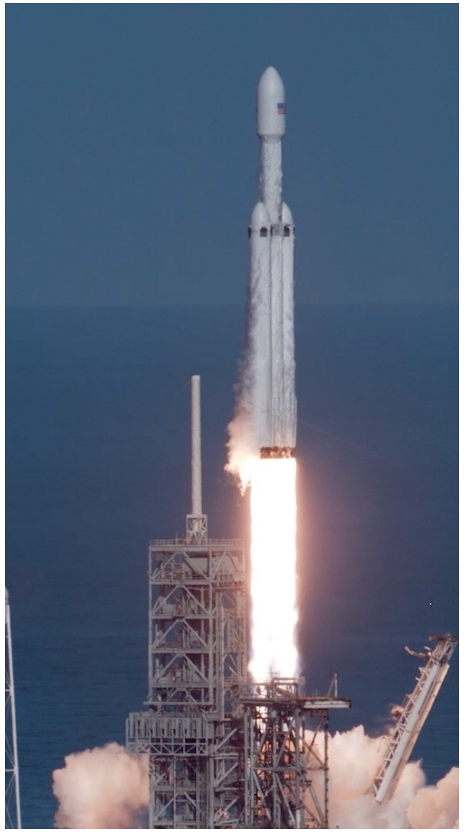


NO_x
H_2O
BC

Kerosene or Methane



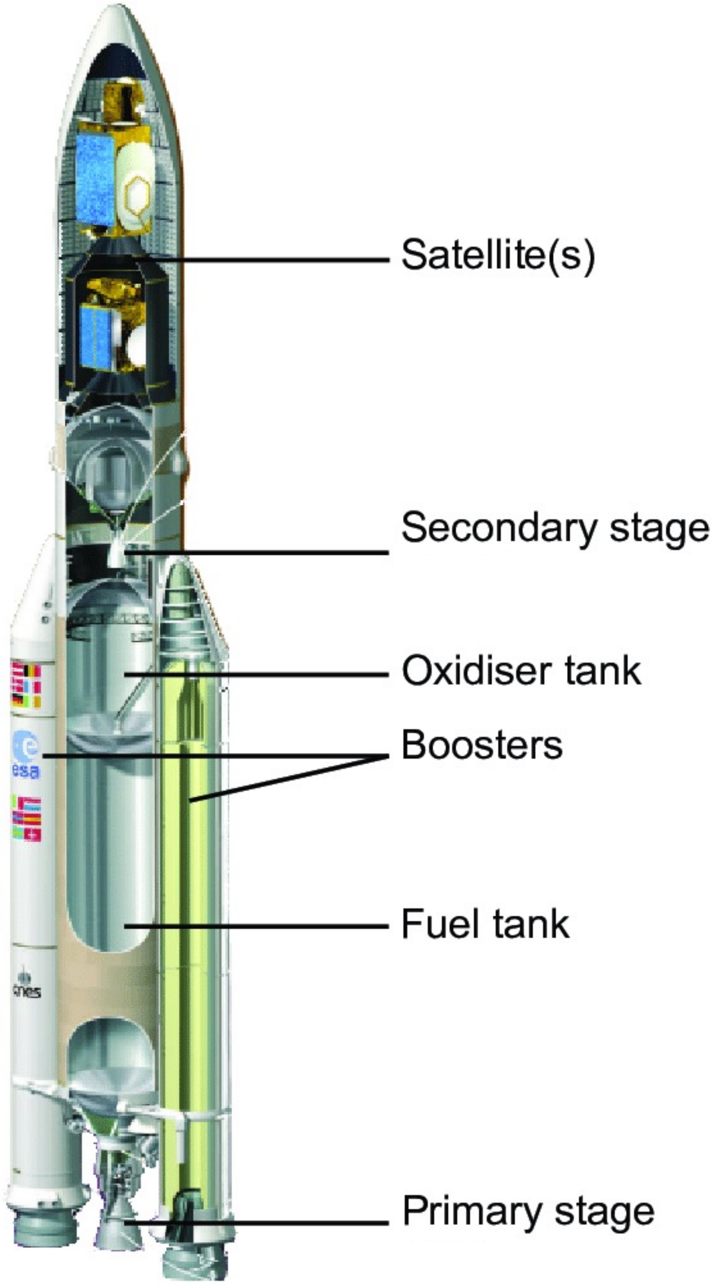
NO_x
H_2O
BC

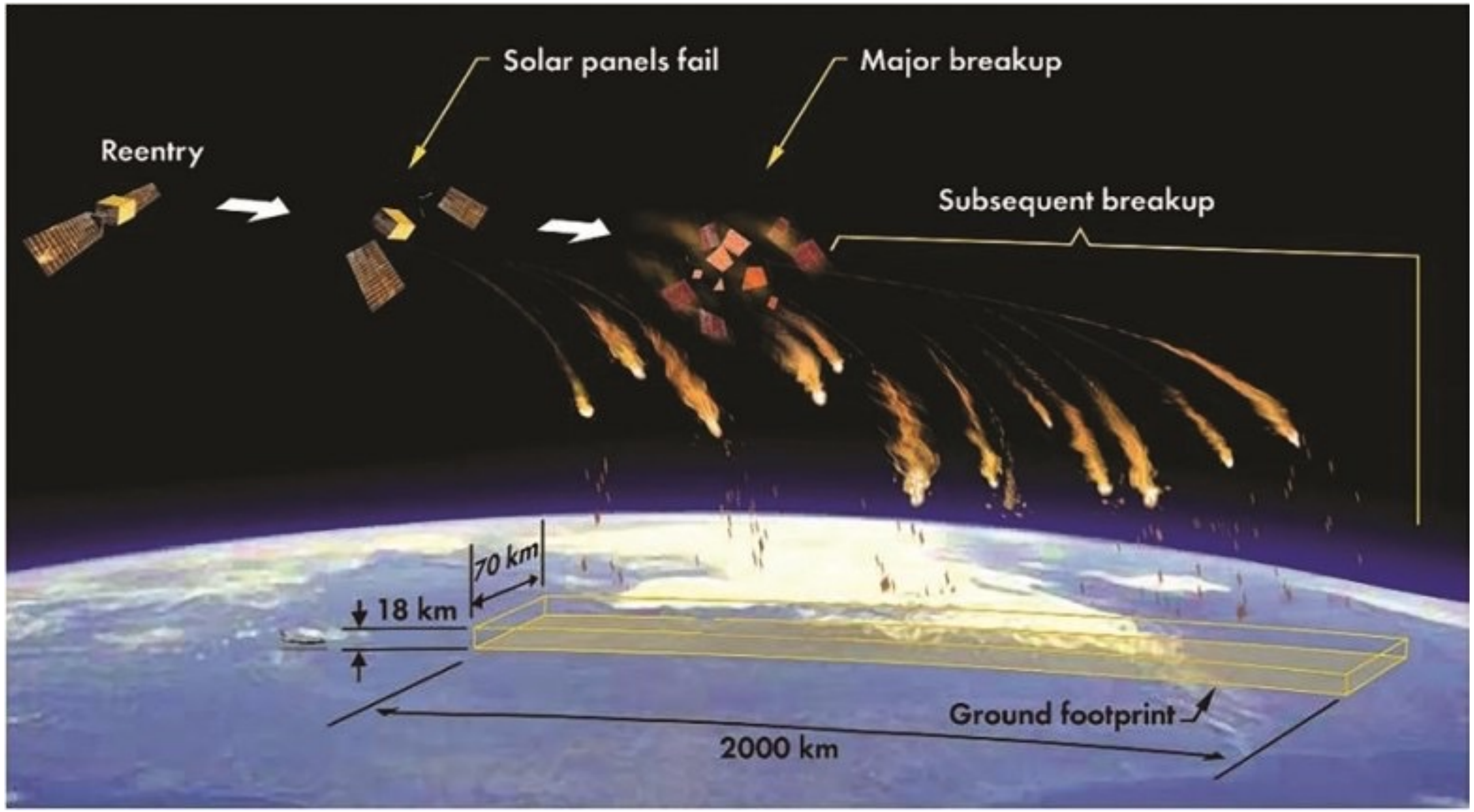
Cryogenic

NO_x
H_2O

Ozone depletion

Air Pollutants Released from Object Re-entries

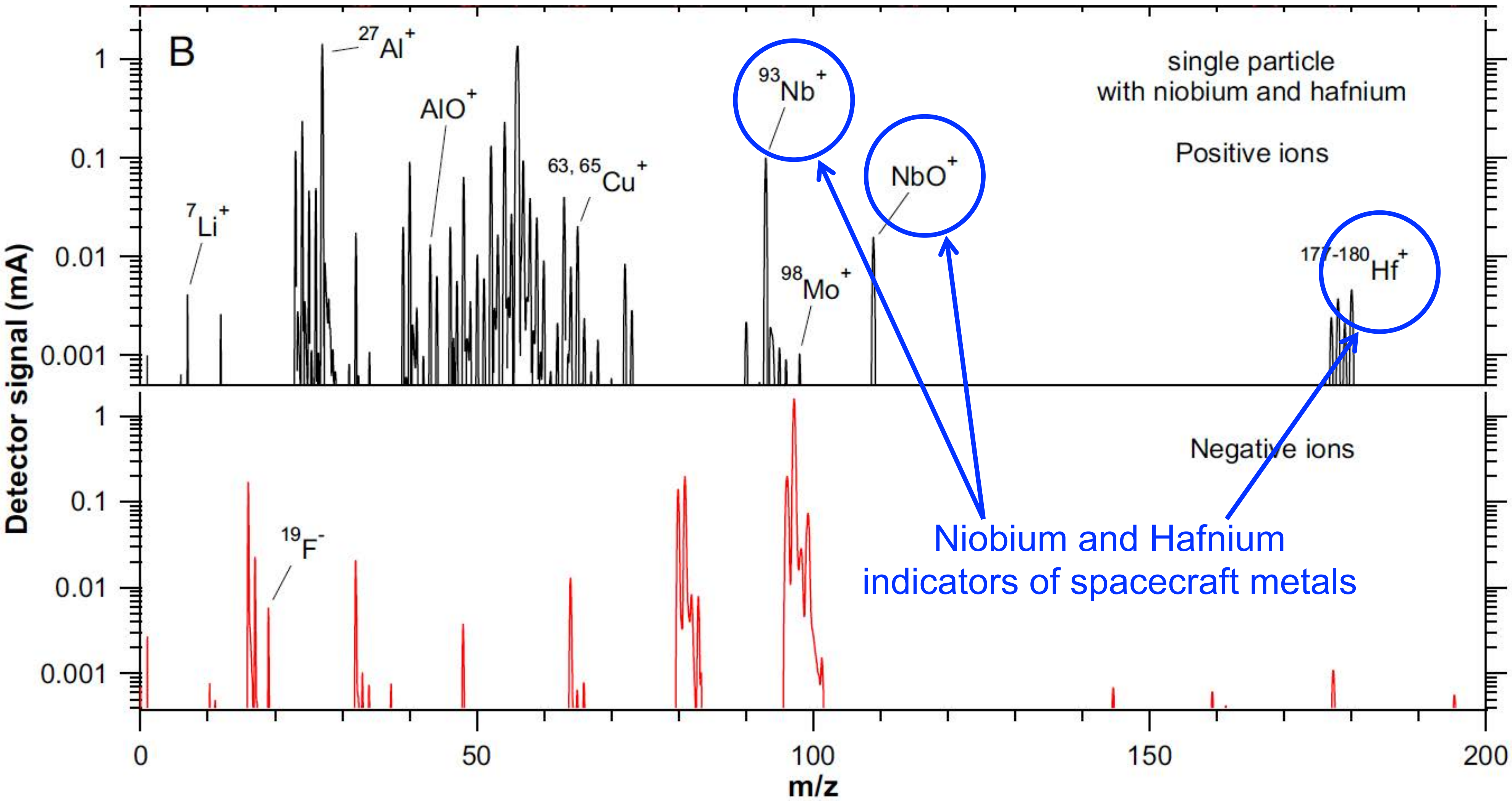




- Many spacecraft components
- Ideally demise completely to reduce risk to life on Earth
- Ablation emits nitrogen oxides (NO_x) from thermal energy
- Ablation emits metals oxides (mostly Al), BC, ammonia (NH_3) and more

Observational Evidence of Pollution from Re-entries

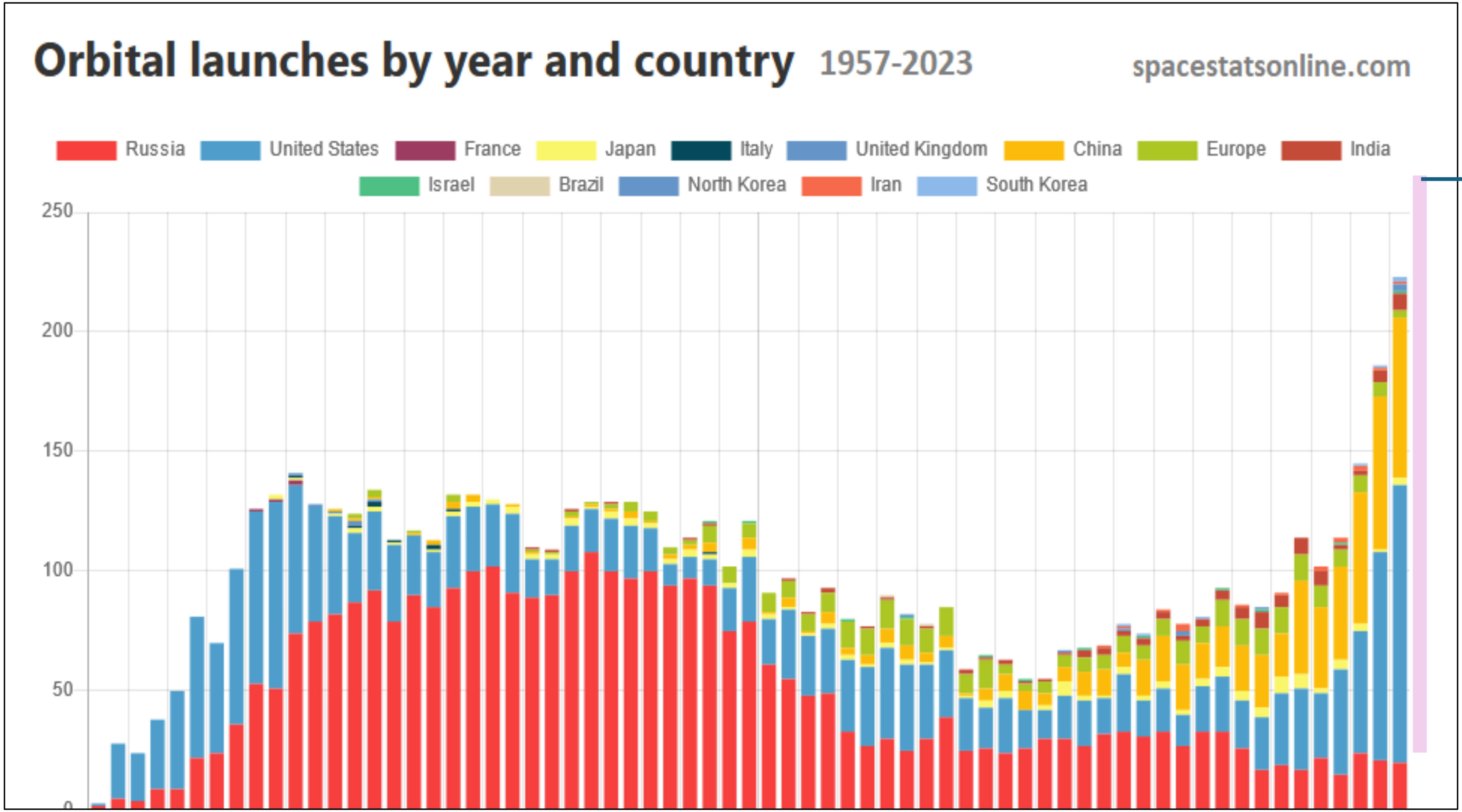
Example Particle Analysis by Laser Mass Spectrometer (PALMS) instrument single stratospheric particle mass spectrum



