Atmospheric Impacts of Rocket Launch and Spacecraft Re-entry Emissions in the New Space Age

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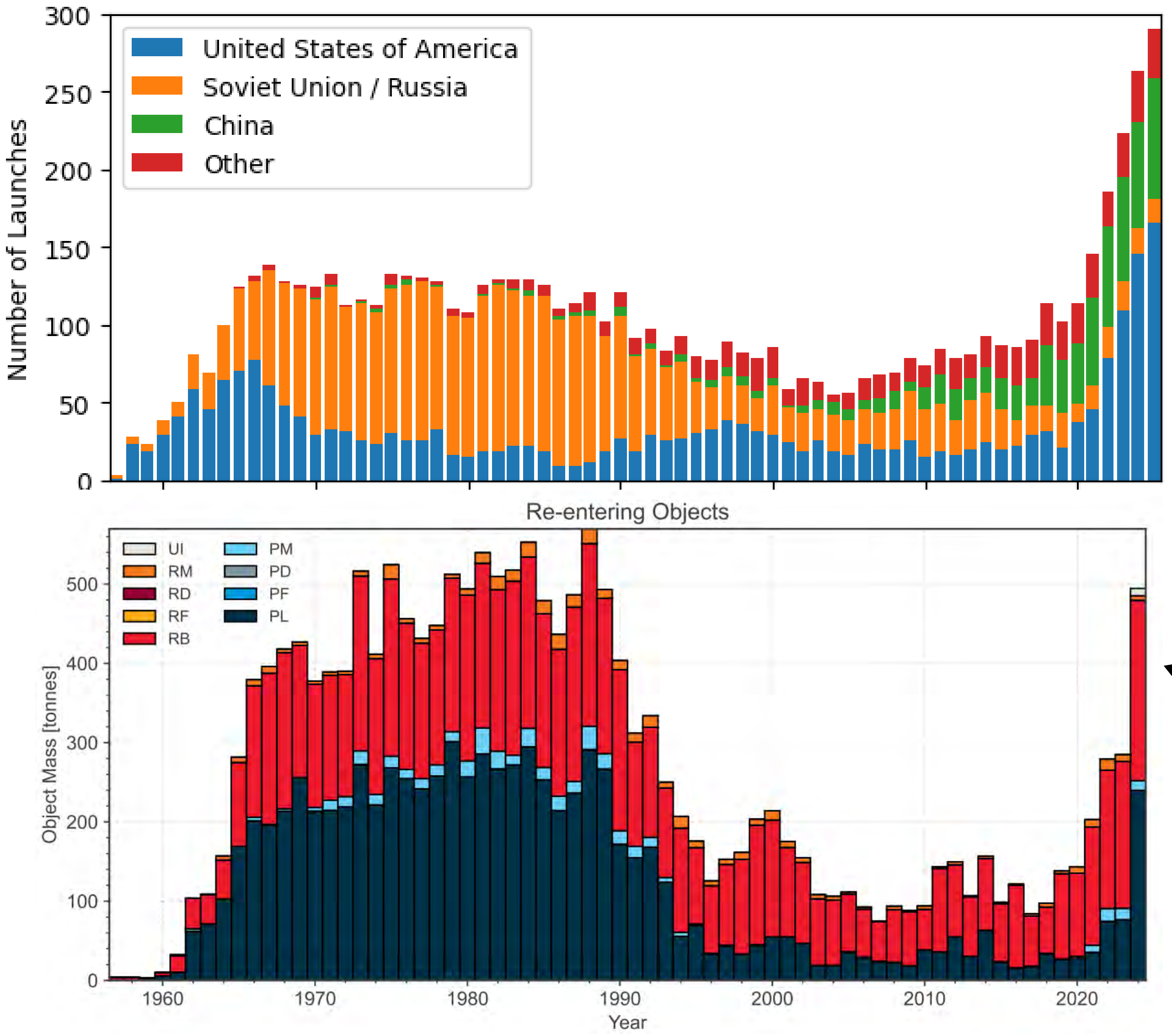
11th December 2025

Recent Surge in Launches and Re-entries



295 this year already!

The US and China now dominate the space environment

Re-entry mass is now close to 1980s levels

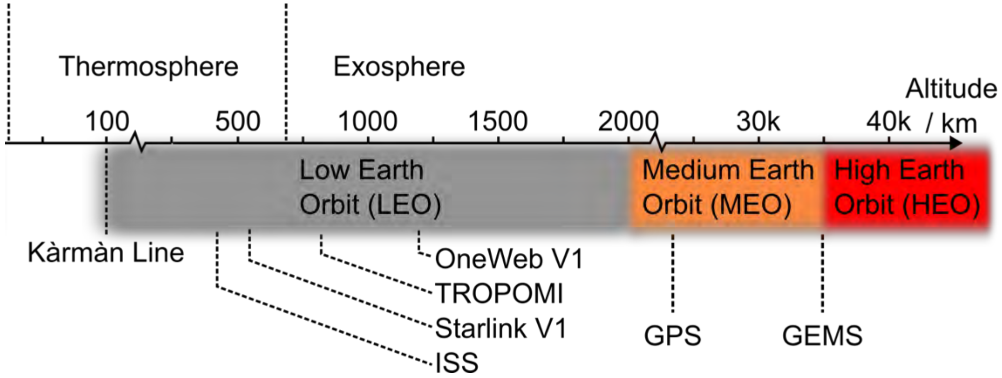
Space Race

Cooperation / Privatisation

New Space Race…

[ESA, Jonathan's Space Report]

Satellite Megaconstellations (SMCs)



SMCs contain 100s – 1000s of satellites in LEO, reducing latency and increasing coverage

SpaceX Starlink (up to 1250 kg)

Eutelsat OneWeb (~150kg)

10501	↑	656
1408	↓	11

Amazon Leo (~571 kg)

>3000 satellites

Thousand Sails (~267 kg)

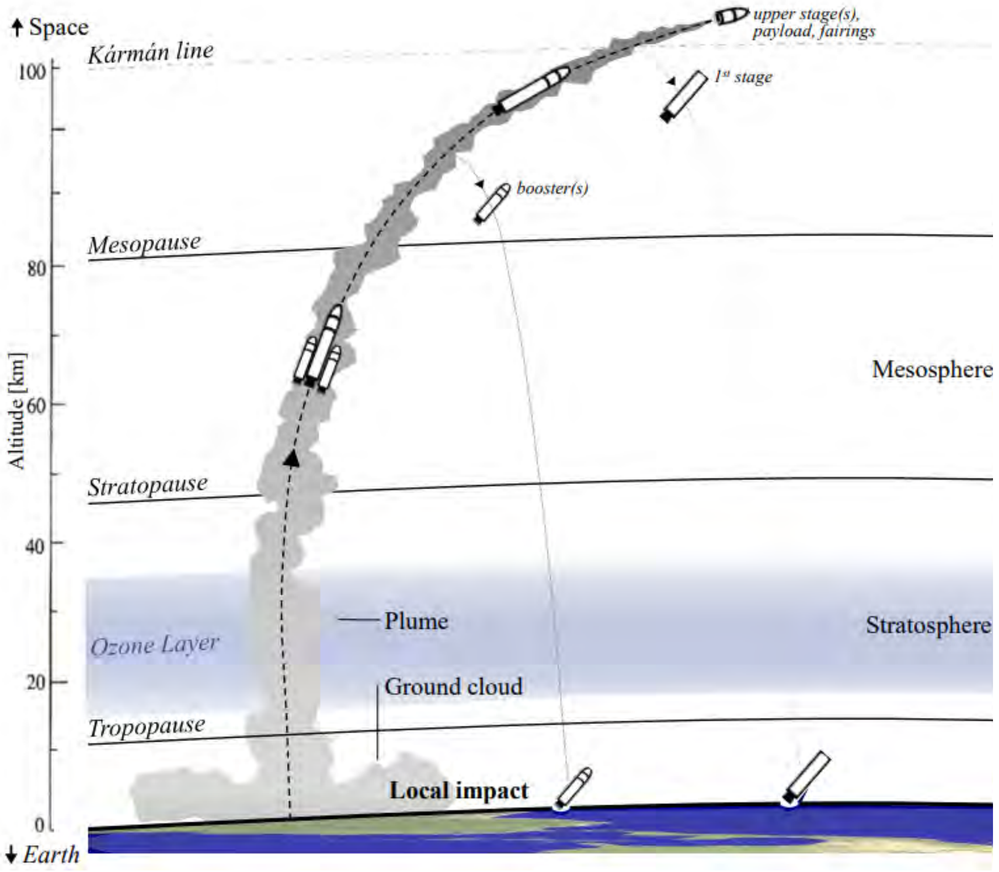
>15,000 satellites

~75% of ~7000 objects in LEO are from SMCs, with 100,000 expected by 2040

SMCs are driving the surge in launches and re-entries, mostly with the SpaceX Falcon rocket (54% of launches in 2025) launching the Starlink constellation.

[Gunter's Space Page, Jonathan's Space Report]

Air Pollutant Emissions from Rocket Launches



Launch emissions are injected throughout all atmospheric layers, with altitude-dependent plume chemistry

Hydrogen

Delta IV Heavy

LOX / LH_2

H_2O

Thermal NO_x

Solid

Long March 11

Al / NH_4ClO_4 / HTPB

H_2O

CO

CO_2

Black Carbon

Thermal NO_x

Fuel NO_x

Chlorine

Alumina (Al_2O_3)

Kerosene

Falcon 9

LOX / RP1

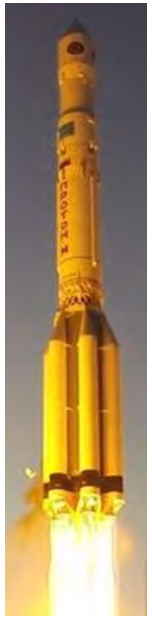
H_2O

CO

CO_2

Black Carbon

Thermal NO_x



Hypergolic

Proton-M

N_2O_4 / UDMH

H_2O

CO

CO_2

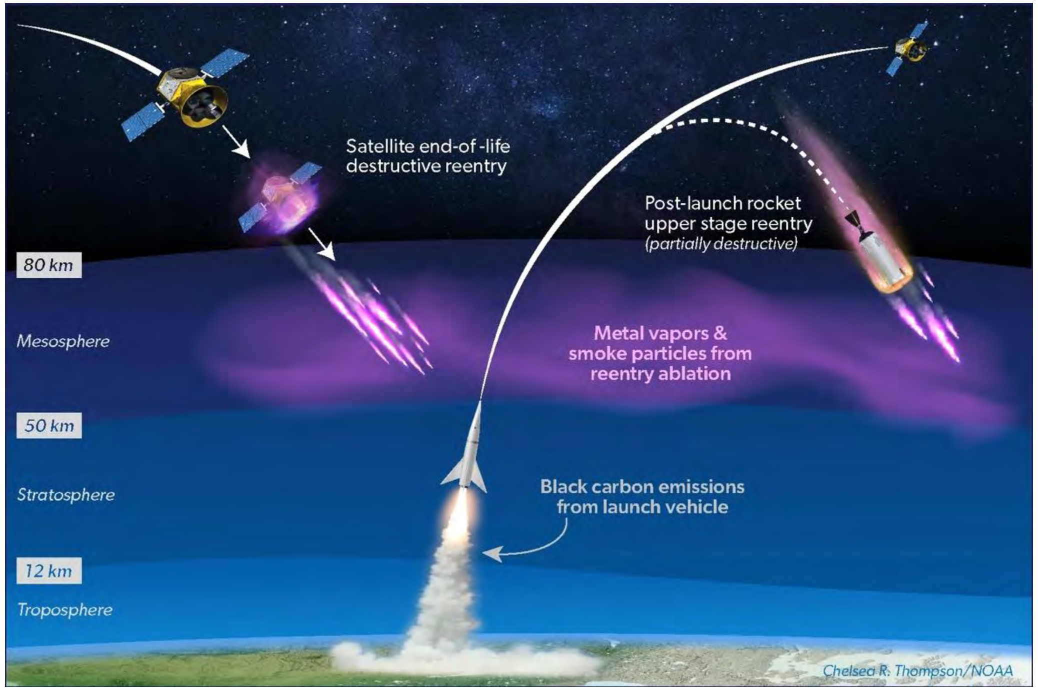
Black Carbon

Thermal NO_x

Fuel NO_x

[Sirieys *et al.* 2022]