[Murphy et al., 2023]

Used these PALMS measurements to infer that 10% of stratospheric aerosol particles contaminated with metals from spacecraft re-entry

Surge in Launches and Re-entries



261 in **2024**

269 so far in **2025**

Recent increase driven by megaconstellation missions. Mostly Falcon9 rockets with reusable first stage, so very little pollution produced on re-entry

Study Steps and Objectives

Build an **inventory** of launch and re-entry air pollutant emissions

Categorize emissions associated with megaconstellation missions

Project emissions to 2029 for a full decade of emissions

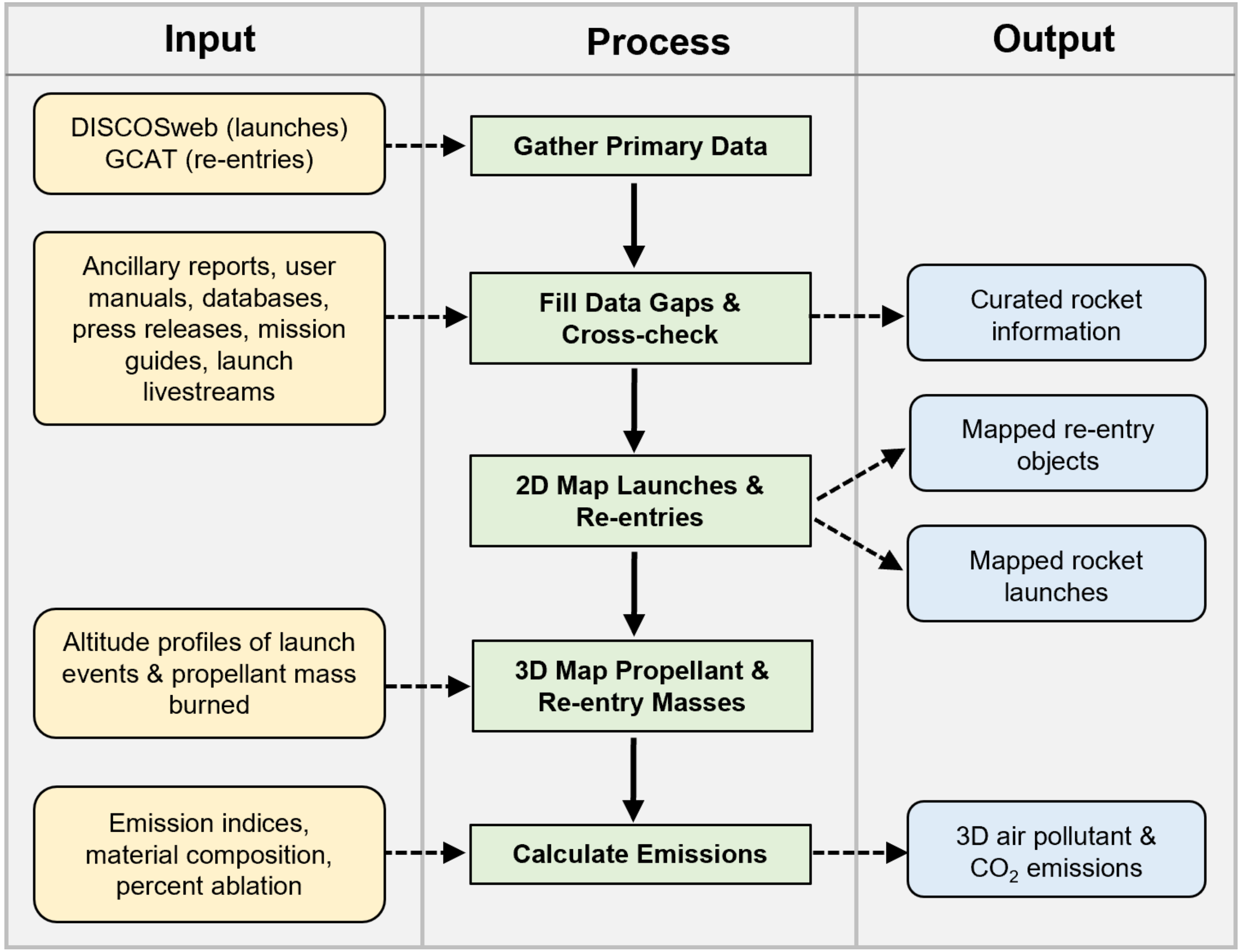
Assess emissions against high-altitude aircraft observations

Implement emissions in chemical transport **model** coupled to radiative transfer model

Quantify **atmospheric impacts** (ozone depletion, radiative forcing) due to all launches and re-entries compared to just those associated with megaconstellation missions

Emissions Inventory Processing Pipeline

Initial inventory developed for **2020-2022** legitimized by peer review



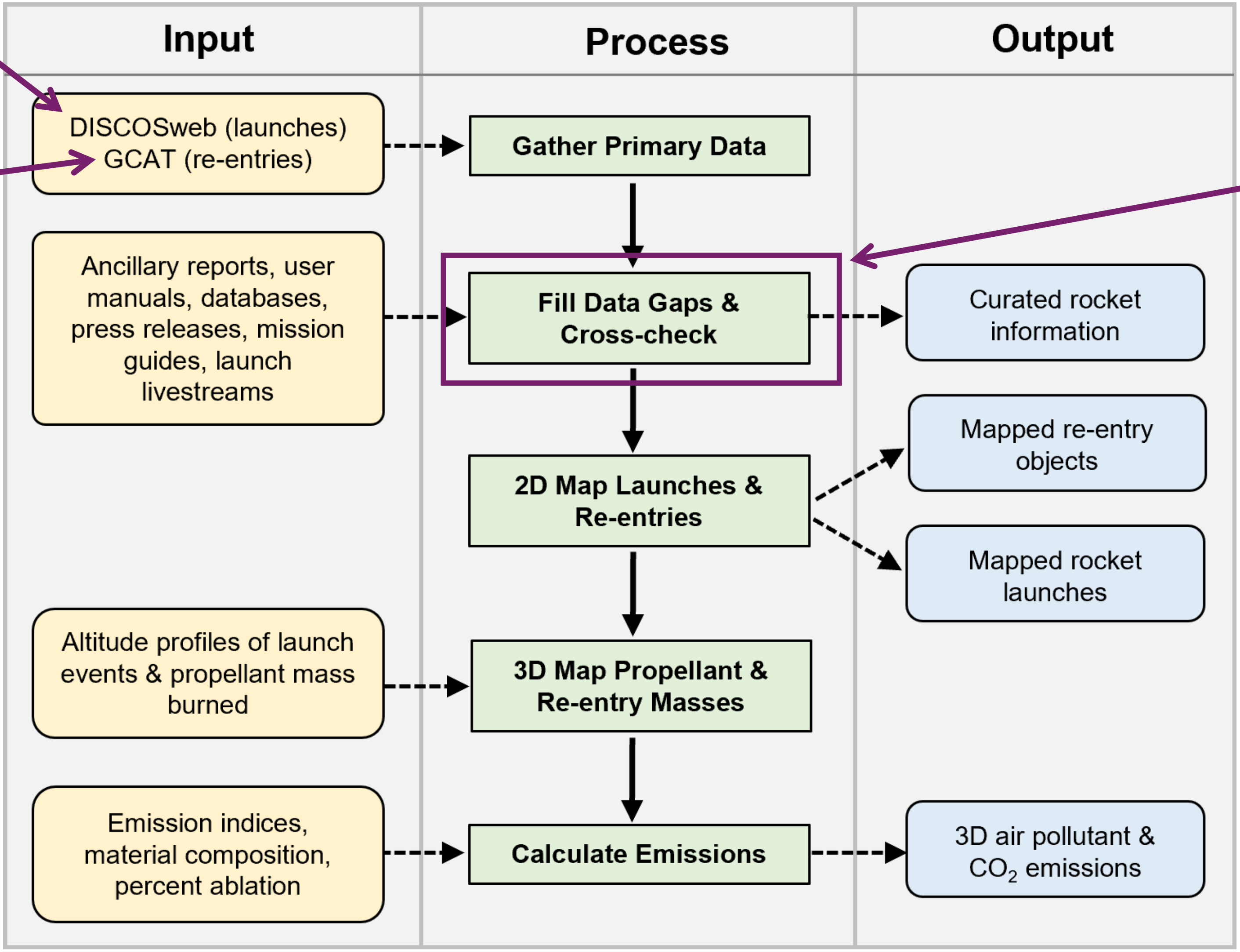
[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

Emissions Inventory Processing Pipeline

Initial inventory developed for **2020-2022** legitimized by peer review

ESA database

Catalogue maintained by Jonathan McDowell

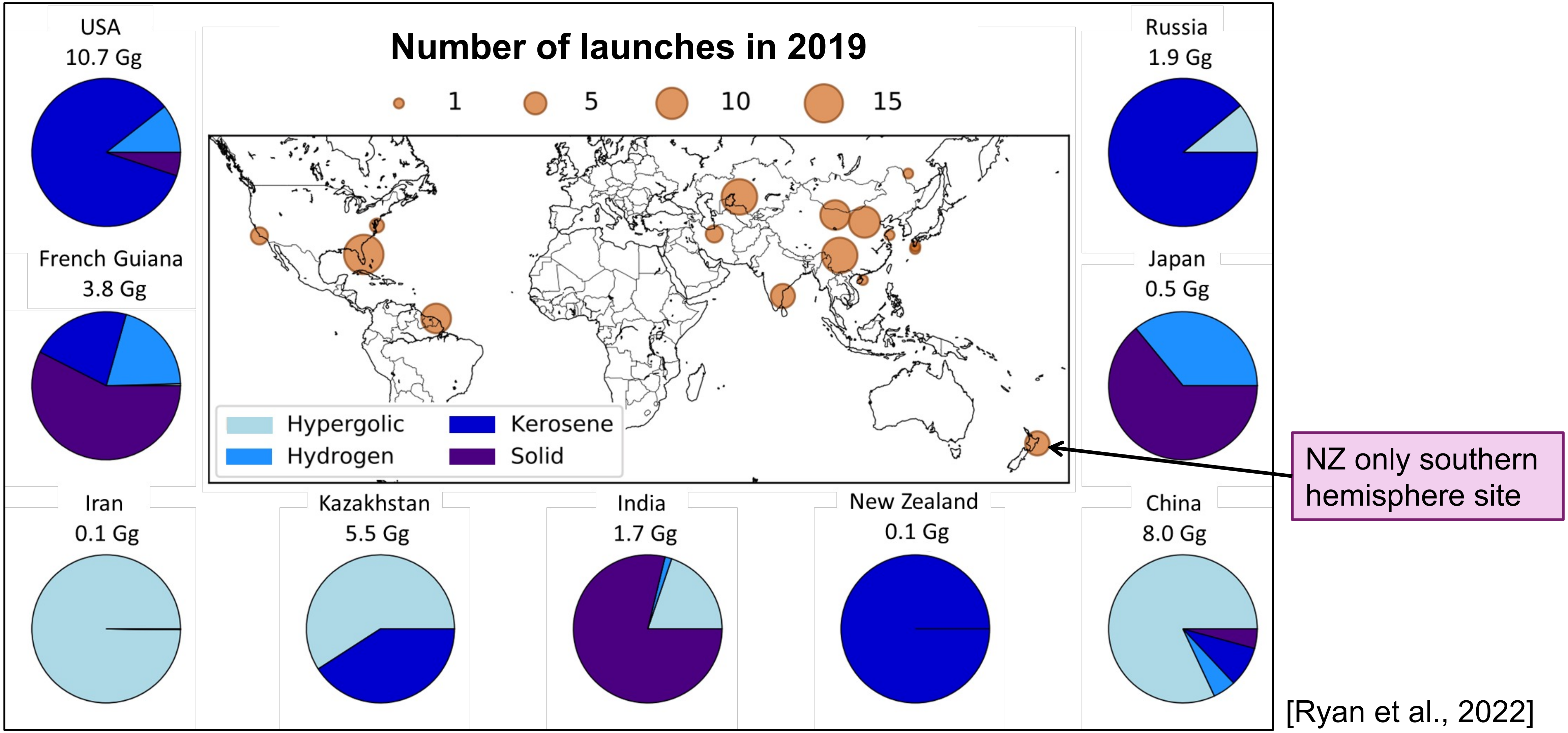


Critical step:

- Data gaps
- Incorrect data
- Inconsistent data

[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

Rocket Launch Locations



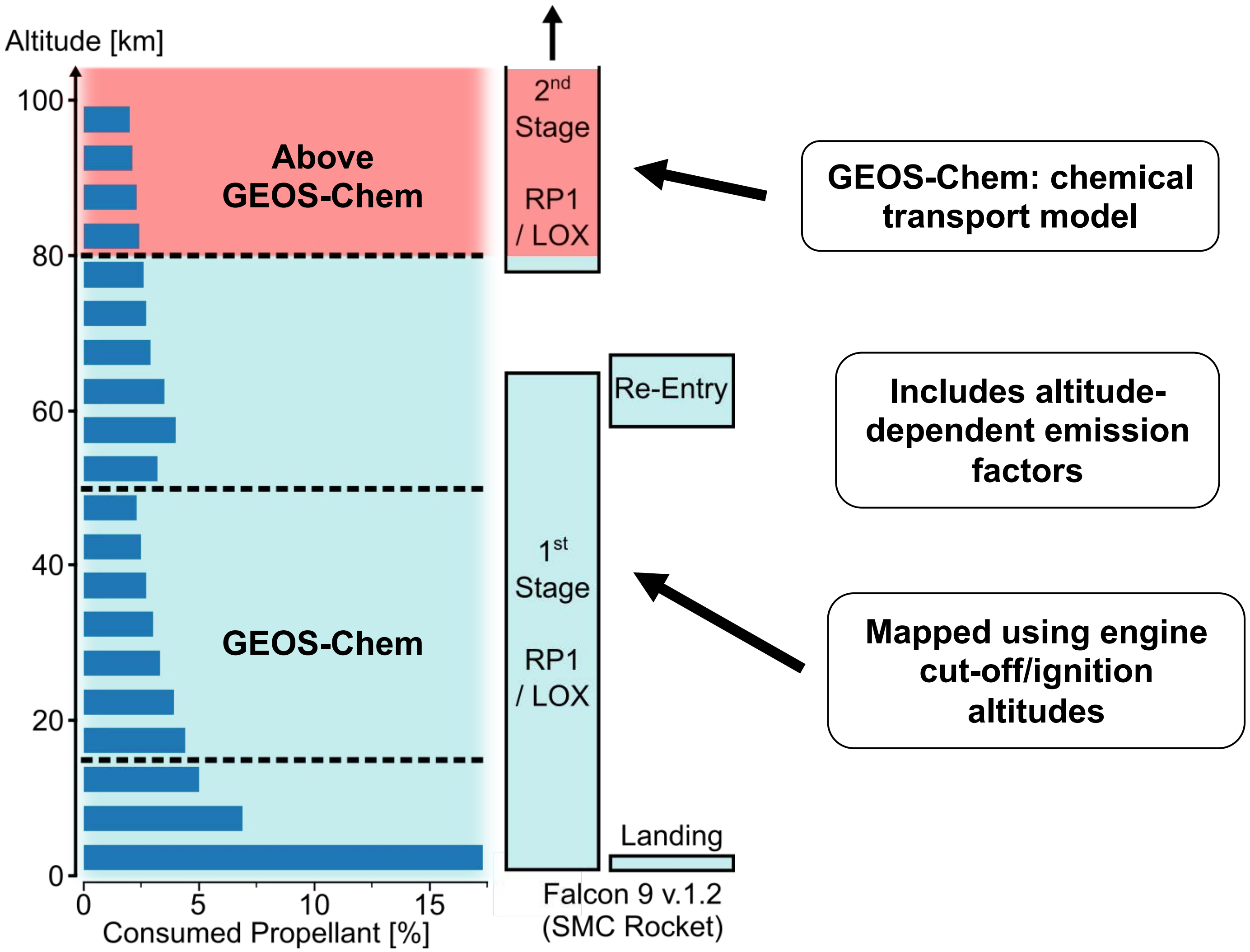
[Ryan et al., 2022]

Different year, but most launch sites similar to those used from 2020 onward

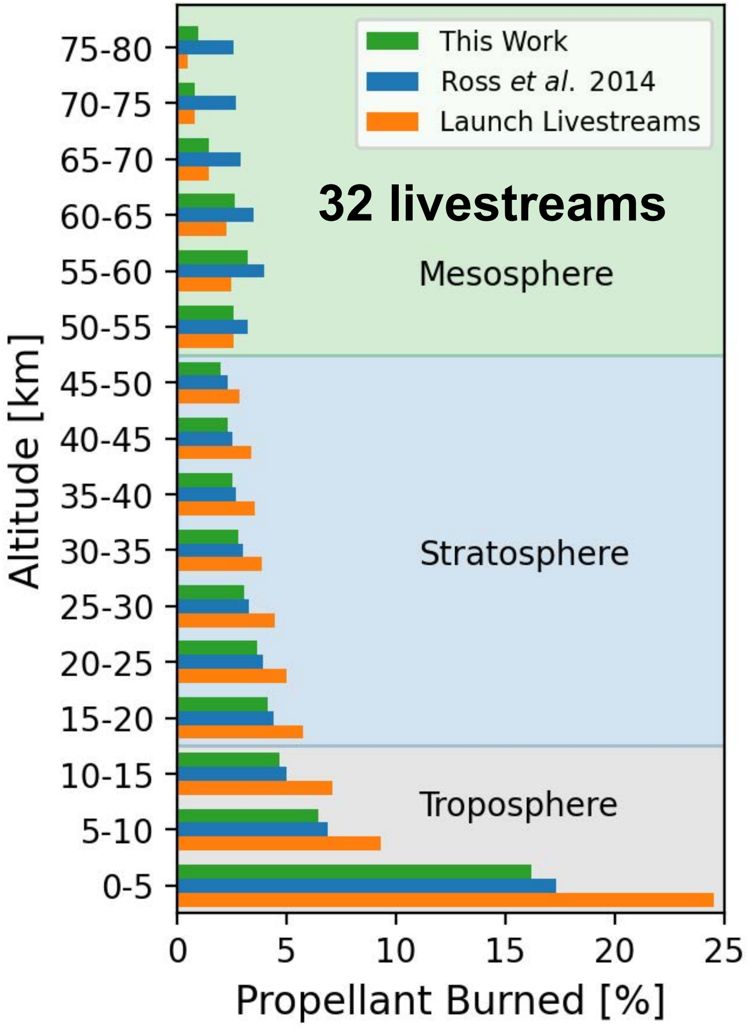
New sites include the UK (Cornwall) in 2023 and Norway in 2025

Vertical Distribution of Launch Emissions

Example vertical mapping of Falcon 9 kerosene (RP1) rocket



Assessment against other constraints

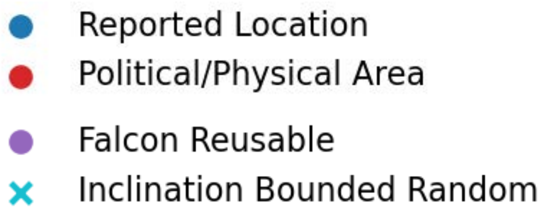


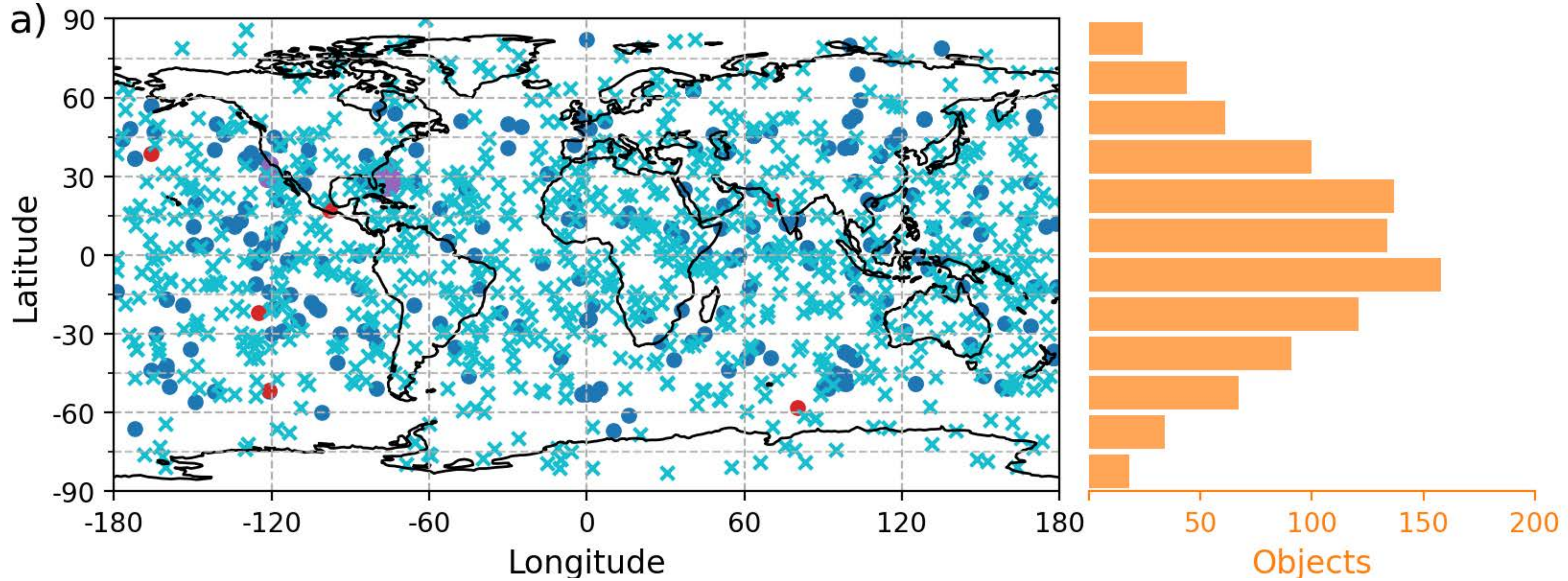
[Barker et al., 2024]

Annual propellant consumption increased from 36 kilotonnes in 2020 to 63 kilotonnes in 2022

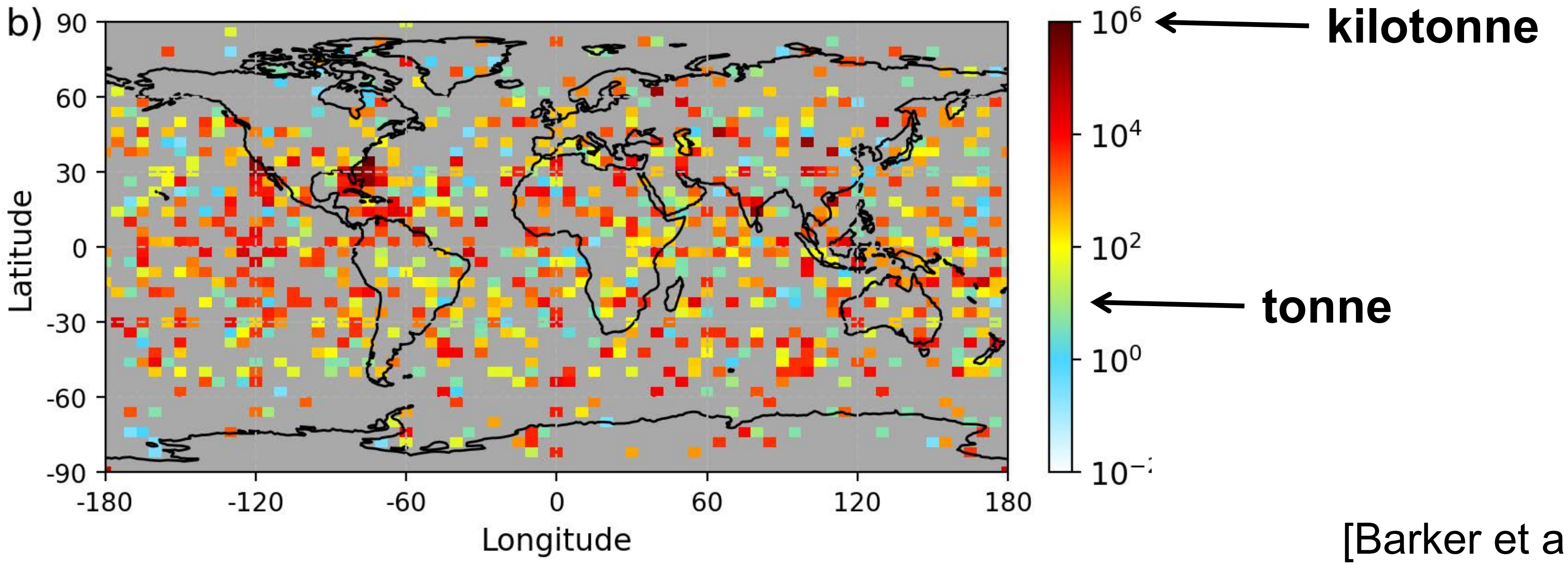
Location and Mass of Reusable and Discarded Re-entries

Re-entry Locations (2022):





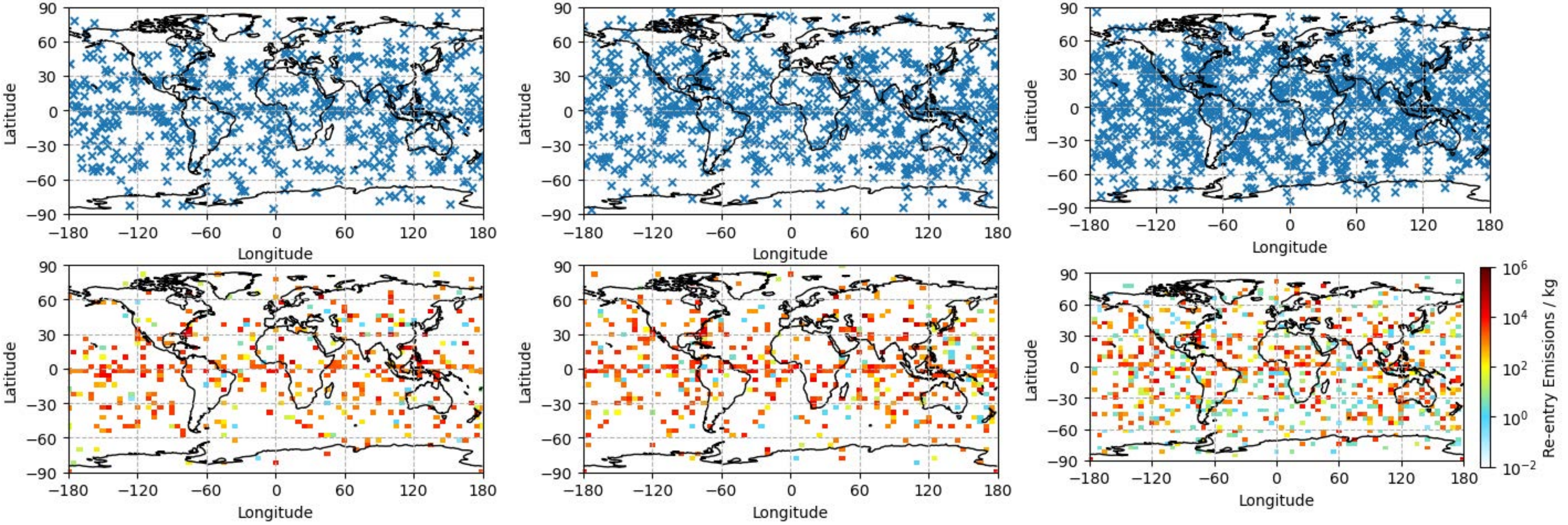
Re-entry Mass (2022):