Air Pollutant Emissions from Object Re-entries



Re-entry emissions are injected into the mesosphere (~60-80 km) over a large area (1000s of km), with altitude-dependent ablation chemistry

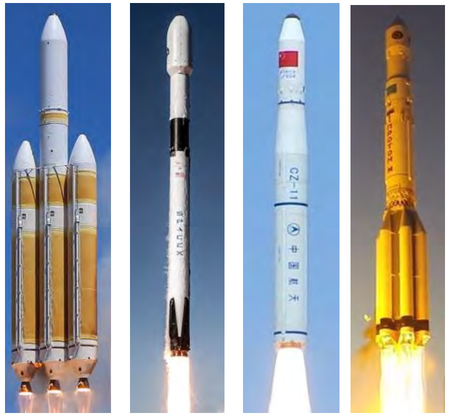
Payloads
Components
Capsules
Rocket Bodies
Debris

Thermal NO_x
Al_2O_3 (and other metal oxides)
Black Carbon
Chlorine

[NOAA, ESA]

Environmental impacts of the space industry

Launches (0 km to orbit)

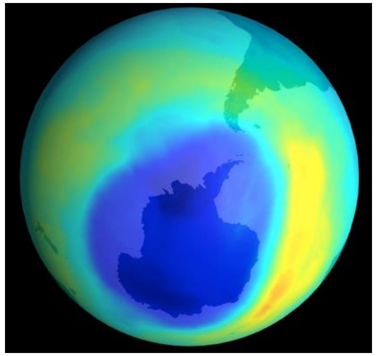


Reentries (60-80 km)

→

→

Stratospheric O_3 depletion



Driven by NO_x, BC, Cl_y, and Al_2O_3

Instantaneous Climate Forcing

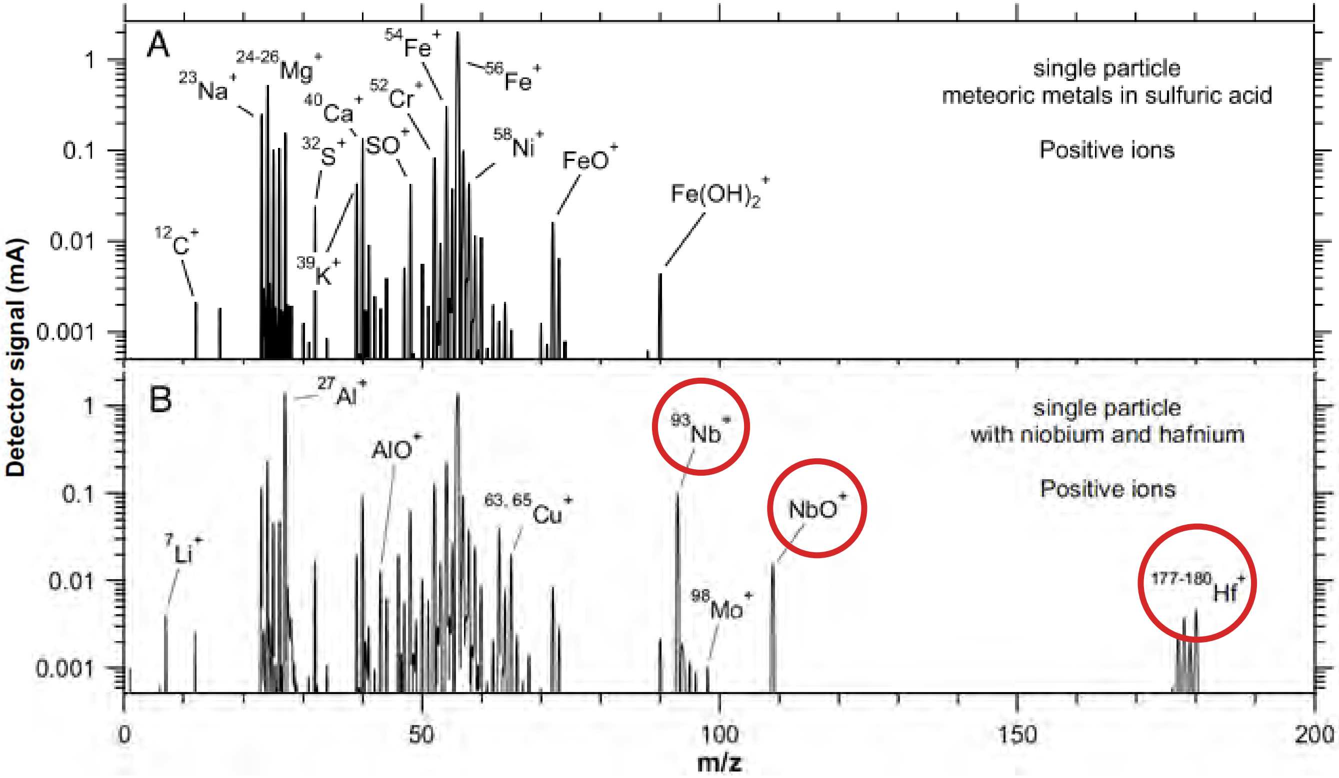
BC	Al_2O_3	Strat. Aerosol
↑ ☀	↑ 🌎 ↓ ☼	↓ ☼

Observational evidence of stratospheric contamination by the space industry

SABRE 2023 Campaign
(NOAA/NASA)

High-latitude sampling
of stratospheric
sulfuric acid particles

Single particle mass spectra from the PALMS instrument



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

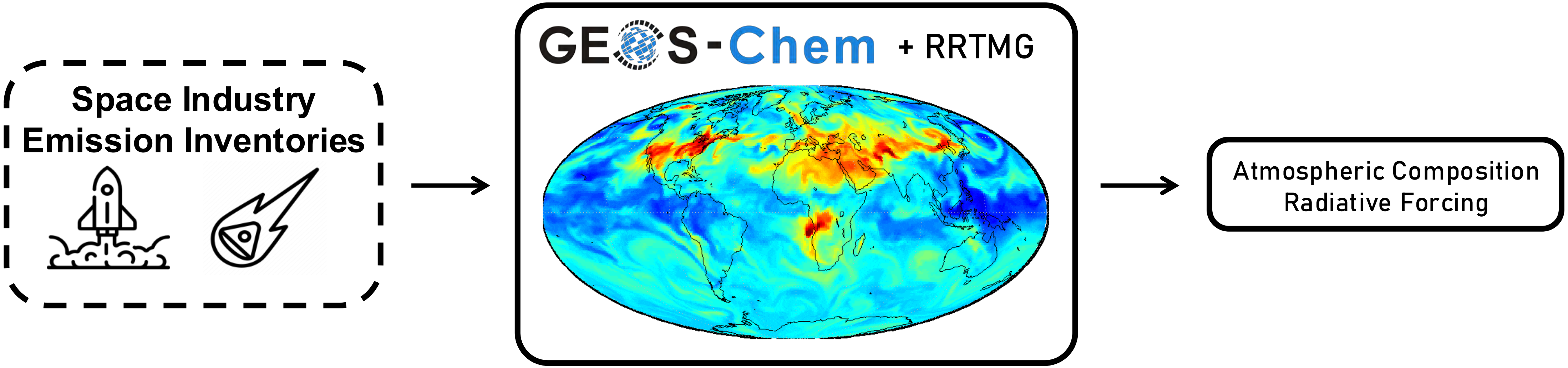
[Murphy *et al.* 2023]

Project Overview

1. Build 3D, global inventories of launch and re-entry air pollutant emissions, categorized by mission type, and validated through observational data.

2. Project emissions to 2029 and implement into a chemical transport model coupled to radiative transfer model.

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



Space Industry Emission Inventories

GEOS-Chem + RRTMG

Atmospheric Composition
Radiative Forcing

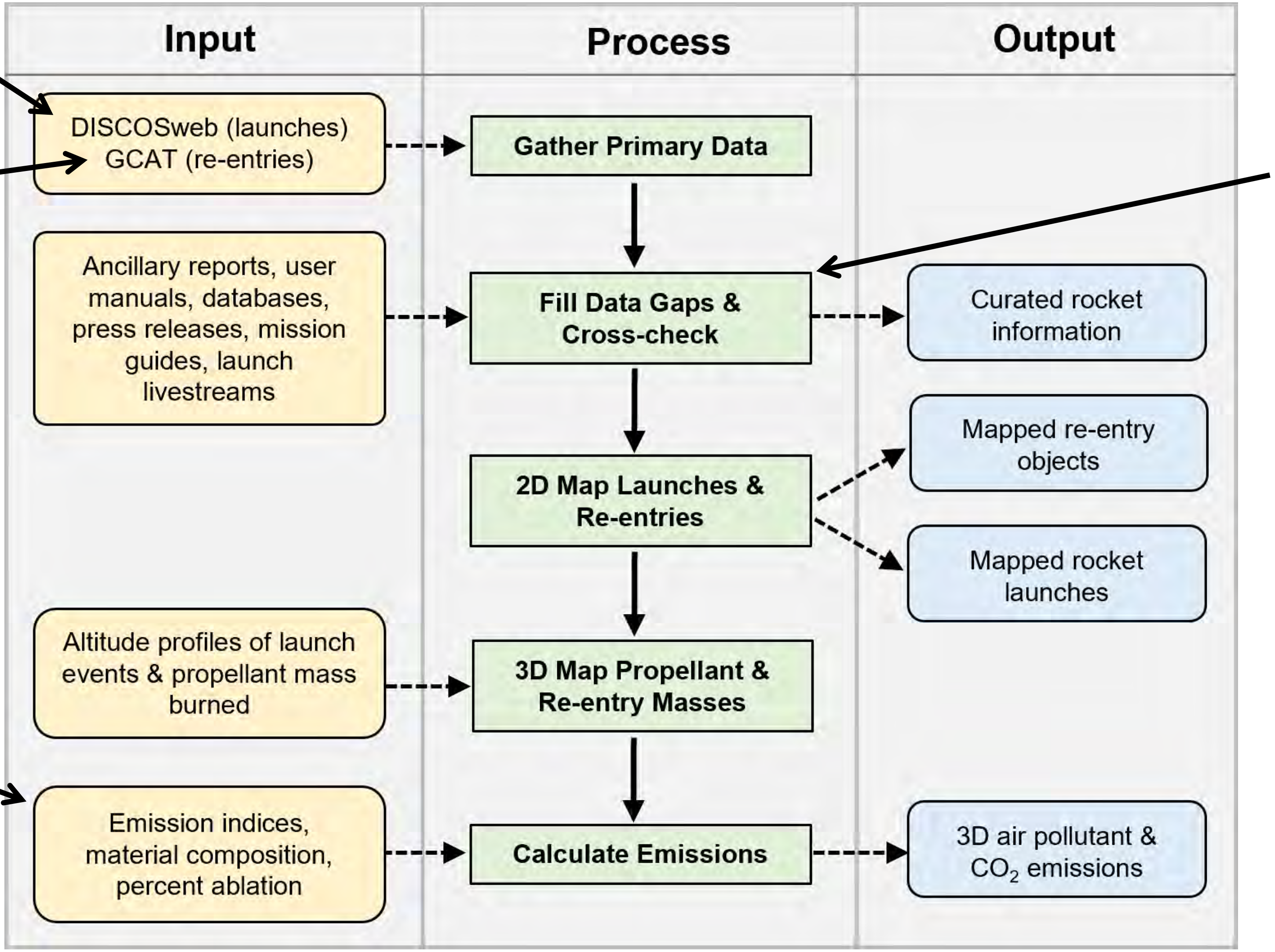
Emissions Inventory Processing Pipeline

Peer-reviewed emission inventory developed for 2020-2022

ESA database

Catalogue maintained by Jonathan McDowell

Knowledge of launch and re-entry chemistry is rapidly evolving



Input

- DISCOSweb (launches)
GCAT (re-entries)
- Ancillary reports, user manuals, databases, press releases, mission guides, launch livestreams
- Altitude profiles of launch events & propellant mass burned
- Emission indices, material composition, percent ablation