[Barker et al., 2024]

Annual Increase in the Number of Re-entering Objects

2020	**2021**	**2022**
878 objects	1095 objects	1650 objects

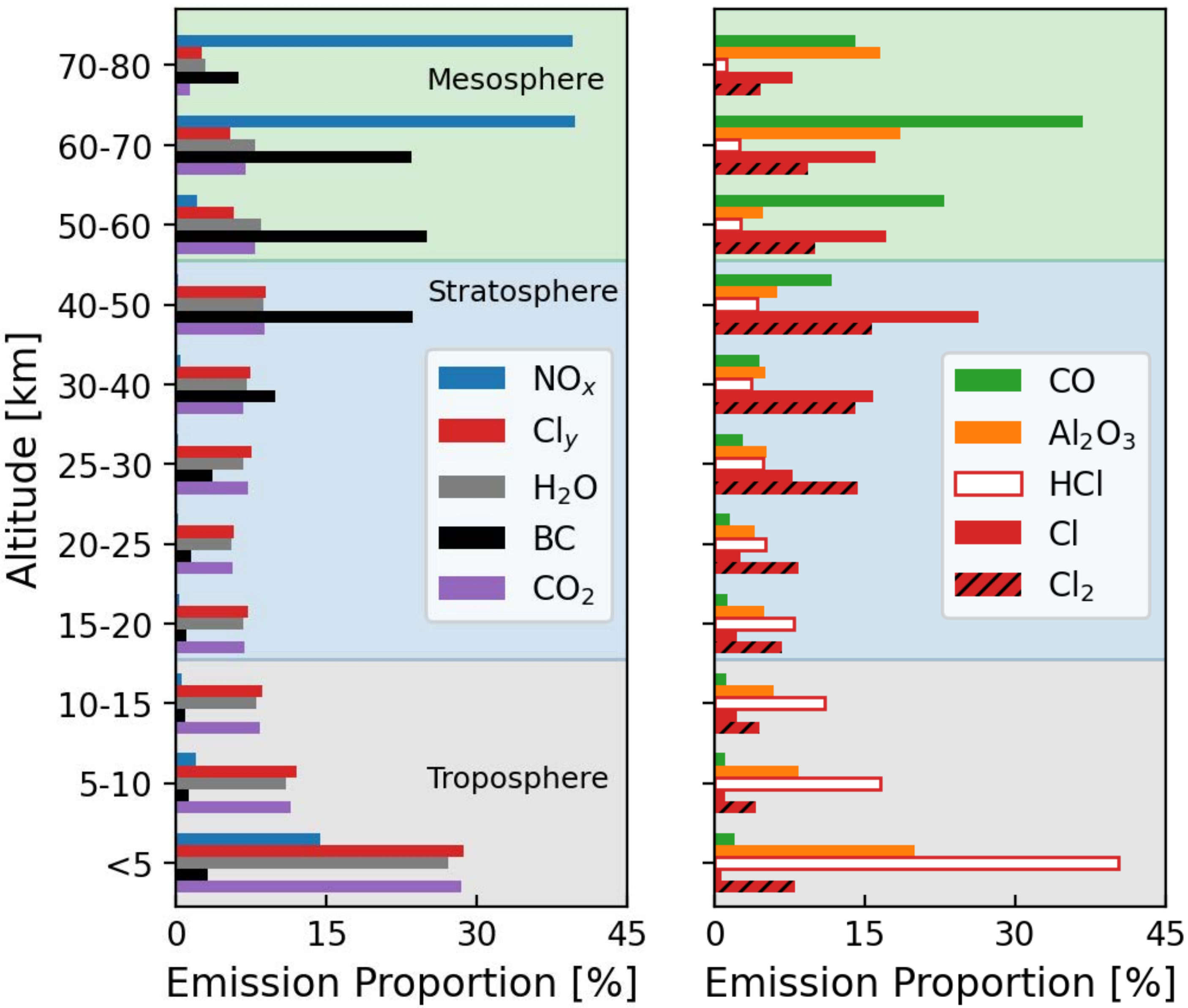


Increase in re-entry mass from 3.2 kilotonnes in 2020 to 5.0 kilotonnes in 2022 (~40% natural influx)

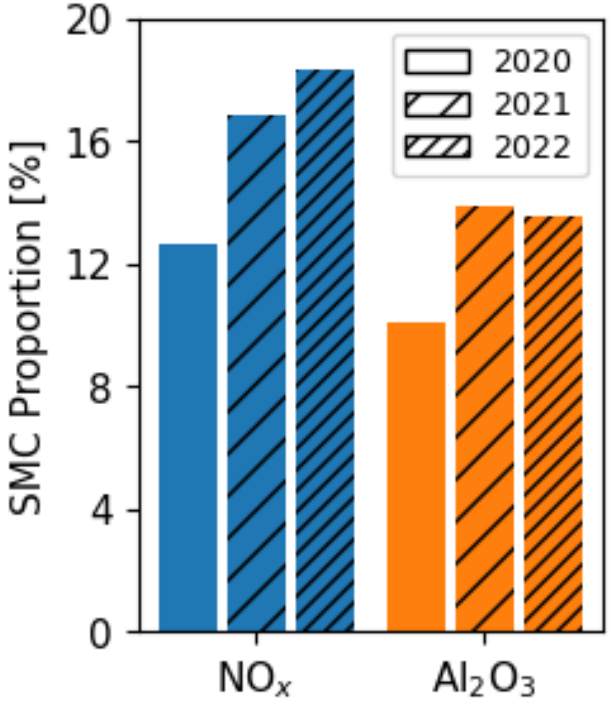
Megaconstellation objects increase from 18% of all re-entering mass in 2020 to 25% by 2022

Vertical Profiles of Air Pollutants and CO_2

Relative distributions for 2022



Re-entry NO_x and Al_2O_3 dominant in mesosphere.



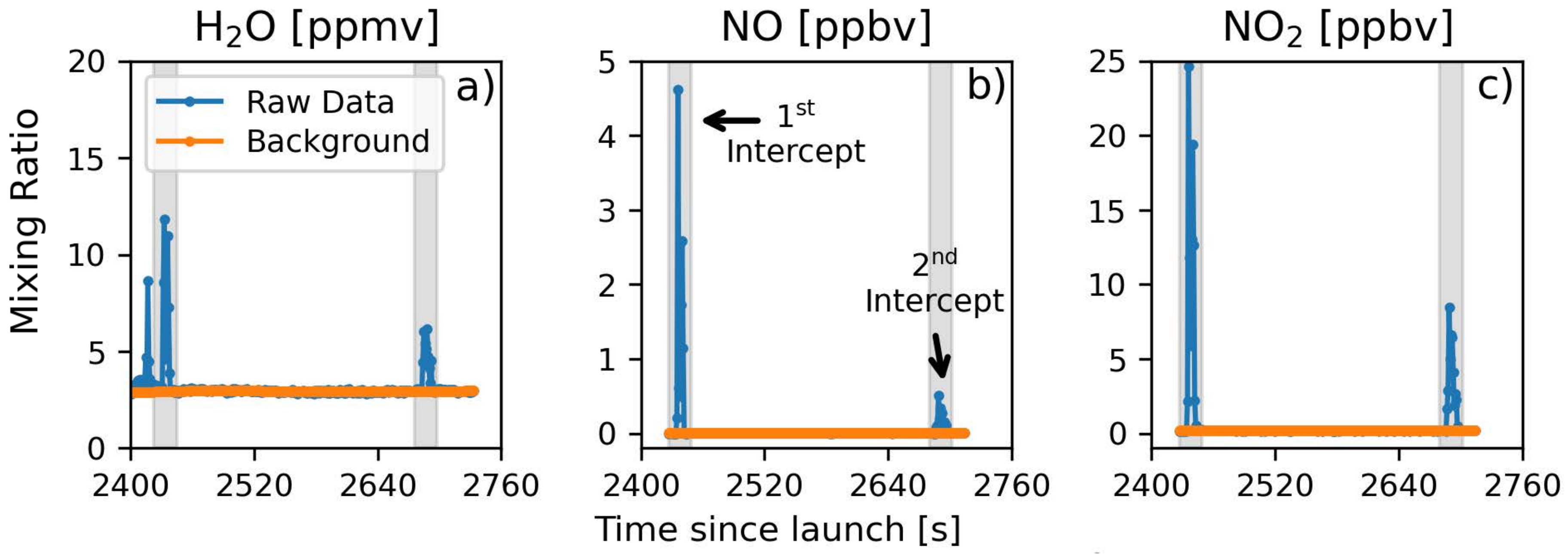
SMC contribution to re-entry NO_x increases from 13% in 2020 to 18% in 2022

[Barker et al., 2024]

Rare Opportunity to Evaluate Emissions

SABRE 2023 campaign measurement by researchers at NOAA and NASA:

G. S. Diskin, J. P. DiGangi, Y. Choi, A. W. Rollins, E. Waxman, T. P. Bui, C. K. Gatebe, J. Dean-Day, R. Poudyal



2 intercepts of a SpaceX **Falcon 9** kerosene fuelled rocket on 18 February 2023

41-45 min after launched at ~16 km altitude (lower stratosphere)

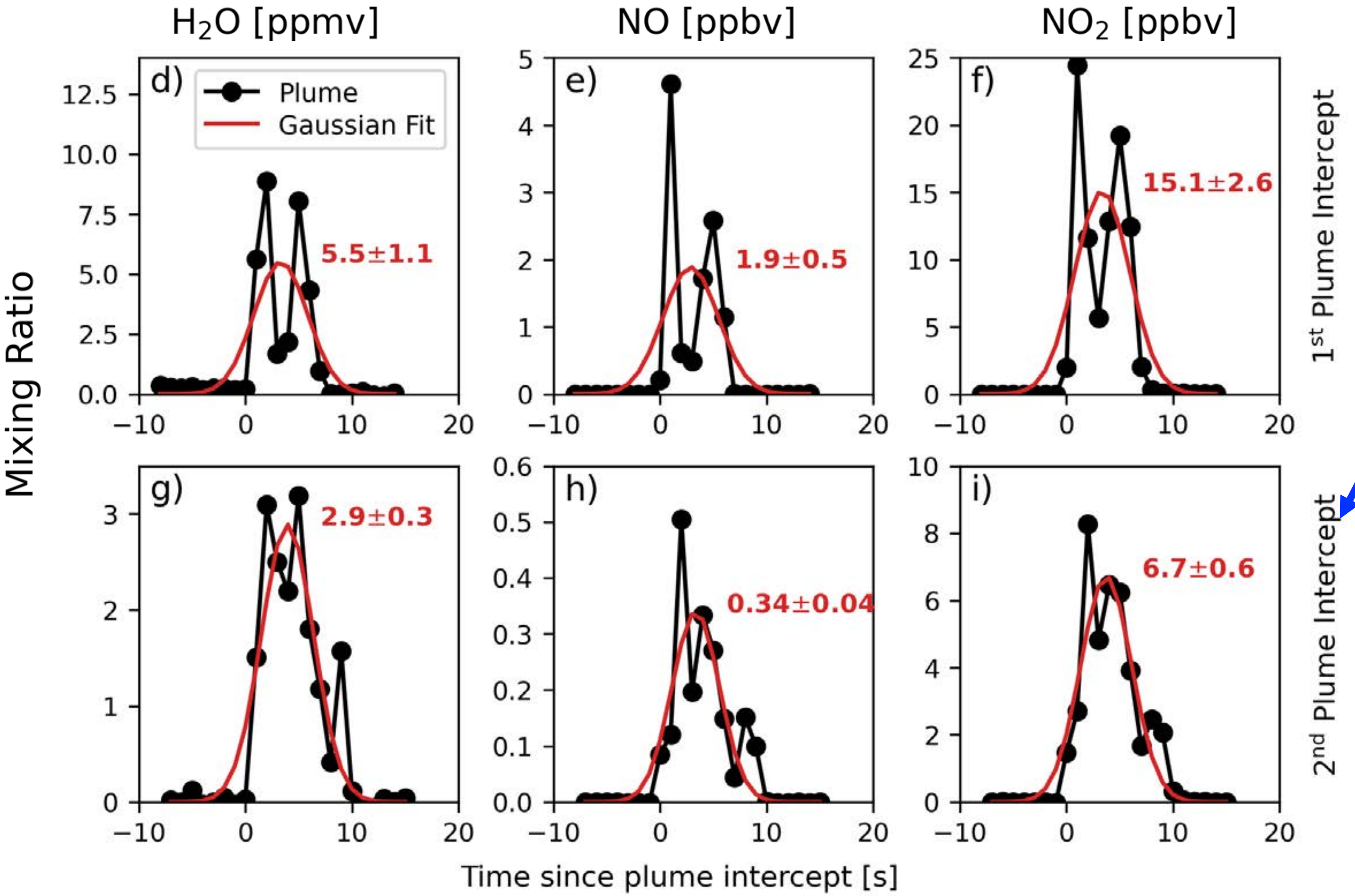
NO_x ($NO + NO_2$) and H_2O preserved (long-lived in the stratosphere)

No SO_2 detected, so not measuring research aircraft exhaust emissions

[Barker et al., *in review*]