Process

- **Gather Primary Data**
- **Fill Data Gaps & Cross-check**
- **2D Map Launches & Re-entries**
- **3D Map Propellant & Re-entry Masses**
- **Calculate Emissions**

Output

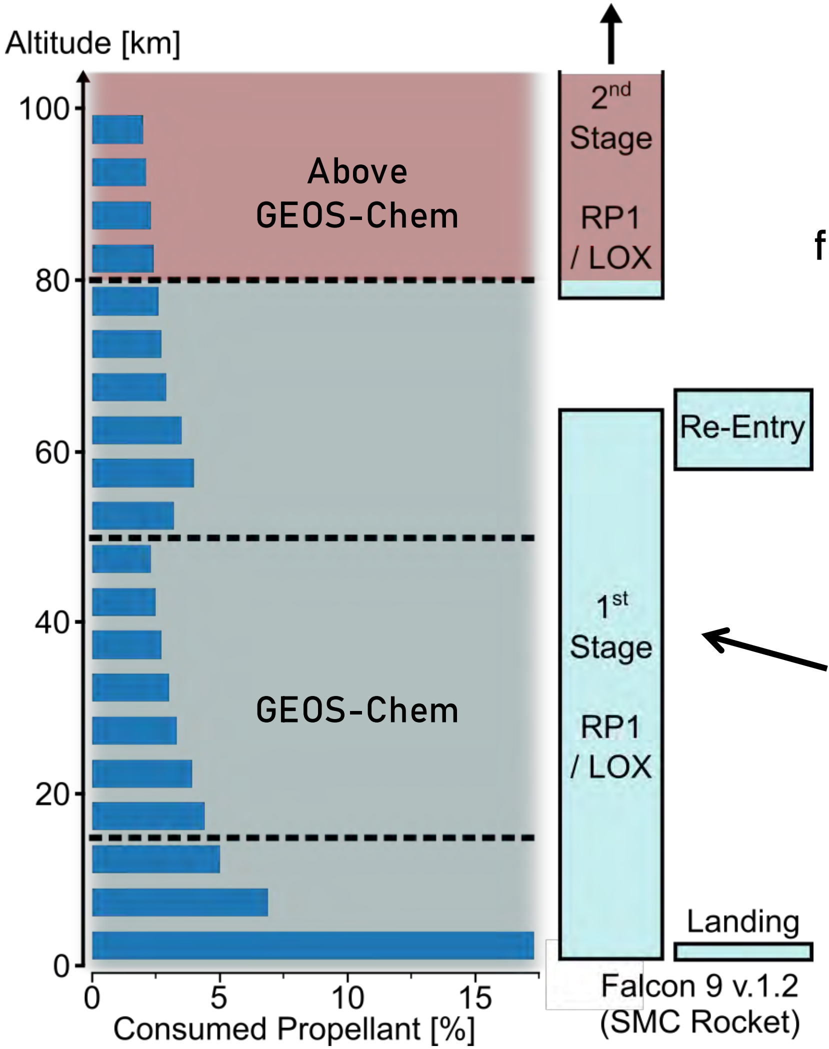
- Curated rocket information
- Mapped re-entry objects
- Mapped rocket launches
- 3D air pollutant & CO_2 emissions

Critical step due to often incomplete and incorrect data from primary sources

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

Building the Emission Inventory

Launch



We include altitude-dependent emission factors and assess our data against launch livestreams.

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

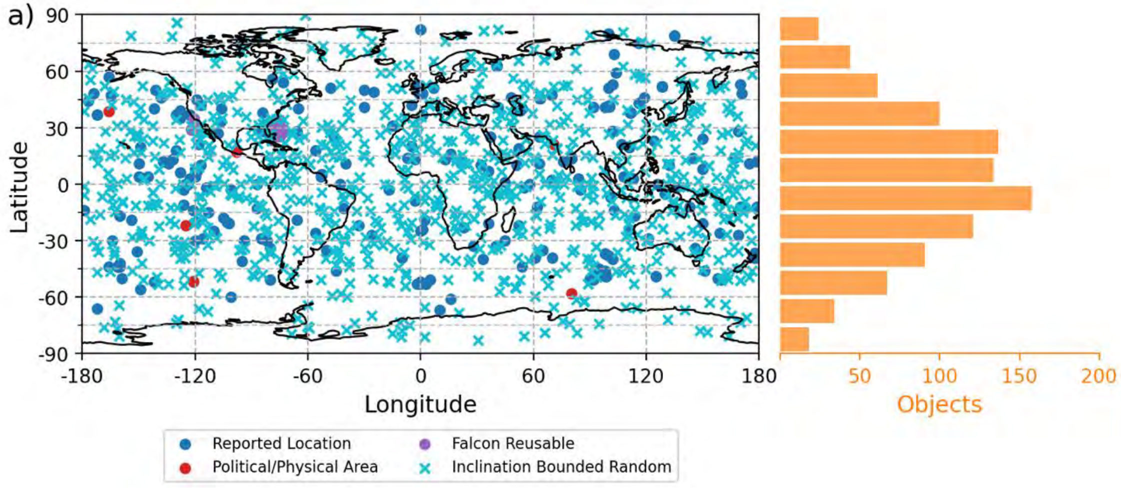
Annual propellant consumption increased from 36-63 Gg in 2020-2022.

Re-entry

Reusable

Expendable

Re-entering Objects in 2022

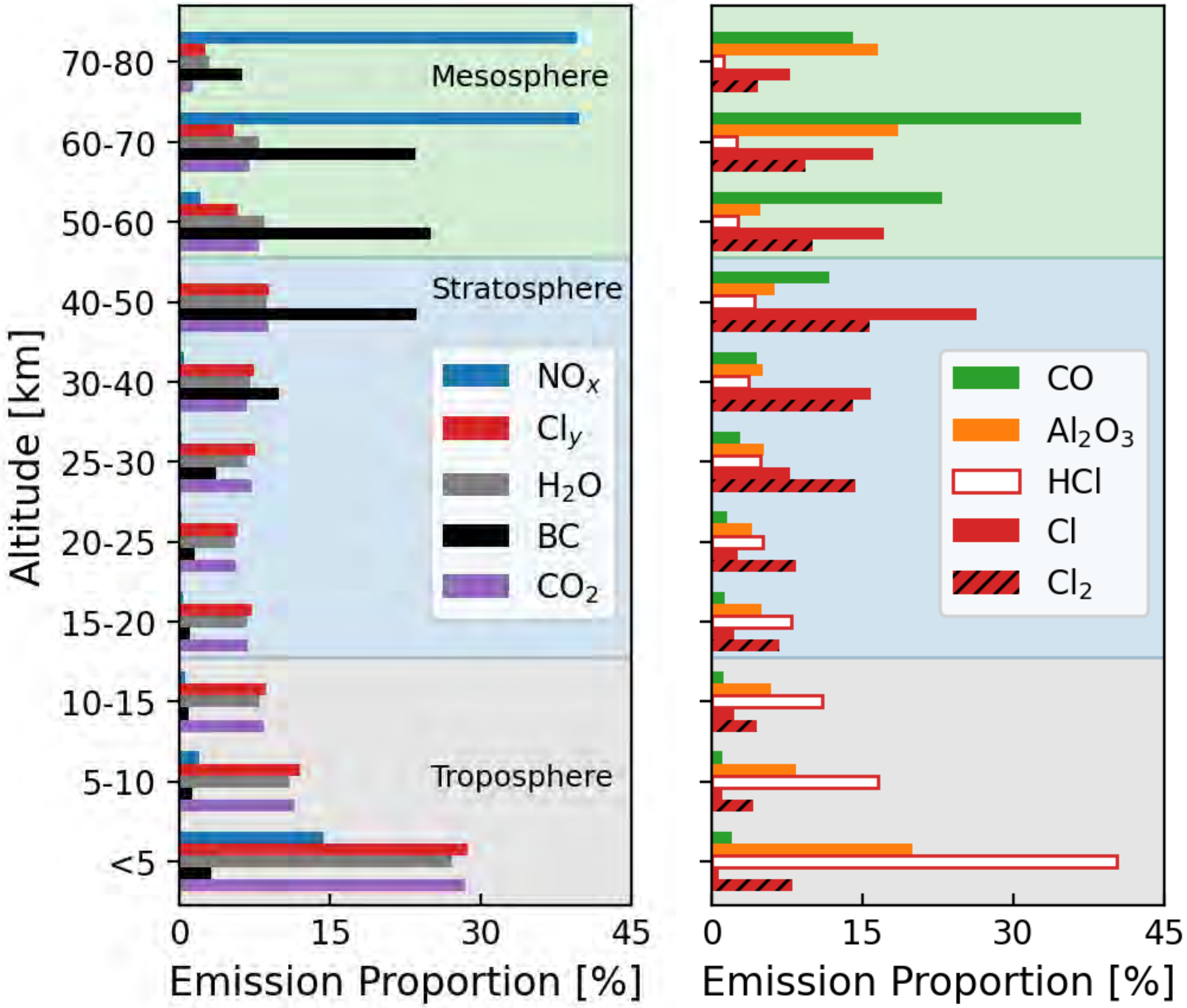


Annual re-entry mass has increased (3-5 kt), and the SMC portion is increasing too (18-26%). This is now ~40% of the influx from natural sources.

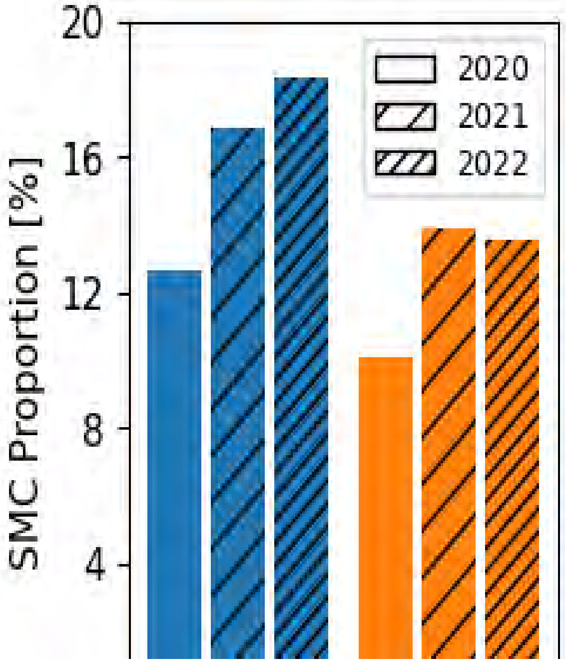
[Ross *et al.* 2014, Barker *et al.*, 2024]

Vertical profiles of air pollutants and CO_2

Relative propellant distributions for 2022



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

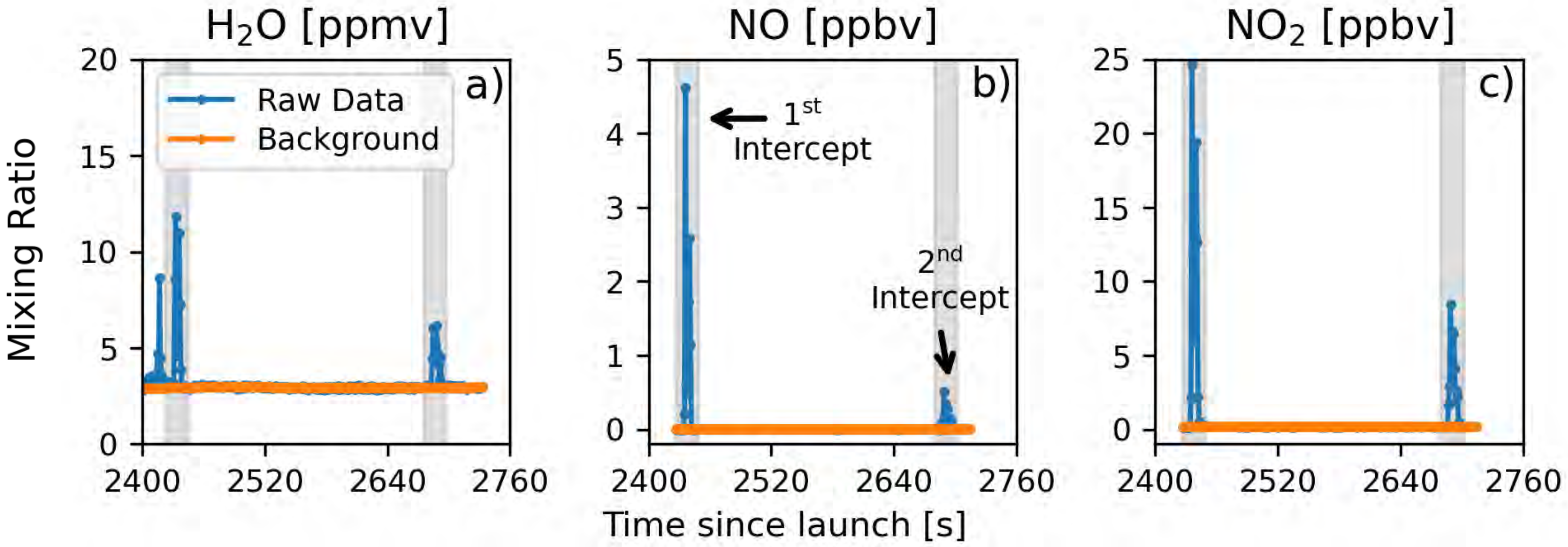


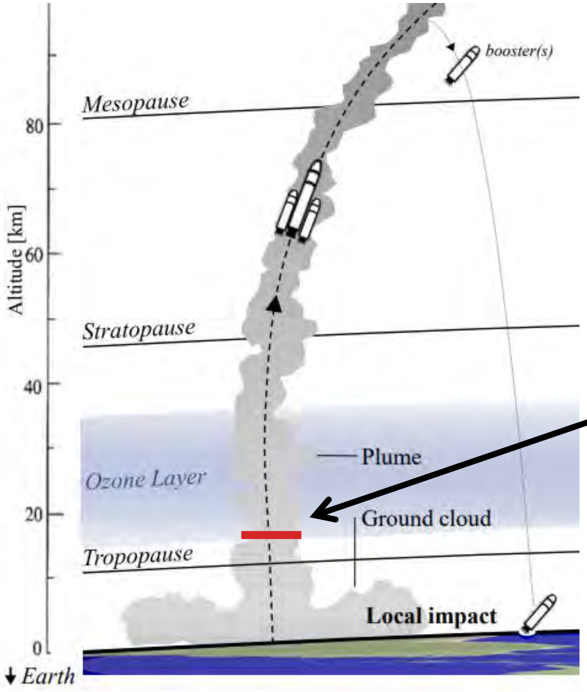
SMC contribution to re-entry emissions is increasing (12-15% in 2022).

[Barker *et al.*, 2024]

Validating the emission inventory using aircraft data

SABRE 2023
18^{th} February 2023





The exhaust plume of a SpaceX Falcon 9 kerosene-fueled rocket was sampled twice at ~16 km altitude (lower stratosphere). Still very low in the launch!

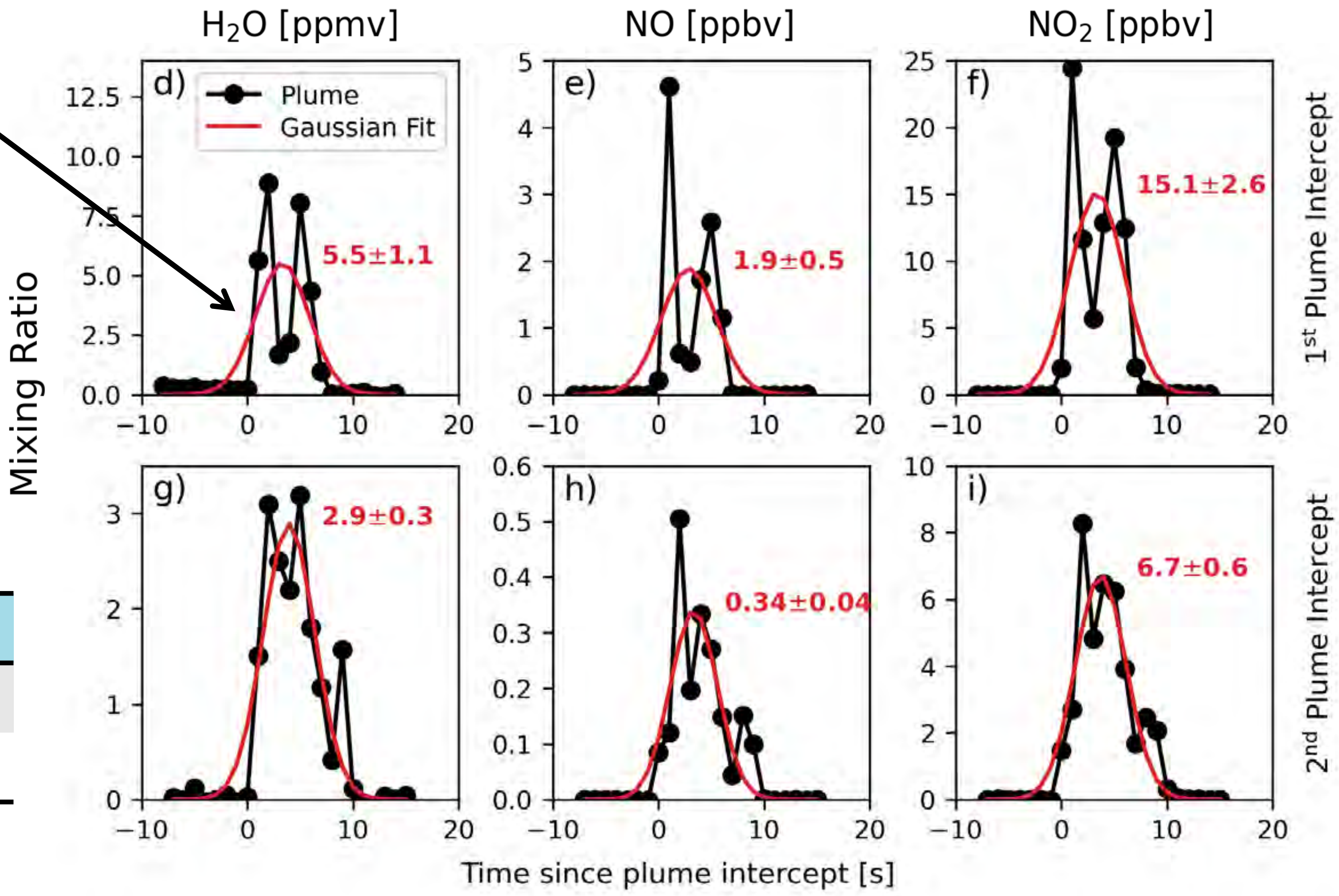
The samples were taken 41-45 min after launch. NO_x ($NO + NO_2$) and H_2O should be preserved (long-lived in the stratosphere). Aircraft plumes containing SO_2 were removed from the analysis.

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

[Barker *et al.*, in review]

Validating the emission inventory using aircraft data

Gaussian used to fit plume, but similar results if using integral



Use H_2O to normalize rather than CO_2, as H_2O is conserved with altitude.

	$\Delta NO_x/\Delta H_2O$ [ppb ppm^{-1}]
Inventory	1.2-1.3
Observations	6.1-7.6

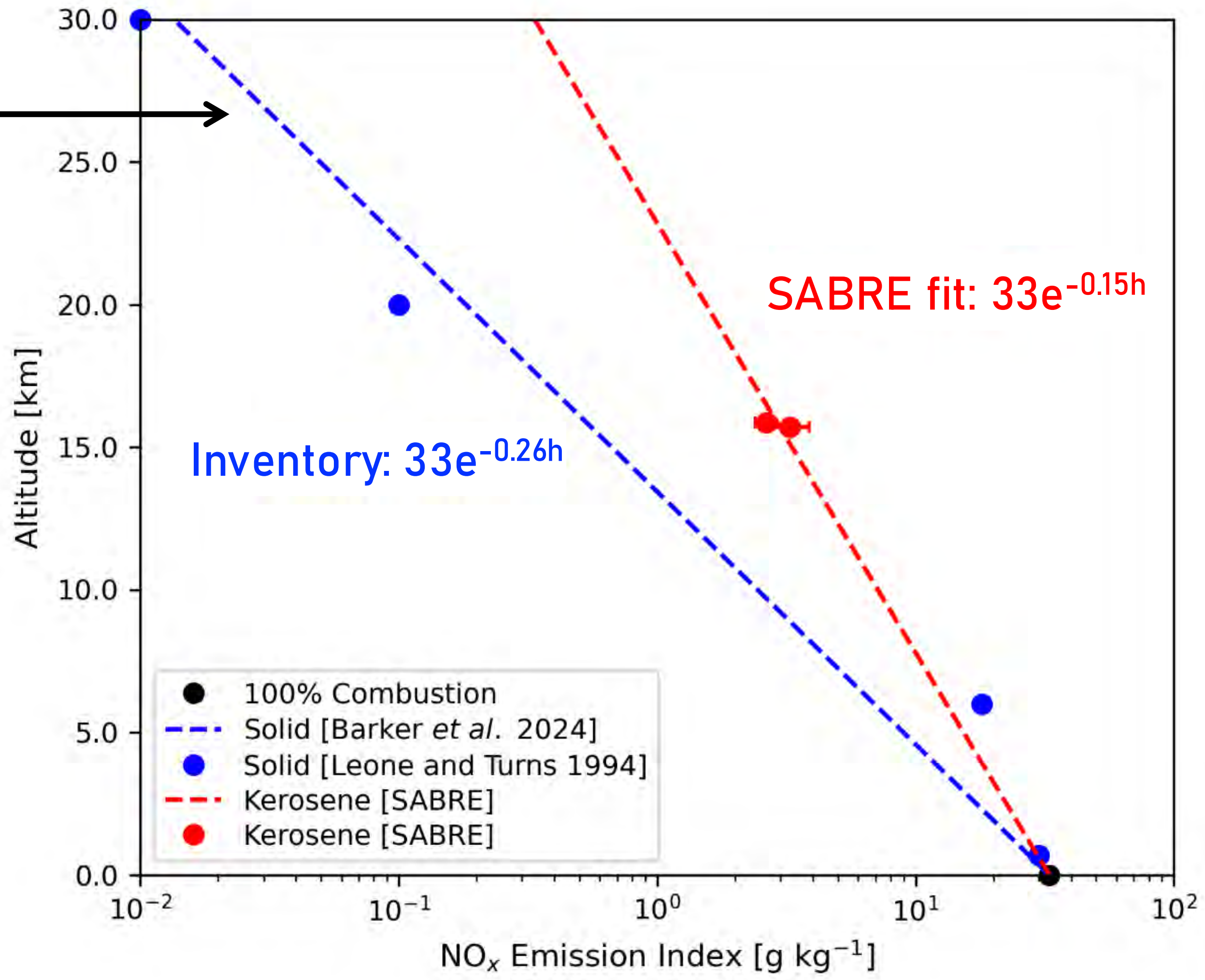
Observational data indicates that much more NO_x is present in the lower stratosphere than previously estimated.