Measured vs Inventory Emission Indices

Gaussian fit to plume to calculate mixing ratios in plume



1st intercept

2nd intercept

<u>Measurements:</u>

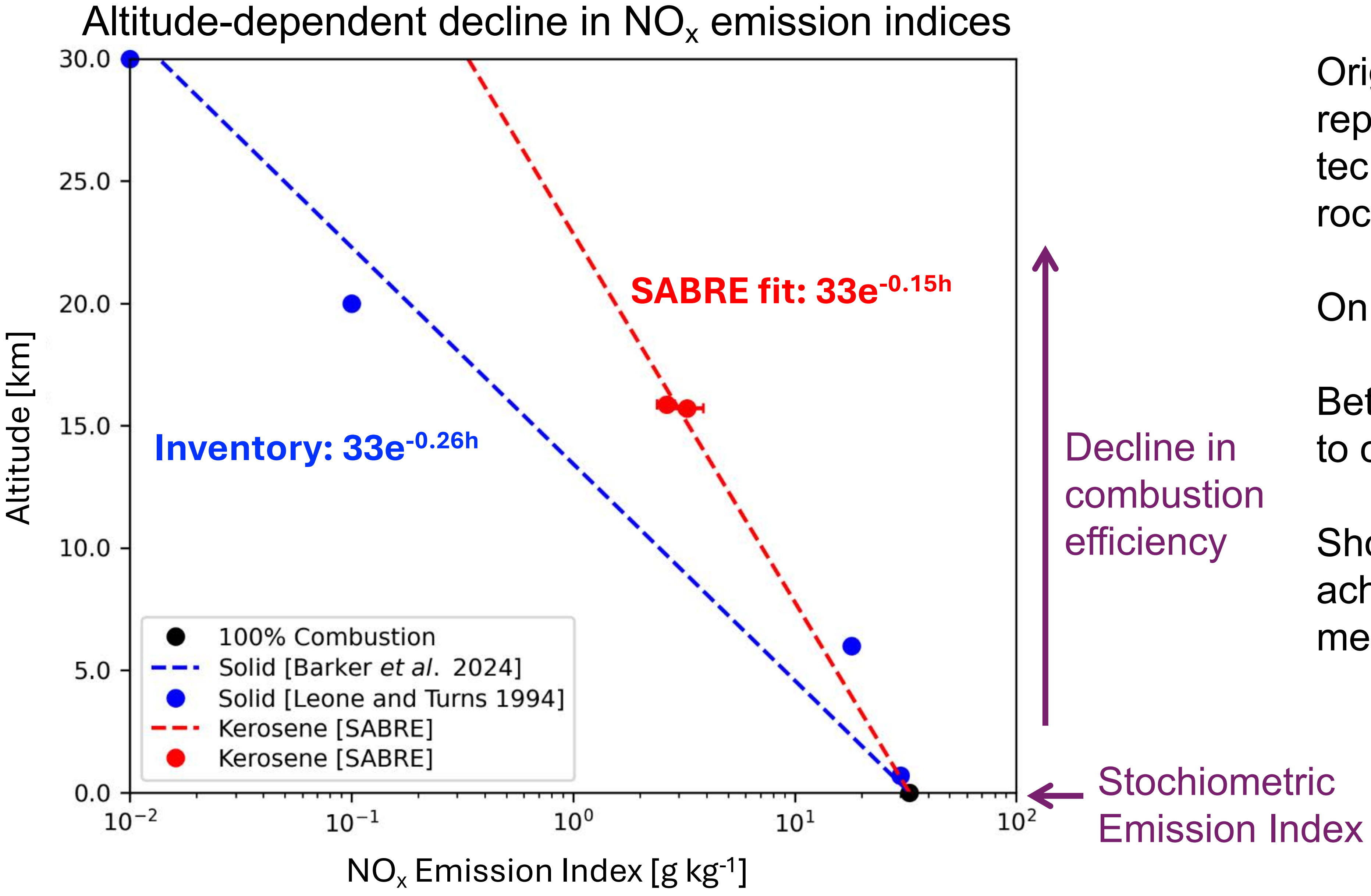
$\Delta NO_x/\Delta H_2O$ = 6.1-7.6 ppb ppm^{-1}

<u>Inventory:</u>

$\Delta NO_x/\Delta H_2O$ = 1.2-1.3 ppb ppm^{-1}

Use H_2O rather than CO_2, as H_2O is conserved with altitude. Similar results if integrate under plume

Measured vs Inventory Vertical Emissions Profiles



Original profile from 1994 report of outdated rocket technologies (mostly solid rockets)

Only 2 plume intercepts

Better than currently using to constrain emissions

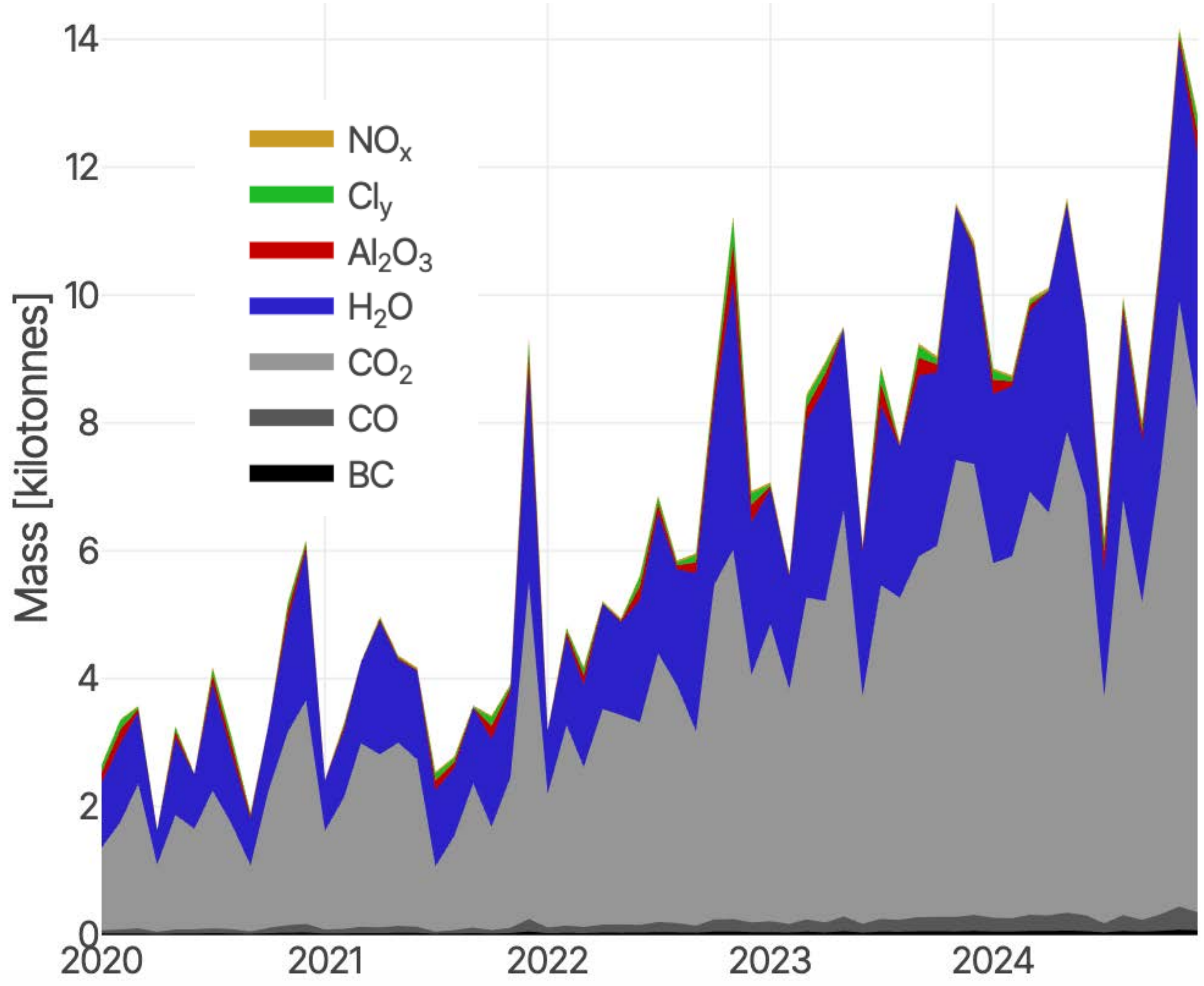
Shows what could be achieved with more measurements!

Comparison suggests decline in combustion efficiency much slower than assumed in the inventory

Online Emissions Tracker for Launches

Extended to include 2023-2024 by UCL Astrophysics summer research student, Eric Tan

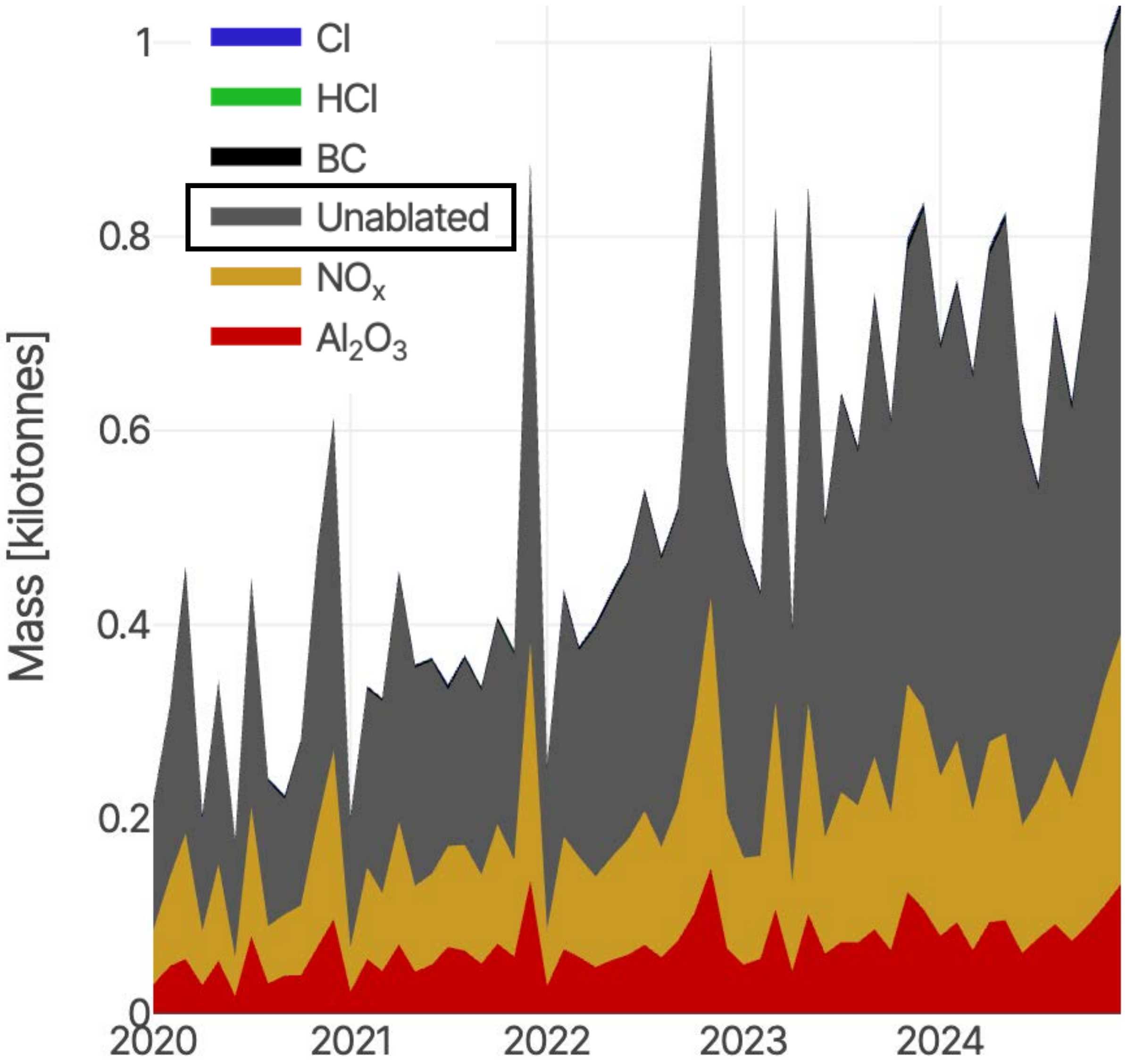
Byproducts from launches:



By 2024, propellant use for megaconstellations surpasses that for all other missions combined

Online Emissions Tracker for Re-entries

Byproducts from re-entries:



Unablated: Increased risk to life on Earth

Includes BC and chlorine emissions not in our published inventory

Give it a try!

Launches byproducts

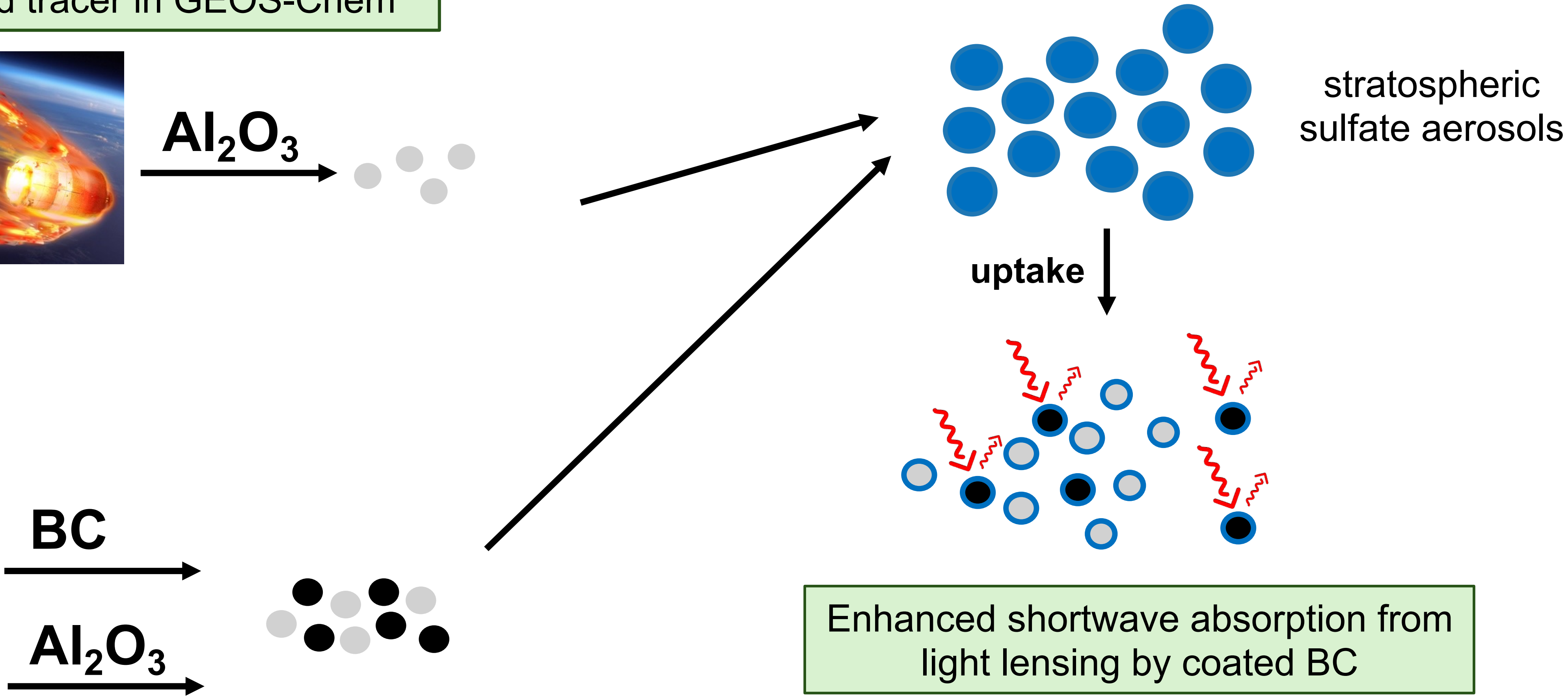
Re-entries byproducts

New developments coming soon:
migrate to dedicated website, extend record to 1957 (start of space race)