[Barker *et al.*, in review]

Validating the emission inventory using aircraft data

Based on a single 1994 modelling study of solid rocket boosters on the Space Shuttle.

Altitude-dependent decline in NO_x emission index



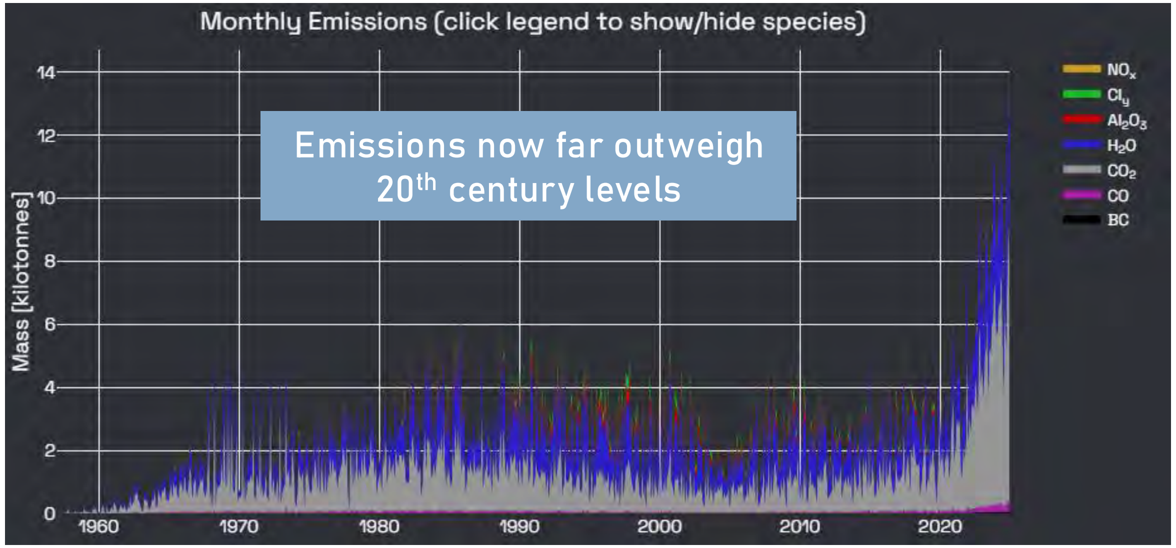
NOx emission index decreases with altitude as combustion efficiency decreases

Aircraft measurements are an invaluable tool to constrain emission inventories, however these campaigns are at risk…

[Barker *et al.*, in review]

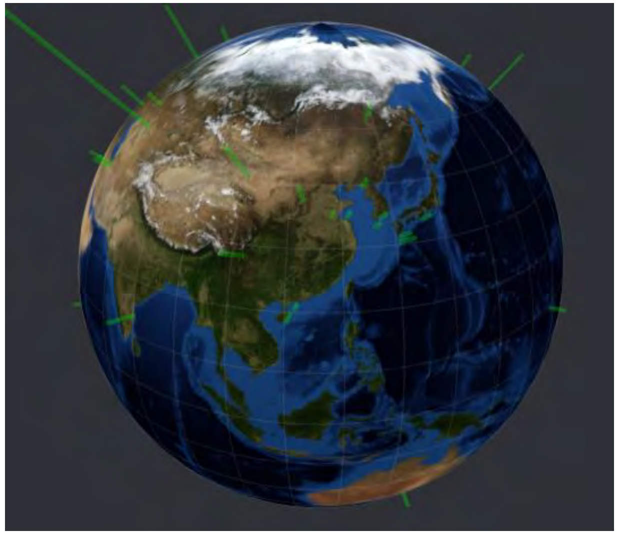
Online Emissions Tracker

Launch emissions from 1957-2024 (first of its kind)

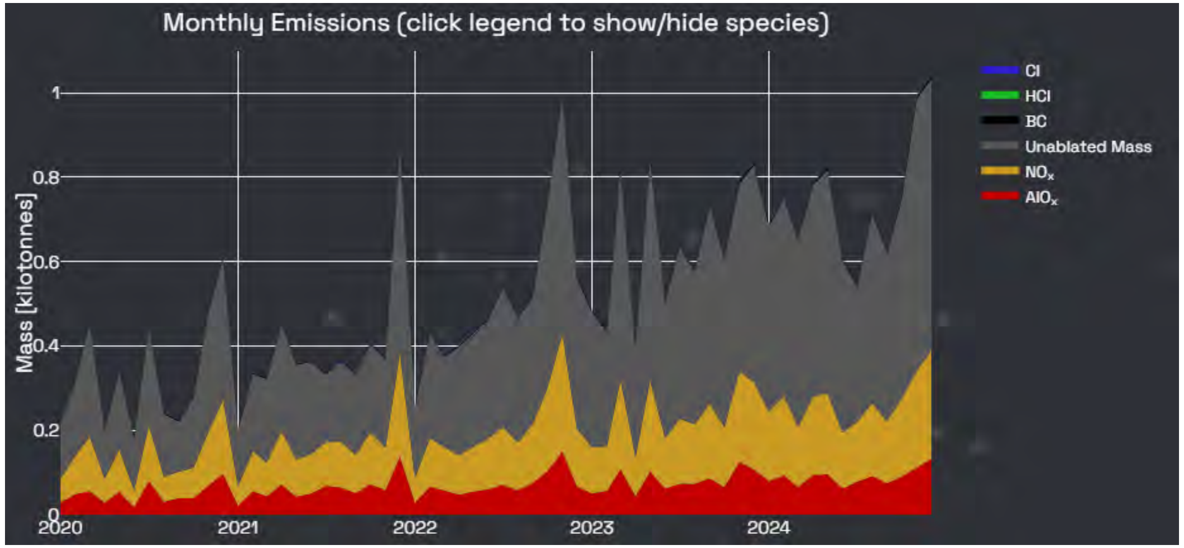


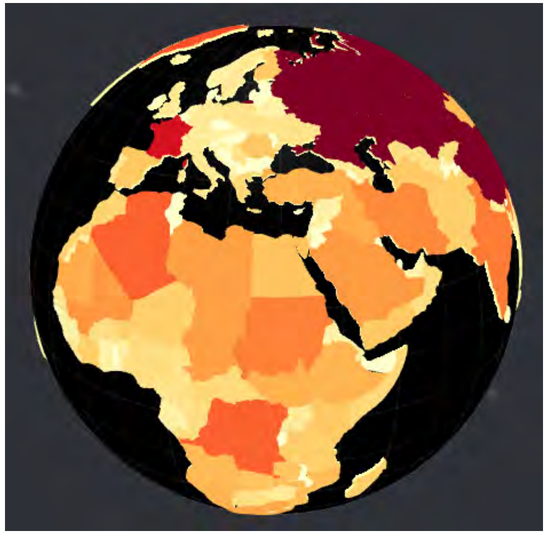
Emissions now far outweigh 20th century levels

By 2024, propellant consumed to launch megaconstellations is larger than all other missions combined!



Re-entry emissions from 2020-2024





Increasing ablated mass represents a risk to terrestrial life.

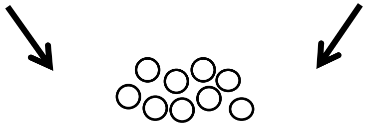
Extended with help from UCL Astrophysics summer research student, Eric Tan.

Updating GEOS-Chem to represent stratospheric aerosol injection

Alumina (Al_2O_3) added as advected chemically-active tracer

Re-entry ablation

Solid rocket fuel



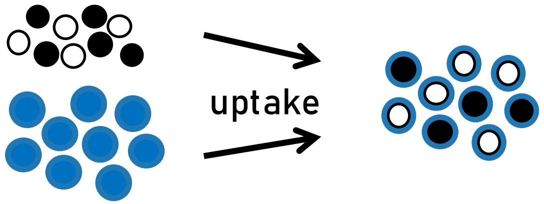
Gravitational settling updated

Al_2O_3

Hydrophobic BC

Added prompt uptake of BC and Al_2O_3 to stratospheric sulfate

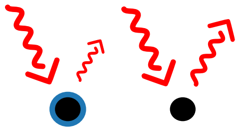
BC + Al_2O_3 emissions



uptake

Stratospheric H_2SO_4

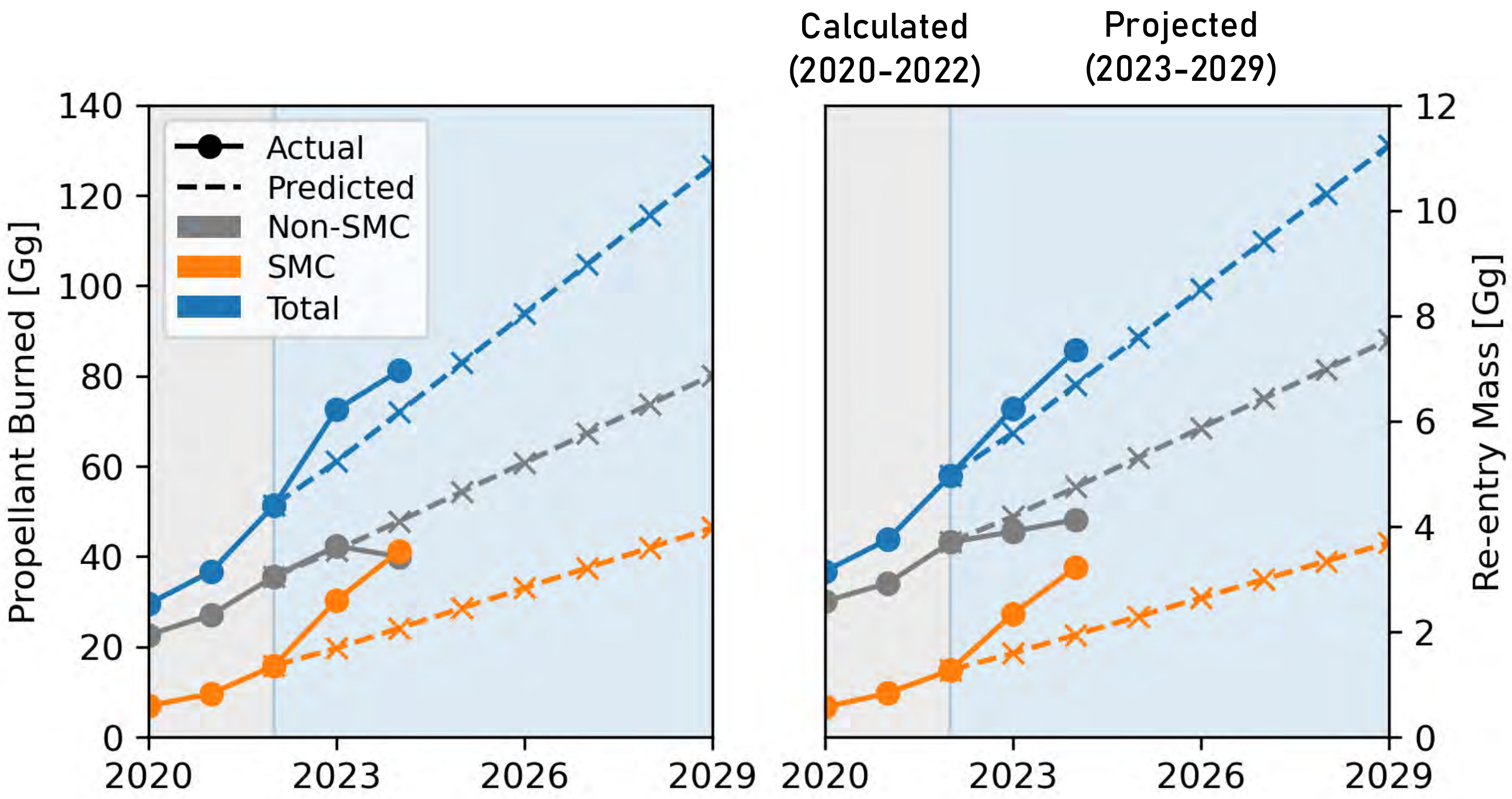
Added enhanced shortwave absorption from lensing effect



Non-absorbing shell focusses light onto absorbing core

[Barker *et al.*, in review]

Projecting the emissions to the end of the decade



Megaconstellation launches and re-entries have grown faster than expected, meaning we underestimate total growth.