Update GEOS-Chem with Latest Science

Alumina (Al_2O_3) added as advected tracer in GEOS-Chem

Prompt uptake of BC and Al_2O_3 to stratospheric sulfate



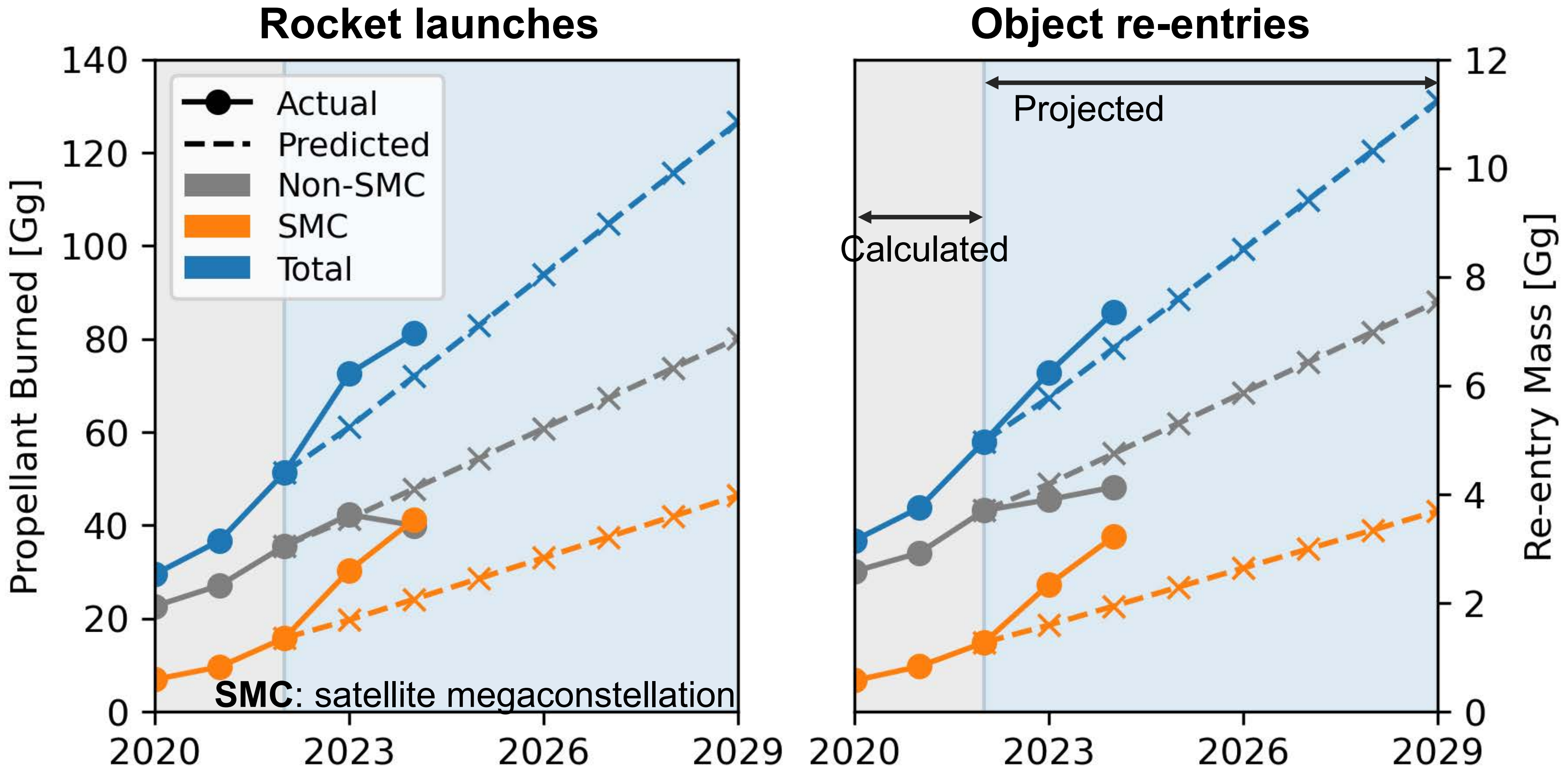
Enhanced shortwave absorption from light lensing by coated BC

Many more aerosol-phase compounds formed during re-entry that depends on composition of ablating material

****not to scale****

Project Emissions to 2029 and Evaluate

Current (2020-2022) and projected (2023-2029) spacecraft launch and re-entry activities



[Barker et al., *in review*]

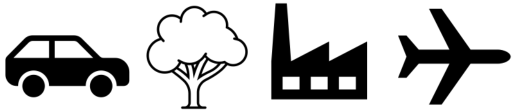
Underestimate growth in launches and re-entries from all missions due to underestimate in growth of activities associated with megaconstellation missions

Implement Emissions in GEOS-Chem

Offline meteorology, so does not respond to composition changes

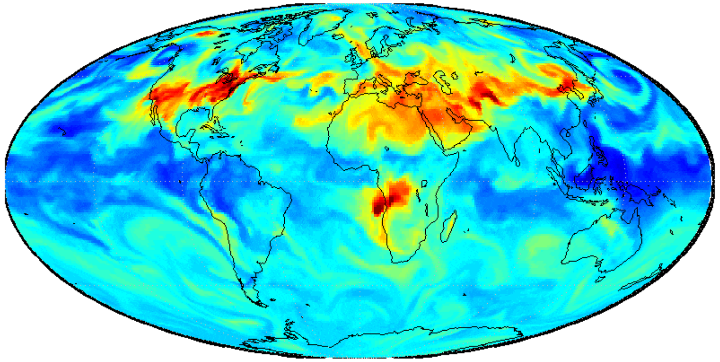
NASA MERRA-2 Meteorology

All typical precursors



GEOS-Chem

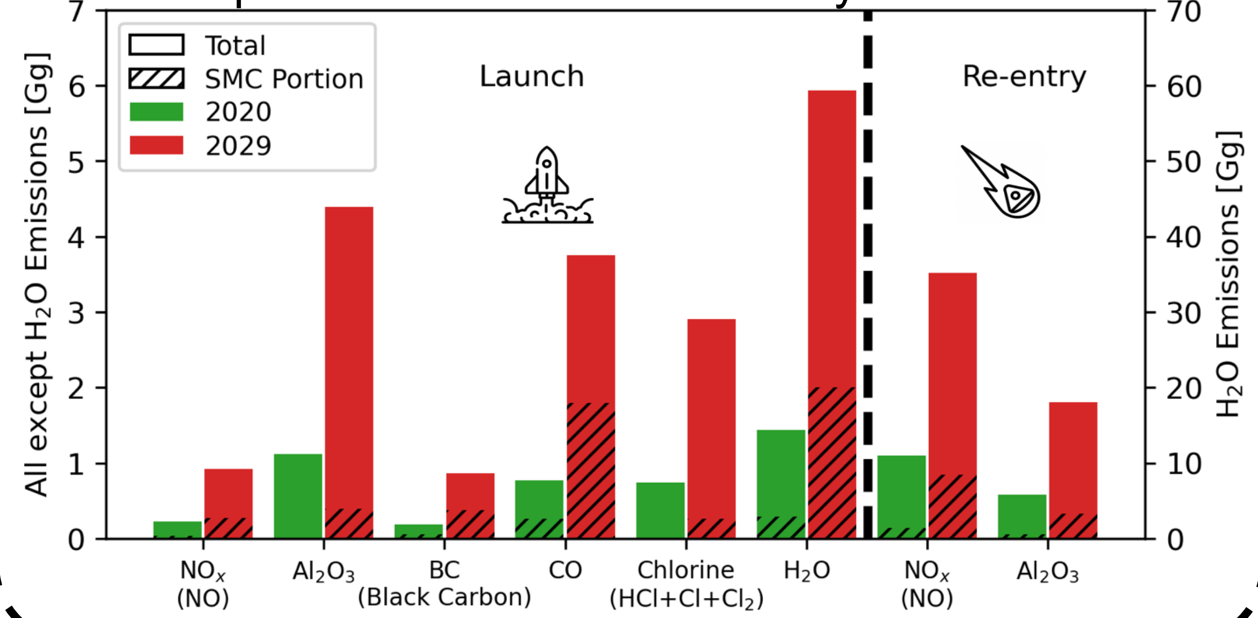
+ Radiative transfer model **(RRTMG)**



2020-2029
4° x 5°, 47 layers to 80 km

one-way coupled, RRTMG updated 3-hourly

Spacecraft launch and re-entry emissions



<u>Simulate 3 scenarios:</u>

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

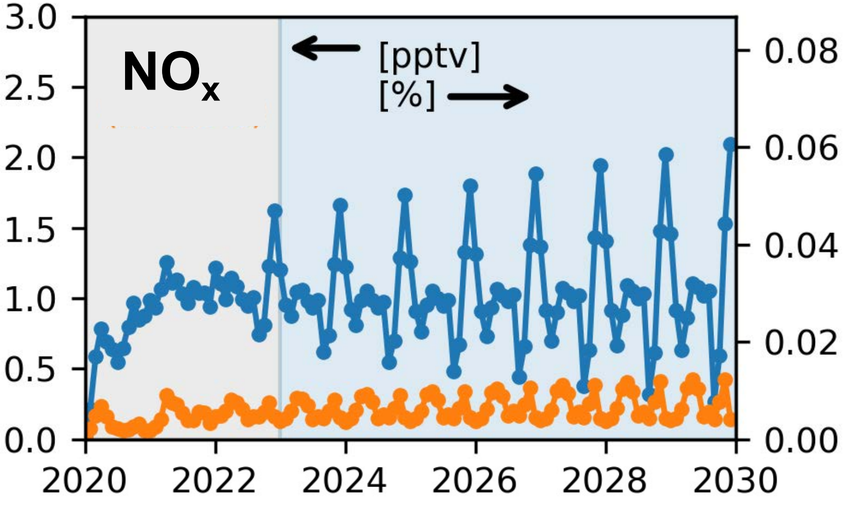
Output:

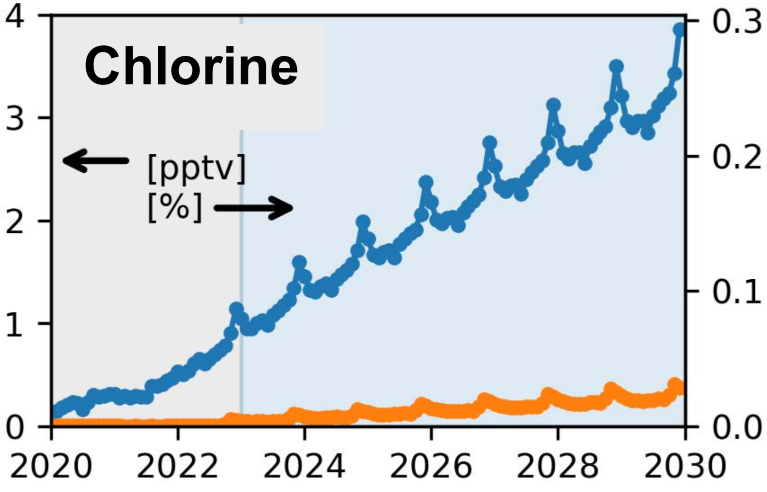
Atmospheric Composition
Radiative Forcing

[Barker et al., *in review*]

Effect on Stratospheric Composition (Gas-phase)

GEOS-Chem changes in global monthly mean stratospheric composition of gaseous compounds





Contribution of SMCs:

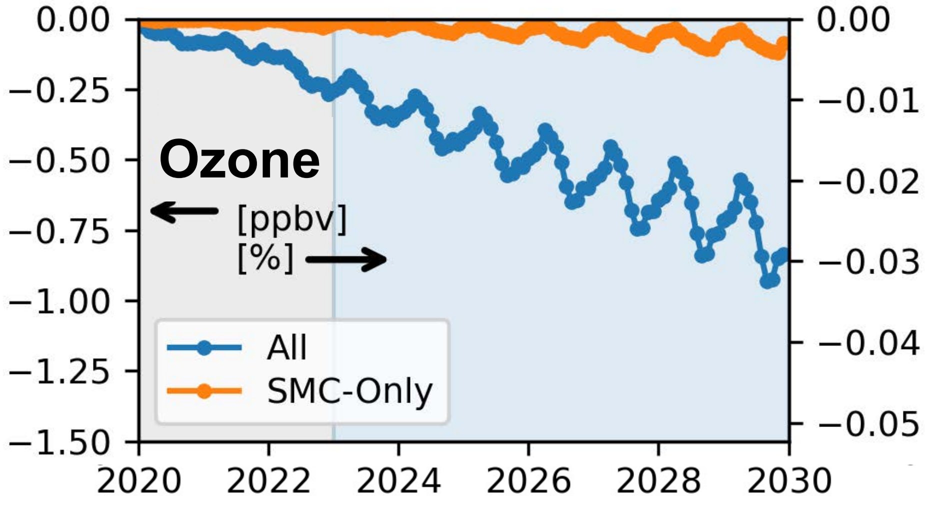
NO_x: 19% (2020) to 23% (2029)

Chlorine: 5% to 9%

Ozone: 7% to 10%

<u>Chlorine (Cl_y)</u>:

$2Cl_2$+$ClNO_3$+$2Cl_2O_2$+ClO+ $ClNO_2$+ClOO+HCl+OClO+ BrCl+HOCl+ICl+Cl

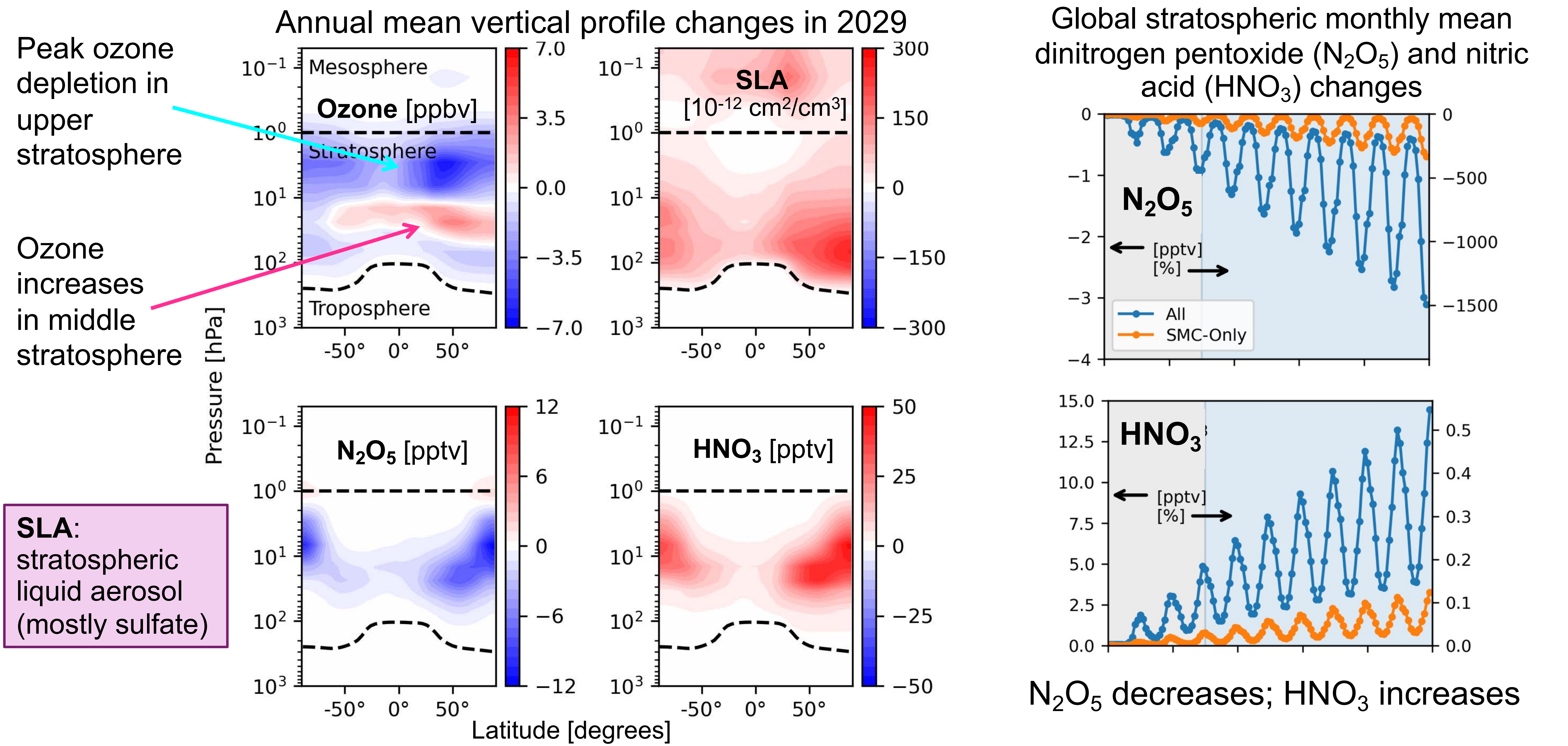


Ozone decline only due to effect of pollutants on single and multiphase chemistry (radiative forcing also important)

Modest decline (0.03%) in ozone compared to CFCs (~2%)

Most of ozone decline due to chlorine from solid propellant not used much currently for megaconstellations

Vertical Distribution of Stratospheric Ozone Changes

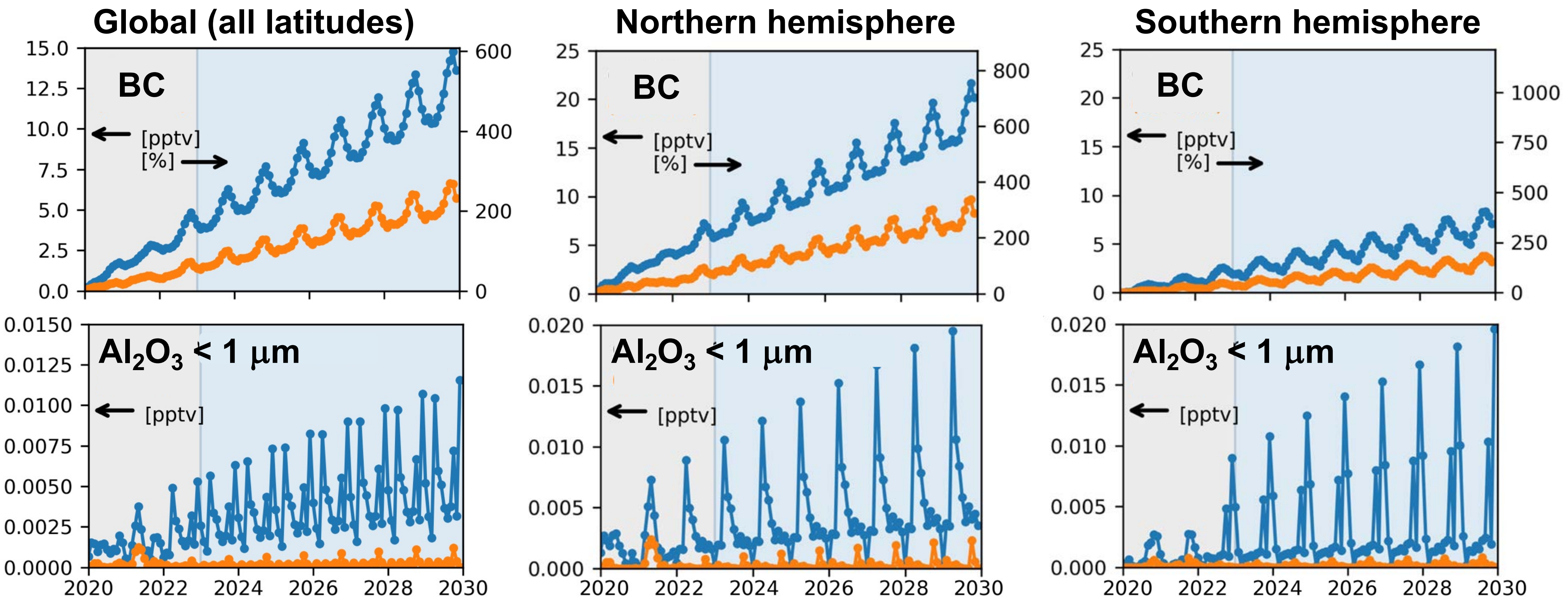


N_2O_5 decreases; HNO_3 increases

SLA increases from uptake of BC and Al_2O_3, facilitates N_2O_5 hydrolysis to HNO_3, suppresses NO_x recycling

Effect on Stratospheric Composition (Aerosols)

GEOS-Chem changes in monthly mean stratospheric composition of directly emitted aerosols



BC: total; **Al_2O_3**: not taken up by stratospheric sulfate

SMC portion for BC increases from 38% in 2020 to 44% in 2029. Al_2O_3 4% in 2020 relatively unchanged

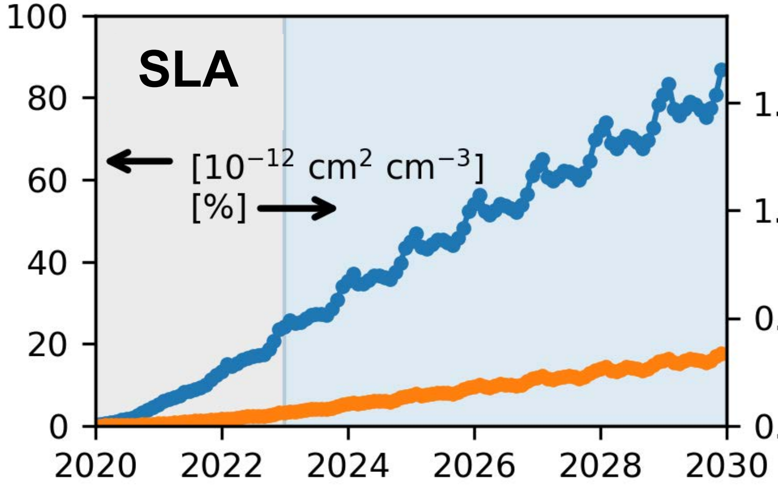
BC governed by northern hemisphere, whereas Al_2O_3 is a mix of launch and re-entry ablation

Effect on Stratospheric Composition (Aerosols)

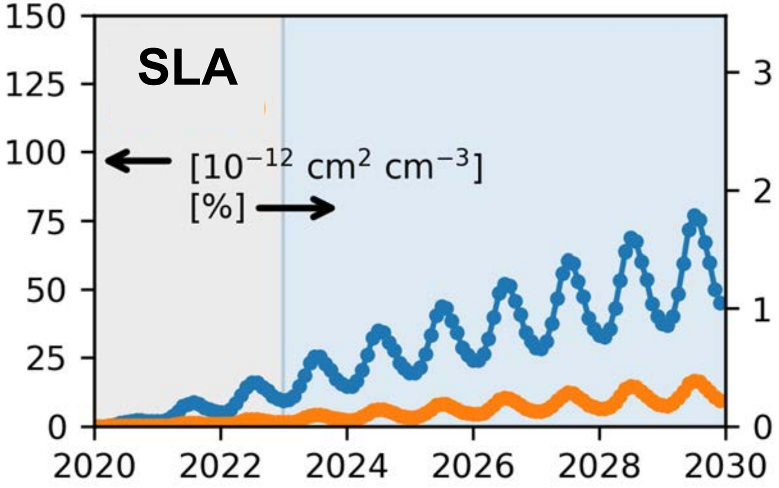
GEOS-Chem monthly mean increases in stratospheric liquid aerosols (SLA) dominated by sulfate

SLA absolute changes are in aerosol surface concentration units of $\mathbf{10^{-12}\ cm^2\ cm^{-3}}$

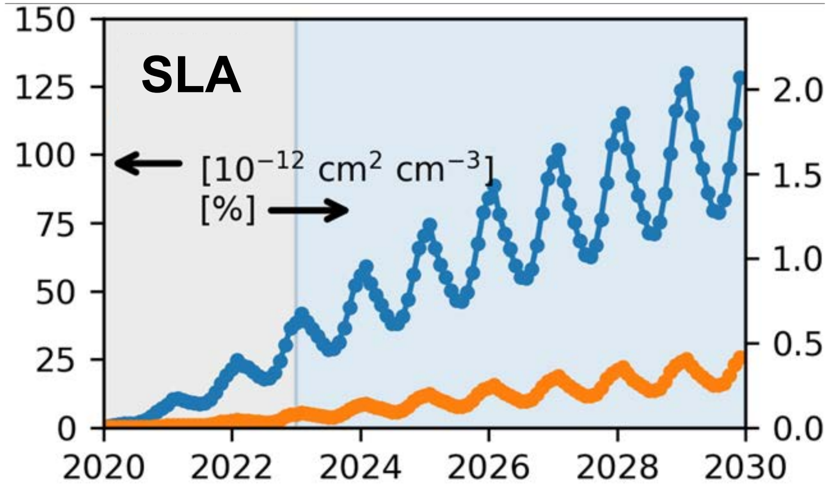
Global (all latitudes)



Northern hemisphere



Southern hemisphere



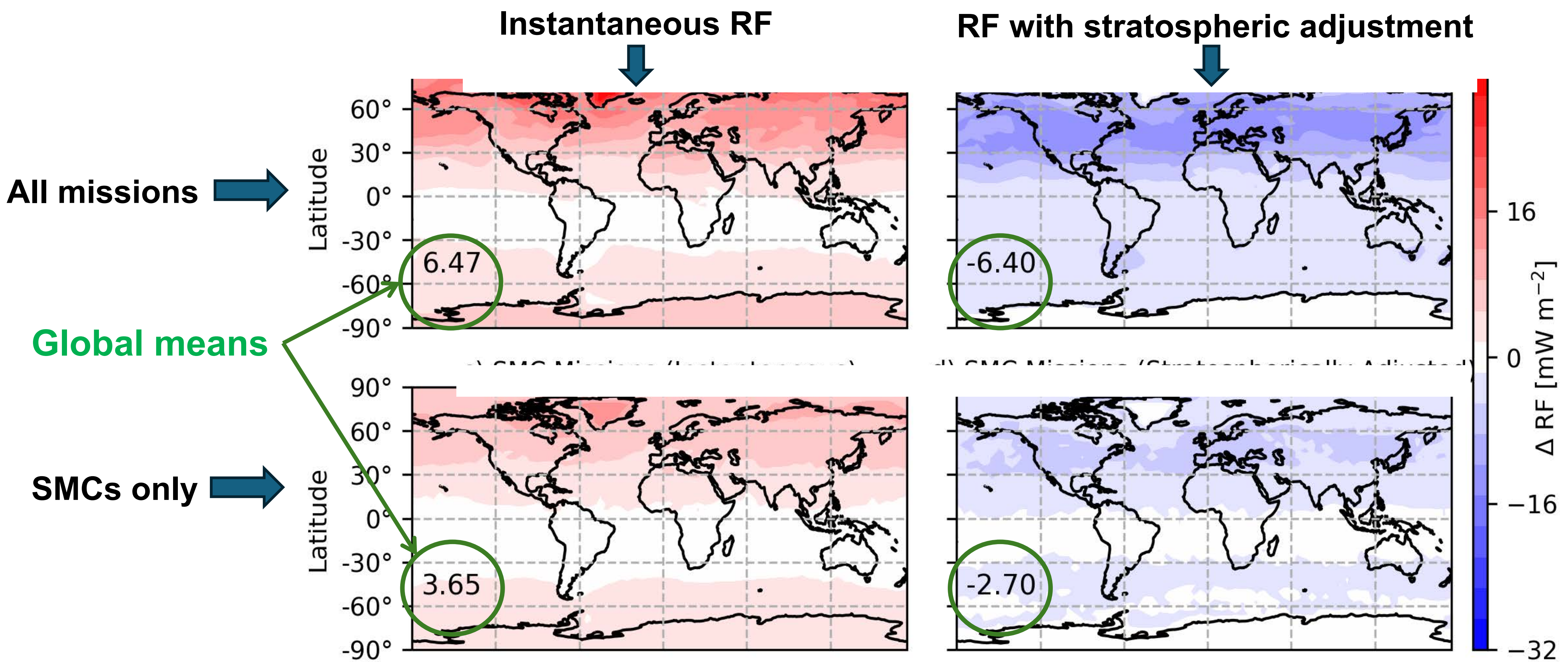
SLA increase mostly due to uptake of launch and re-entry Al_2O_3