[Barker *et al.*, in review]

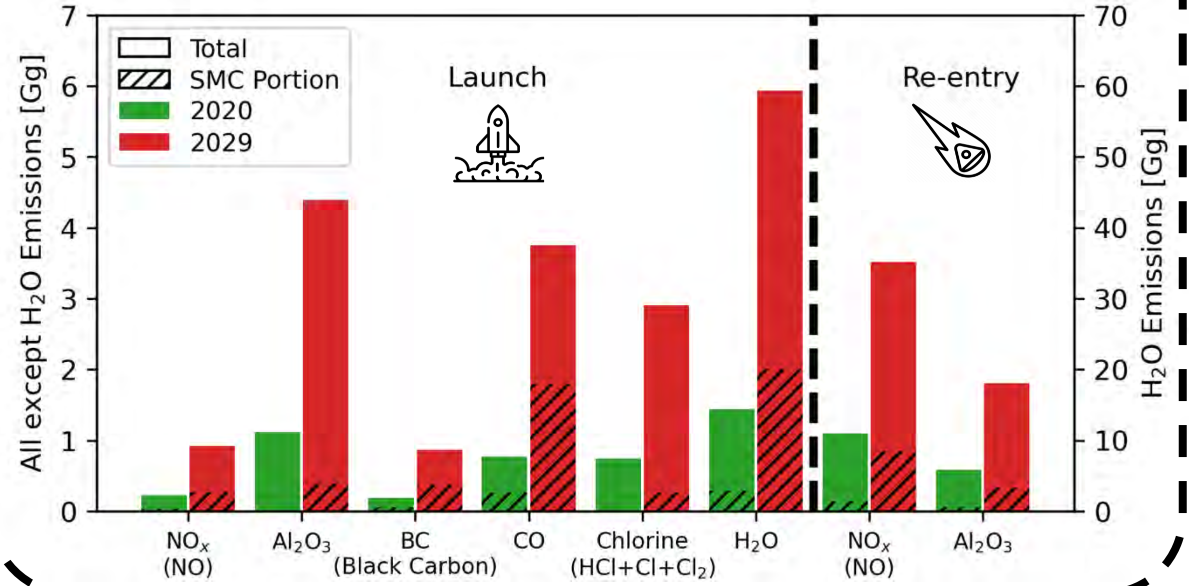
Implementing space activity emissions into a global model of atmospheric chemistry

Updated radiative forcing

Offline Meteorology

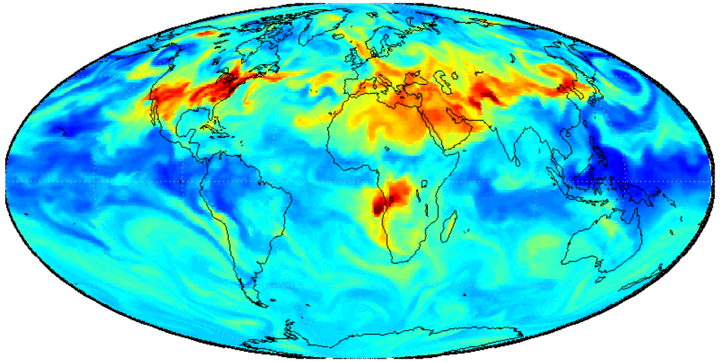
Biogenic / Anthropogenic Emissions

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

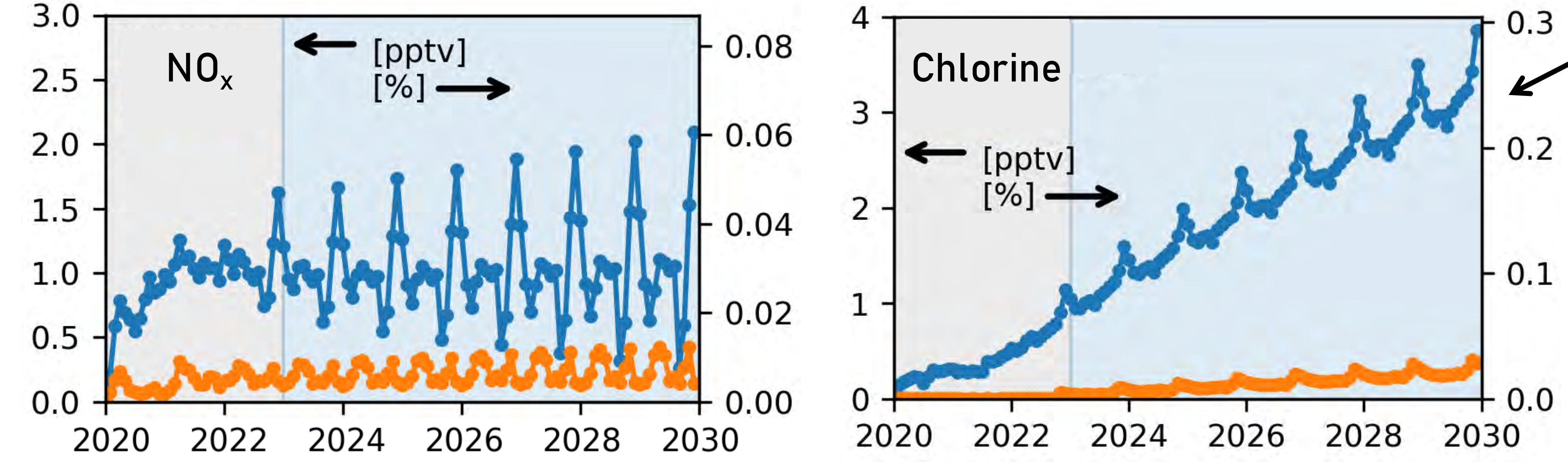
Meteorology and radiative transfer are offline, so modelling does not include feedbacks.

Atmospheric Composition
Radiative Forcing

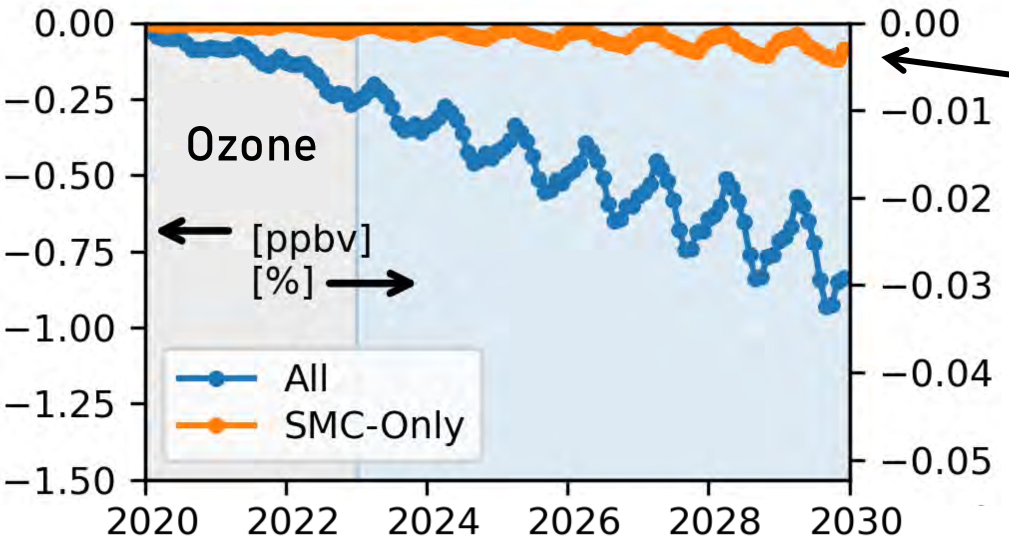
[IPCC, Barker *et al.*, in review]

Stratospheric ozone depletion by the space industry

Monthly mean change in stratospheric concentration



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



Depletion by megaconstellations is negligible due to minimal chlorine emissions from solid fuel

SMC Contribution

	2020	2029
NO$_x$	19%	23%
Chlorine	5%	9%
Ozone	7%	10%

Global stratospheric ozone depletion by the space industry is modest (0.03%) compared to surface sources (~2%).

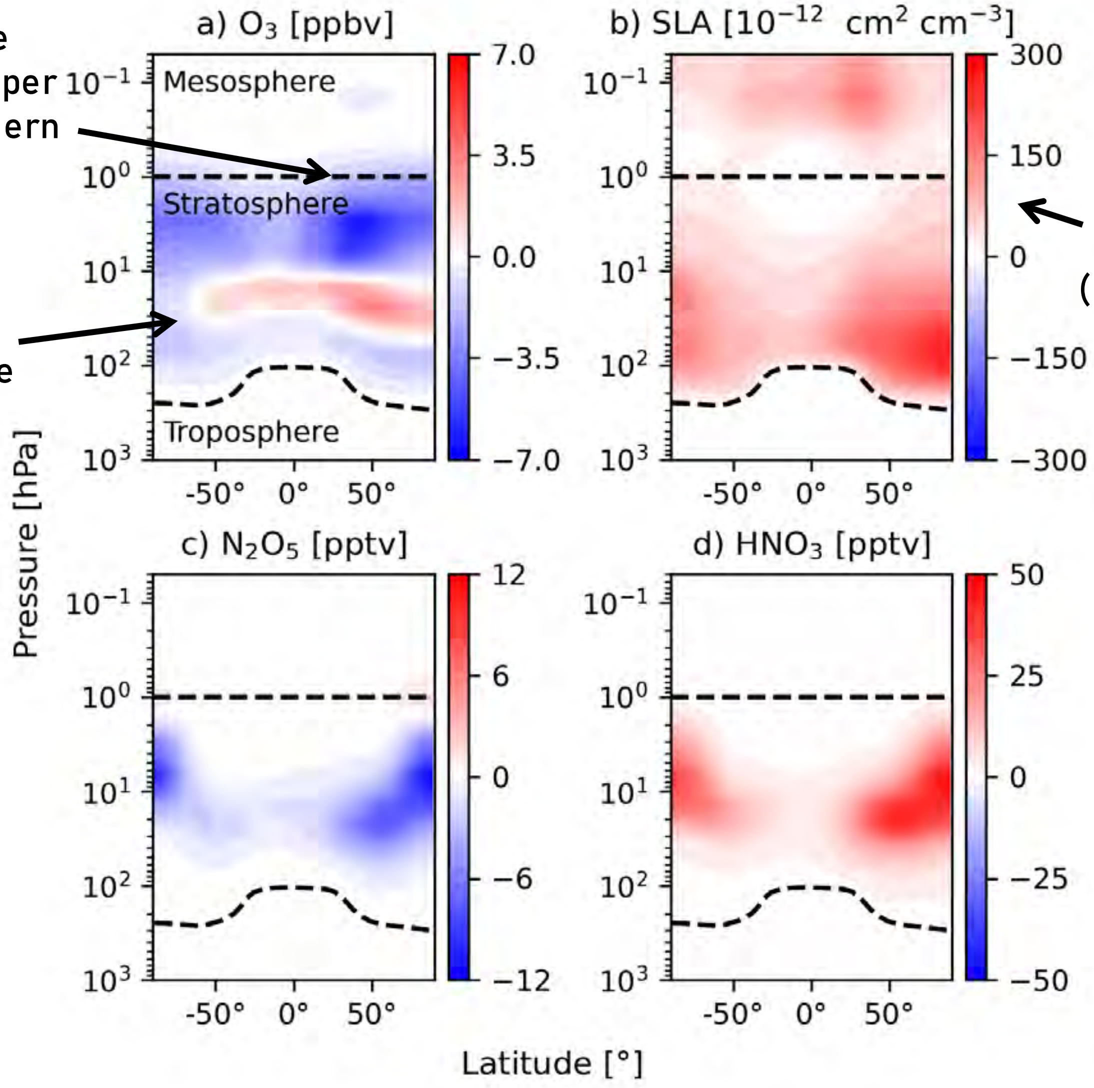
[Barker *et al.*, in review]

Stratospheric ozone depletion by the space industry

Annual mean changes in vertical profile (2029)

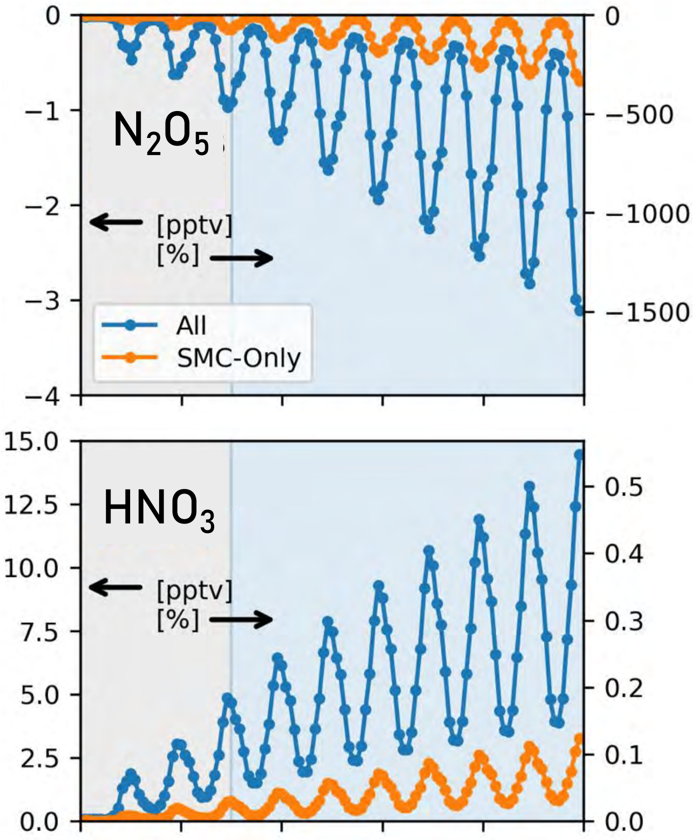
Maximum ozone depletion in the upper stratosphere northern hemisphere

Maximum ozone production in middle stratosphere



SLA: stratospheric liquid aerosol (mostly sulfate)

Monthly mean change in stratospheric composition



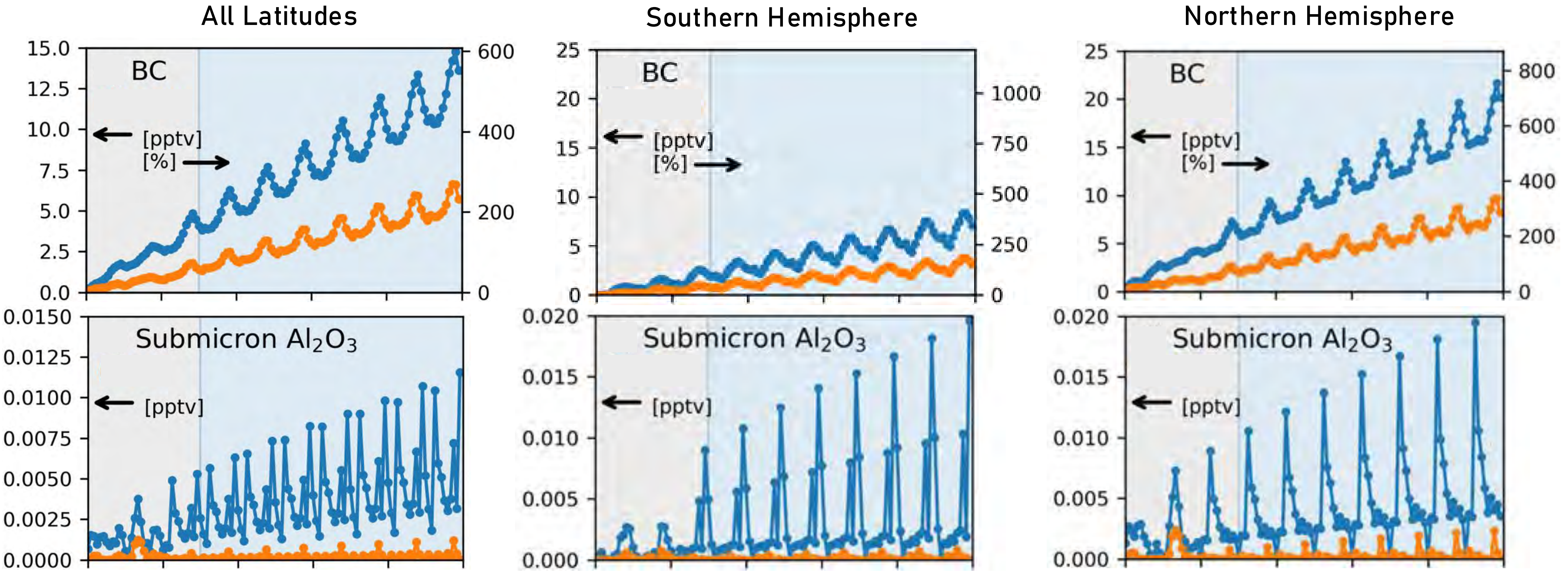
Uptake of aerosols to SLA increases surface area, increasing rate of hydrolysis of N_2O_5 to form HNO_3. This suppresses NO_x recycling.

Stratospheric aerosol chemistry

Monthly mean change in stratospheric concentration

Total BC (coated and uncoated)

Uncoated Al_2O_3



SMC Contribution

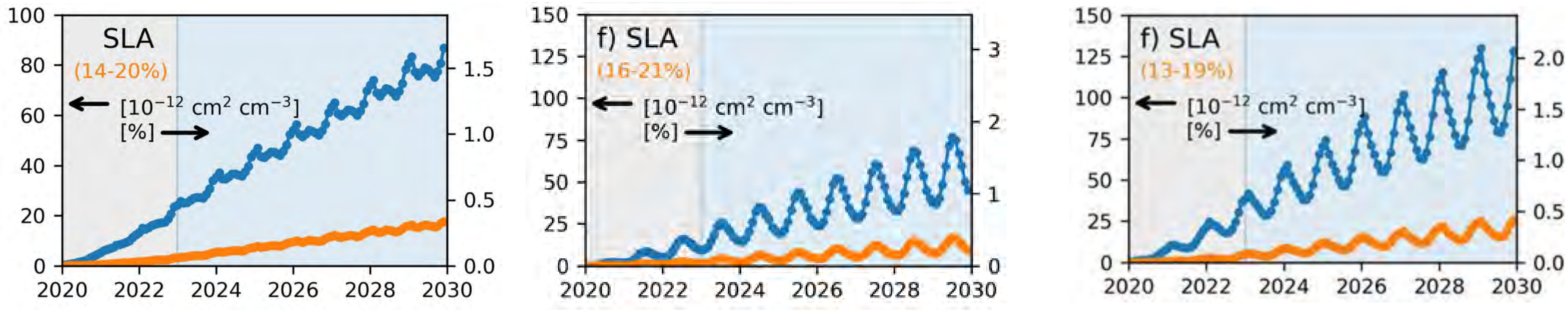
	2020	2029
BC	38%	44%
Al_2O_3	4%	5%

BC seasonality is governed by northern hemisphere (launches), while Al_2O_3 is a mix of launches and re-entries.

[Barker et al., in review]

Stratospheric aerosol chemistry

Monthly mean change in stratospheric surface area concentration



All Latitudes

Southern Hemisphere

Northern Hemisphere

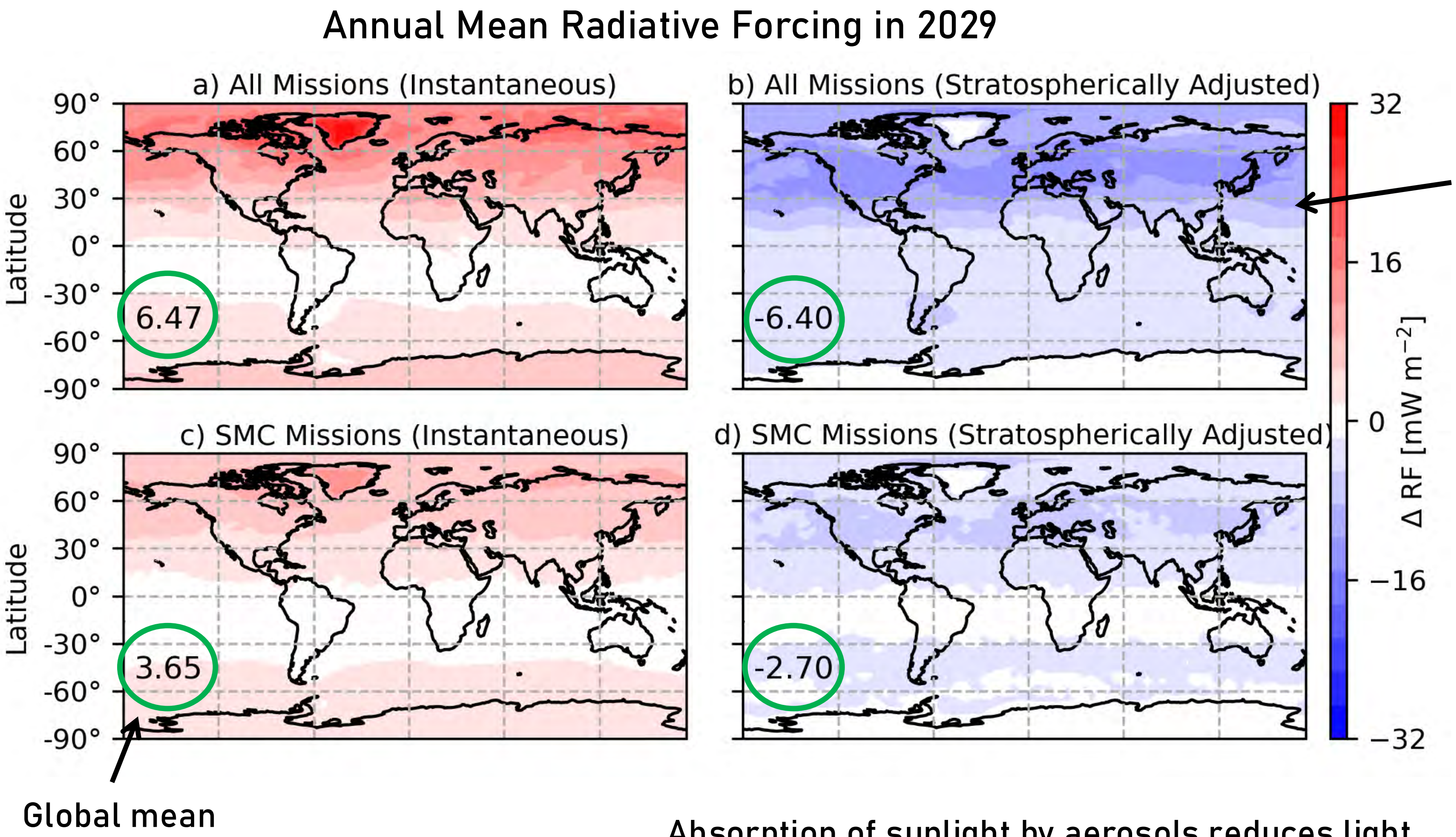
This increase is primarily due to uptake of Al_2O_3 rather than BC.

Opposite seasonalities in each hemisphere give flat trend in the global mean.