Distinct opposite seasonalities in each hemisphere cause relatively flat seasonality in the global mean

Growth in SLA represents an indirect effect on ozone (more surface to activate chlorine to deplete ozone)

Global Radiative Forcing Changes

Annual mean radiative forcing by 2029 calculated with the RRTMG radiative transfer model



Instantaneous positive in response to absorption of incoming sunlight by aerosols in the stratosphere

Decline in incoming sunlight reaching the troposphere leads to negative stratospherically adjustment values

Biggest effect is in the northern hemisphere where almost all launches occur

Contribution of Individual Forcers

Annual global mean speciated radiative forcing in 2029 also calculated with the RRTMG

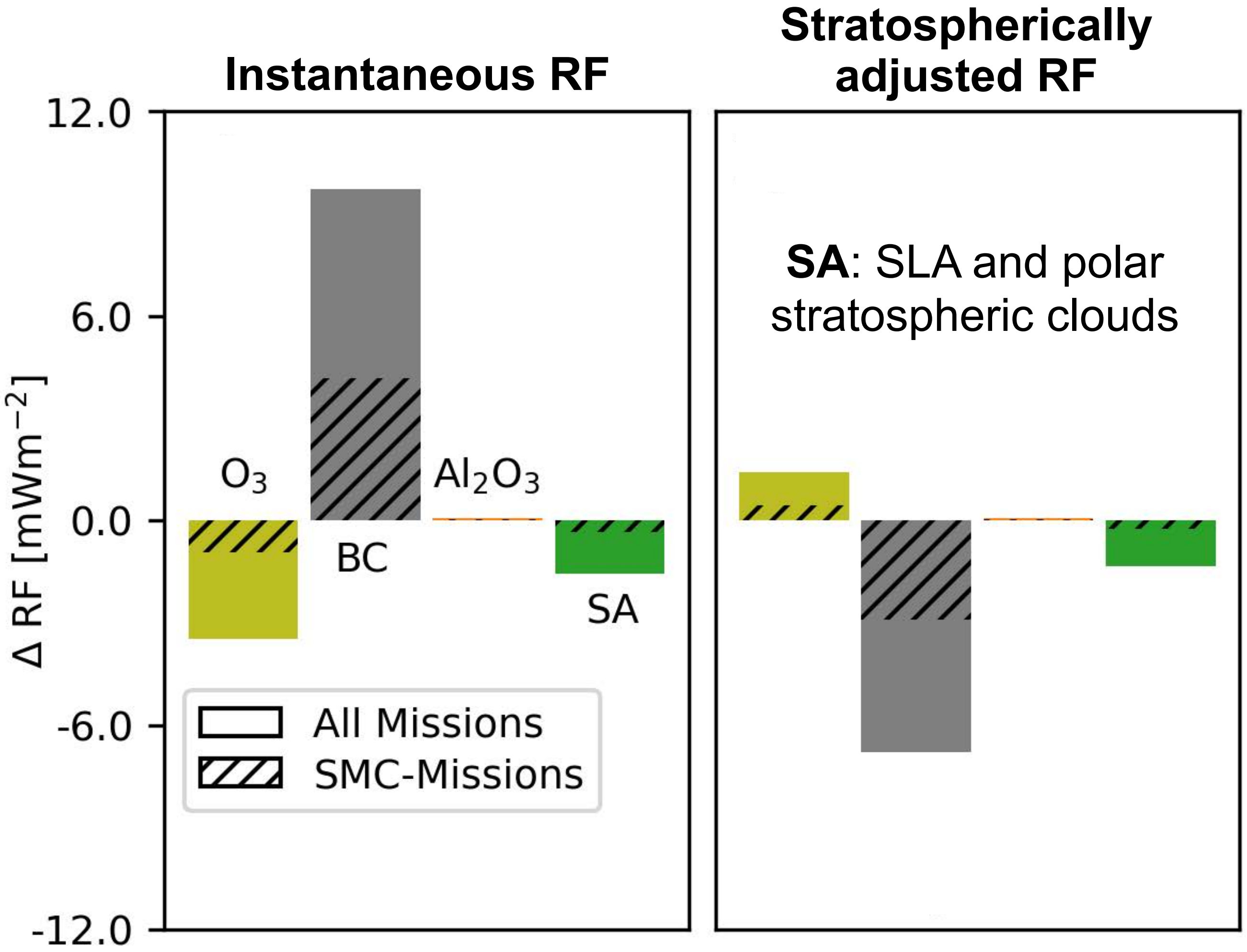
Sign of instantaneous RF:

Ozone: depleted in stratosphere, so absorbs less incoming sunlight

BC: greater absorption of incoming sunlight

Al_2O_3: negligible

SA: greater reflection of incoming sunlight

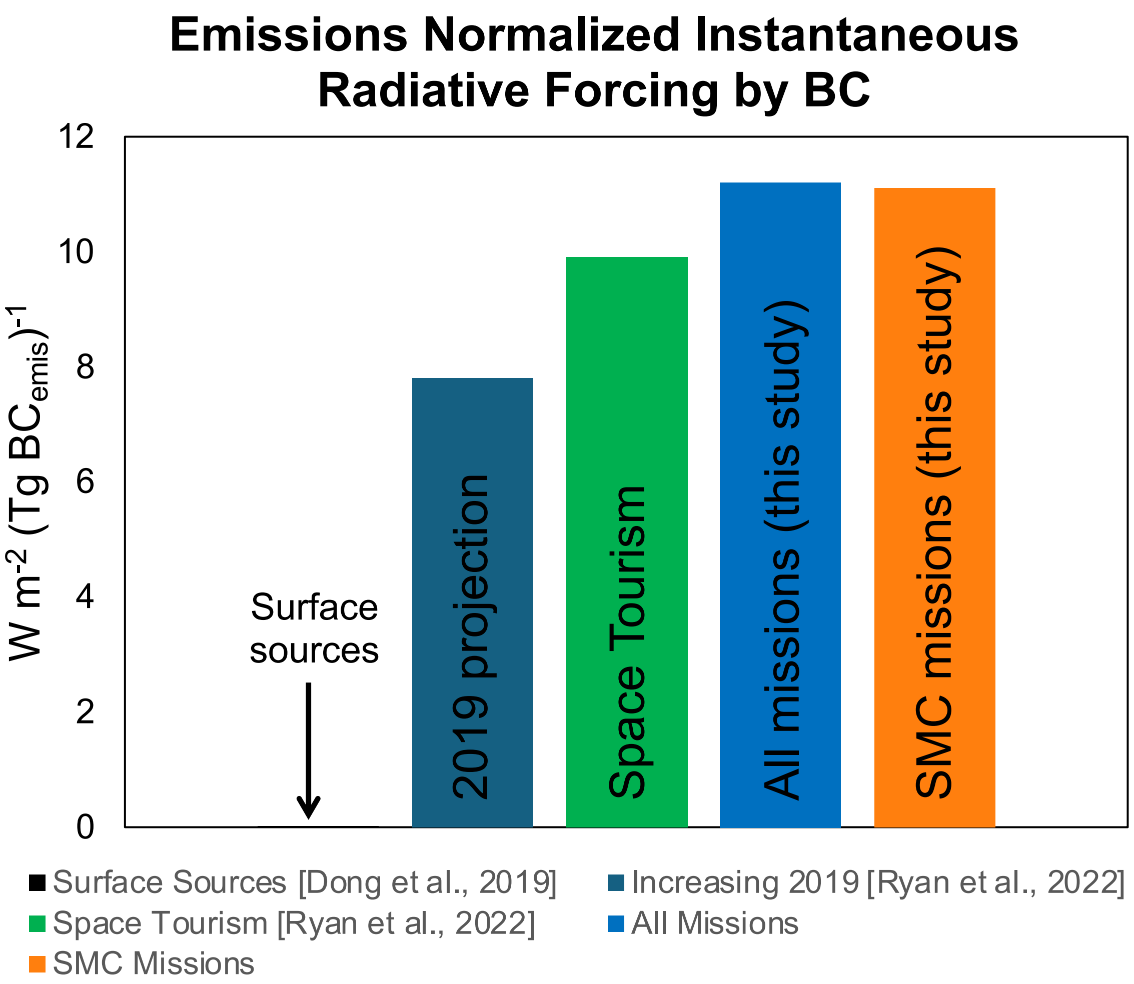


Sign flips for stratospherically adjusted RF if forcer absorbs incoming sunlight (ozone and BC), as alter amount of sunlight reaching troposphere (premise of geoengineering)

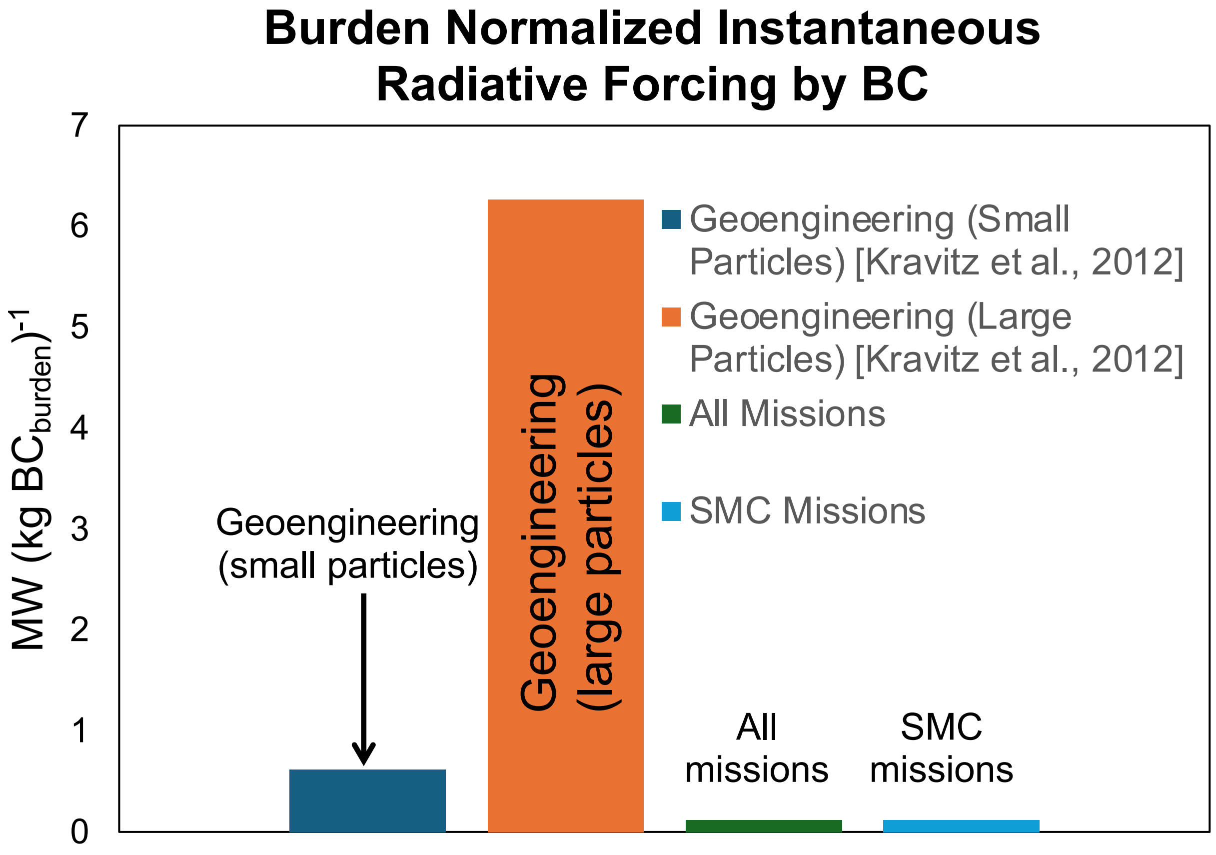
Global radiative forcing dominated by absorption of incoming sunlight by sulfate-coated BC above the tropopause

By 2029, SMCs account for 56% of the instantaneous forcing and 42% of the stratospherically adjusted forcing

Attempt at Giving Spacecraft Radiative Forcing Context



Emissions normalized forcing is ~540 times more than all Earth-bound sources, as BC persists for longer higher up



Burden normalized forcing less than theoretical geoengineering studies assessing 3 orders of magnitude more BC released to the stratosphere than is emitted by spacecraft

Summary of Main Findings

- Falcon 9 inventory NO_x emissions decline much faster with altitude than aircraft measurements suggest
- Future emissions projections for megaconstellations modest in comparison to reality
- Global ozone depletion is 0.03% from all mission types, and an order of magnitude less from SMCs, as few (<2%) SMC launches use solid rocket fuel producing ozone-depleting chlorine
- Sulfate-coated black carbon absorbs shortwave radiation above the tropopause, leading to positive instantaneous forcing and negative stratospherically adjusted forcing
- SMCs account for about half the estimated radiative forcing.
- Negative stratospherically adjusted radiative forcing is synonymous with the intent of geoengineering with stratospheric aerosols, but is untested and uncontrolled.
- Large uncertainties in chemistry of re-entry metals remains, include actual speciation of aluminium (may be aluminium hydroxide rather than alumina)

Relevant Links:

Emissions data **paper** link: https://www.nature.com/articles/s41597-024-03910-z

Emissions inventory **data** link: https://doi.org/10.5522/04/26325382

Atmospheric impacts **paper** preprint link: https://doi.org/10.22541/essoar.175978287.77438242/v1

NERC DTP PhD Studentship

DTP website: https://www.trees-dla.ac.uk/

Deadline: 17 December

Project title: Is SpaceX the Next Air Pollution Frontier?

Project page: https://www.trees-dla.ac.uk/projects/spacex-next-air-pollution-frontier

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