SLA growth has implications for ozone depletion (more surfaces for chlorine activation) and climate (more reflective stratosphere).
But the uptake mechanism is poorly understood.

[Barker et al., in review]

Global changes in radiative forcing



Most launches occur in the northern hemisphere

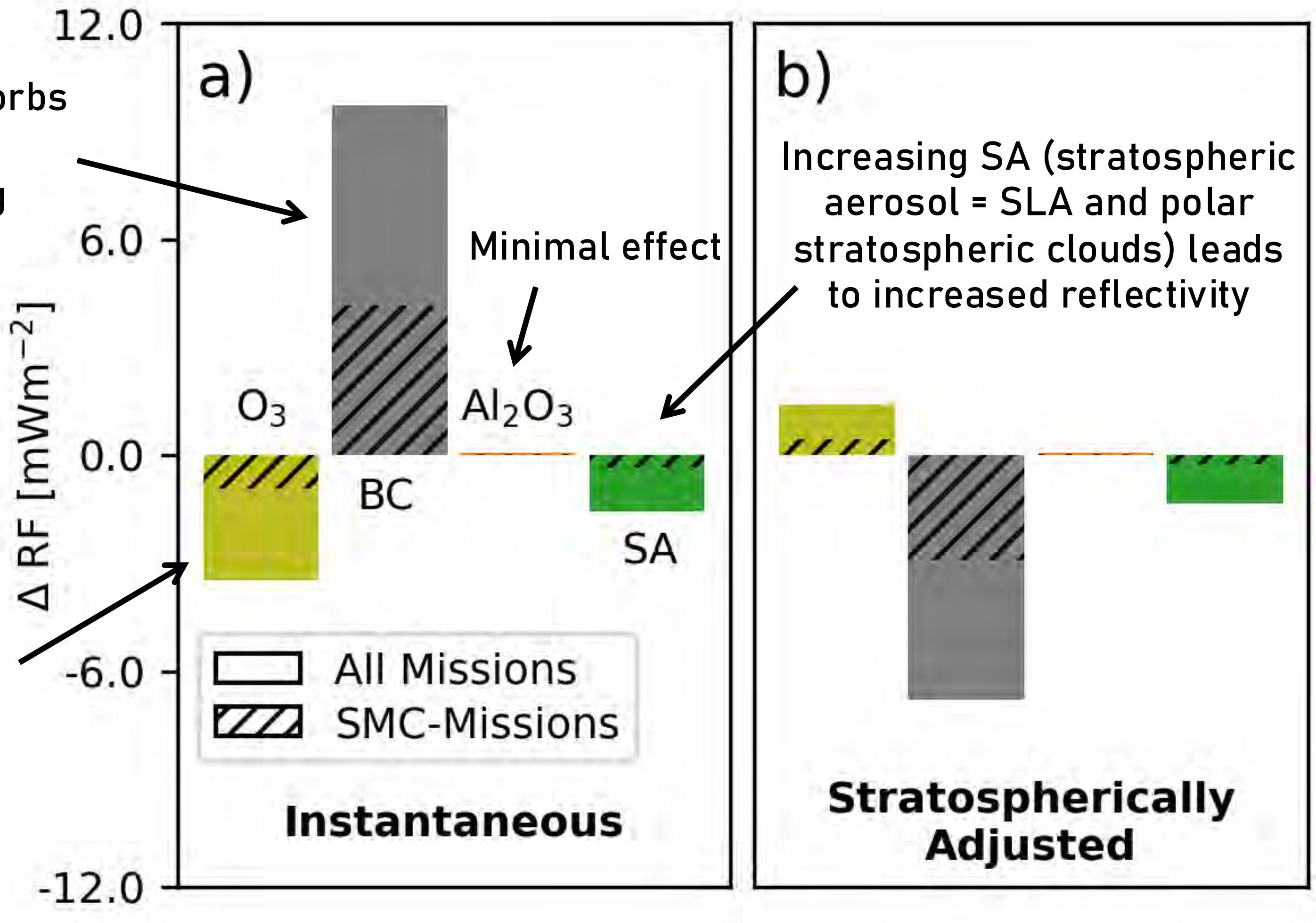
By 2029, SMCs account for 56% of the instantaneous forcing and 42% of the stratospherically adjusted forcing.

Absorption of sunlight by aerosols reduces light reaching the troposphere, leading to negative stratospherically adjusted radiative forcing.

[Barker et al., in review]

Radiative forcing by individual species

Annual Mean Speciated Radiative Forcing in 2029



Sulfate-coated BC absorbs sunlight, causing instantaneous warming

Minimal effect

Increasing SA (stratospheric aerosol = SLA and polar stratospheric clouds) leads to increased reflectivity

Ozone is a greenhouse gas, so a reduction means a cooling effect

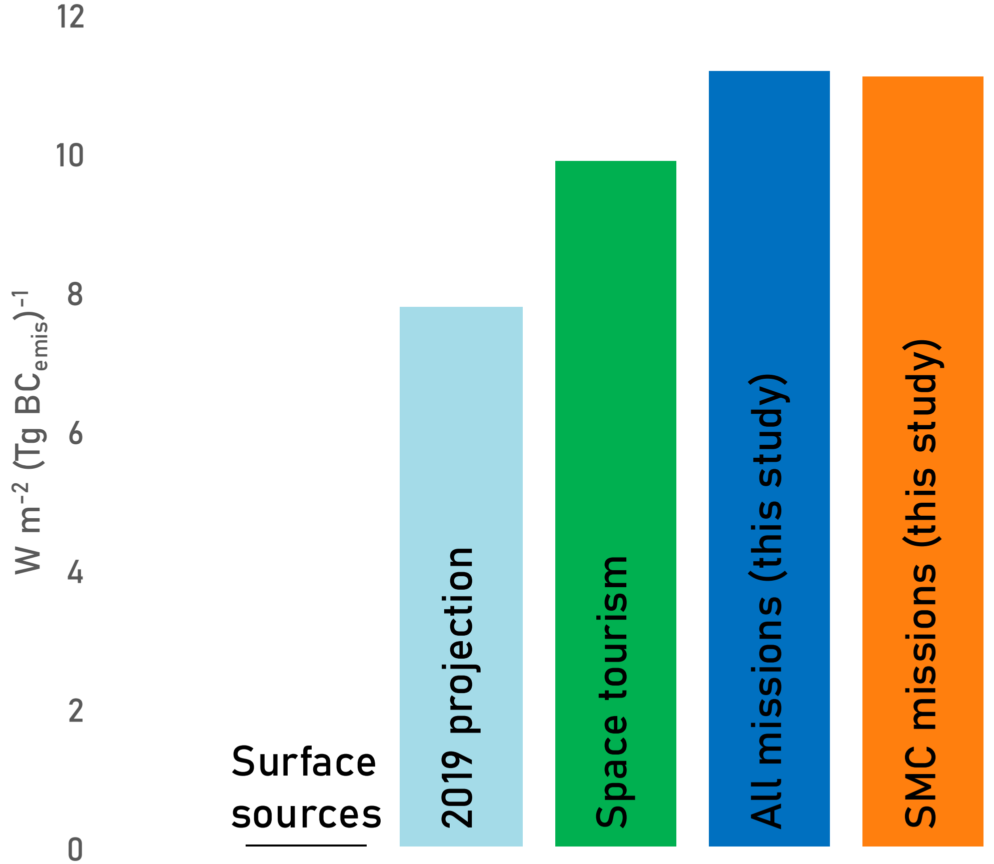
Sign flips for stratospherically adjusted RF if forcer absorbs incoming sunlight (ozone and BC), as alter amount of sunlight reaching troposphere (premise of geoengineering)

Radiative forcing is dominated by BC absorption of incoming sunlight by sulfate-coated BC above the tropopause

[Barker et al., in review]

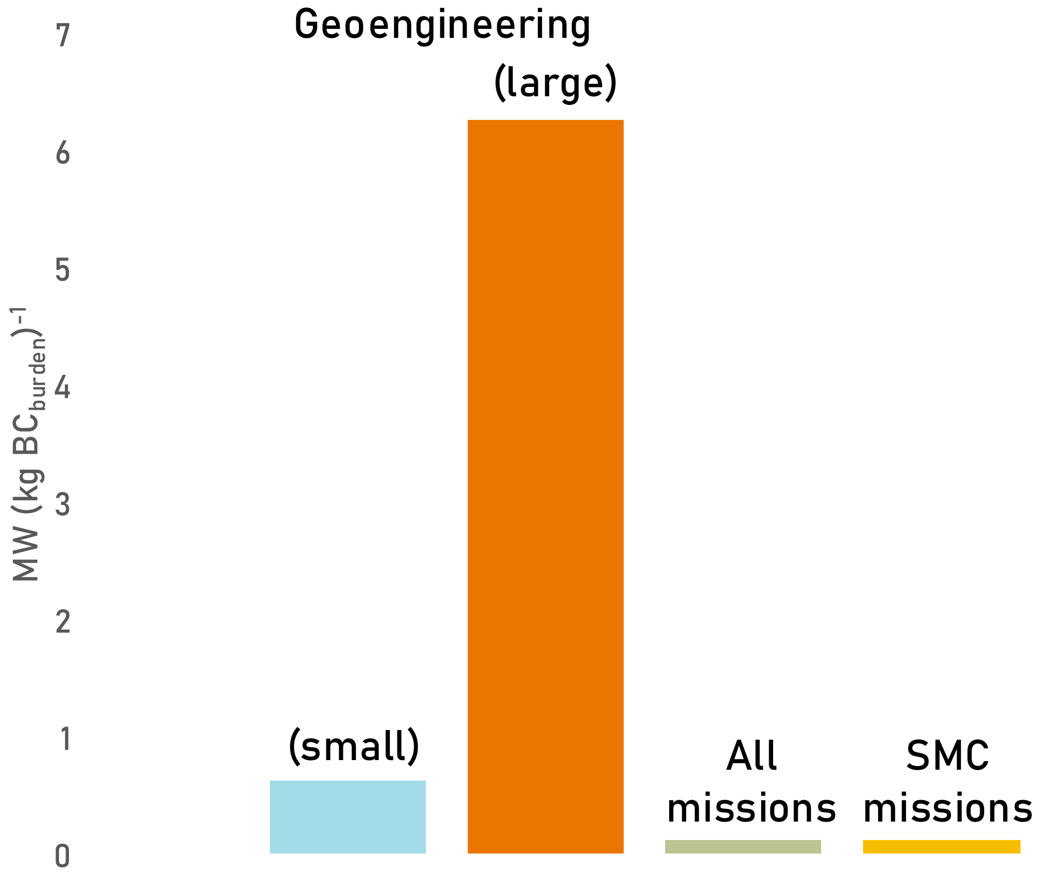
Putting the radiative forcing into context

Instantaneous radiative forcing by BC – normalized by emissions



BC released above the tropopause is long-lasting, resulting in forcing >500 times more than surface sources.

Instantaneous radiative forcing by BC – normalized by mass burden



The normalized forcing is smaller than similar geoengineering studies.

[Barker *et al.*, in review, Ryan *et al.* 2022, Dong *et al.* 2019, Kravitz *et al.* 2012]

Summary

- Observational data shows that NO_x emissions decline much slower than our inventory predicts.
- Megaconstellations have continued their exponential growth, making our projections 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. This is still low, but enough to slow ozone recovery by the Montreal Protocol.
- 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 of this forcing.
- Negative stratospherically adjusted radiative forcing is synonymous with the intent of geoengineering with stratospheric aerosols, but is untested and uncontrolled.

Next Steps:

- Unanswered scientific questions – speciation of re-entry Al into oxide or hydroxide, extent of afterburning into the middle stratosphere, does aerosol uptake to stratospheric sulfate deactivate or enhance absorption?
- Emission inventory intercomparison study – international effort to compare emission estimates to identify major gaps in data.
- Future pathways – collaboration to design IPCC style pathways of space emission growth.

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

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Launch 🚀 Re-entry 🛰