Environmental Impacts of the 21st Century Space Industry

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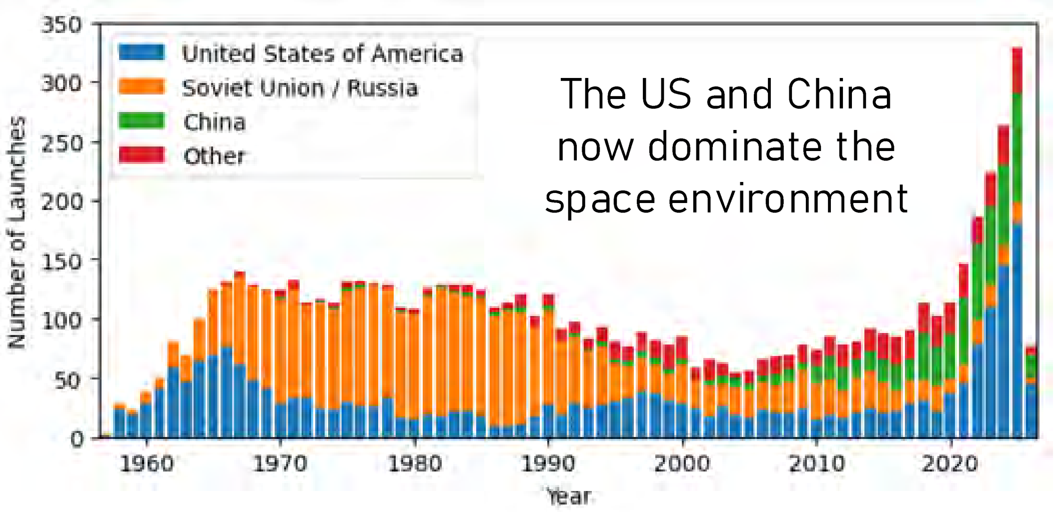
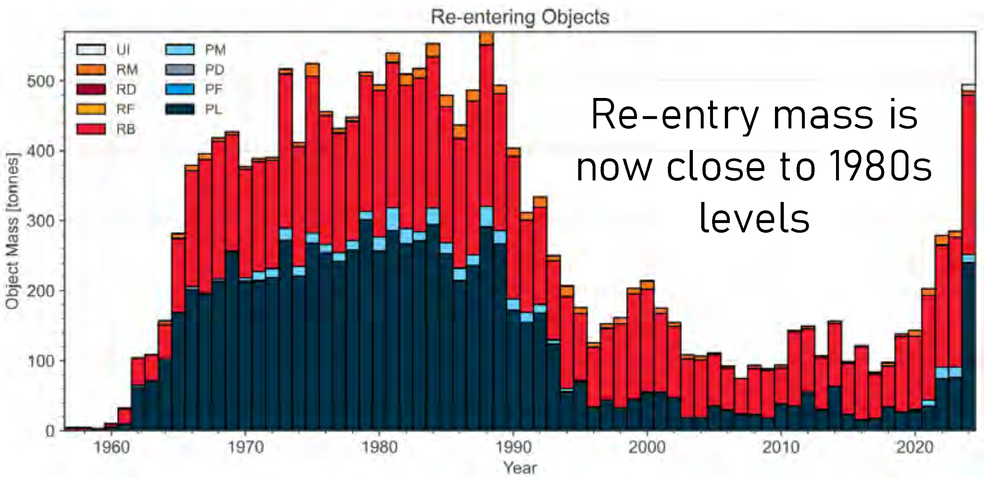
An evolving space industry





Satellite Megaconstellations (SMCs)

SpaceX Starlink (up to 1250 kg)

Eutelsat OneWeb (~150kg)

11762	↑	660
1585	↓	6

Amazon Leo (~571 kg)

amazon leo

>3000 satellites

Thousand Sails (~267 kg)

>15,000 satellites

SpaceX AI (~2600kg?)

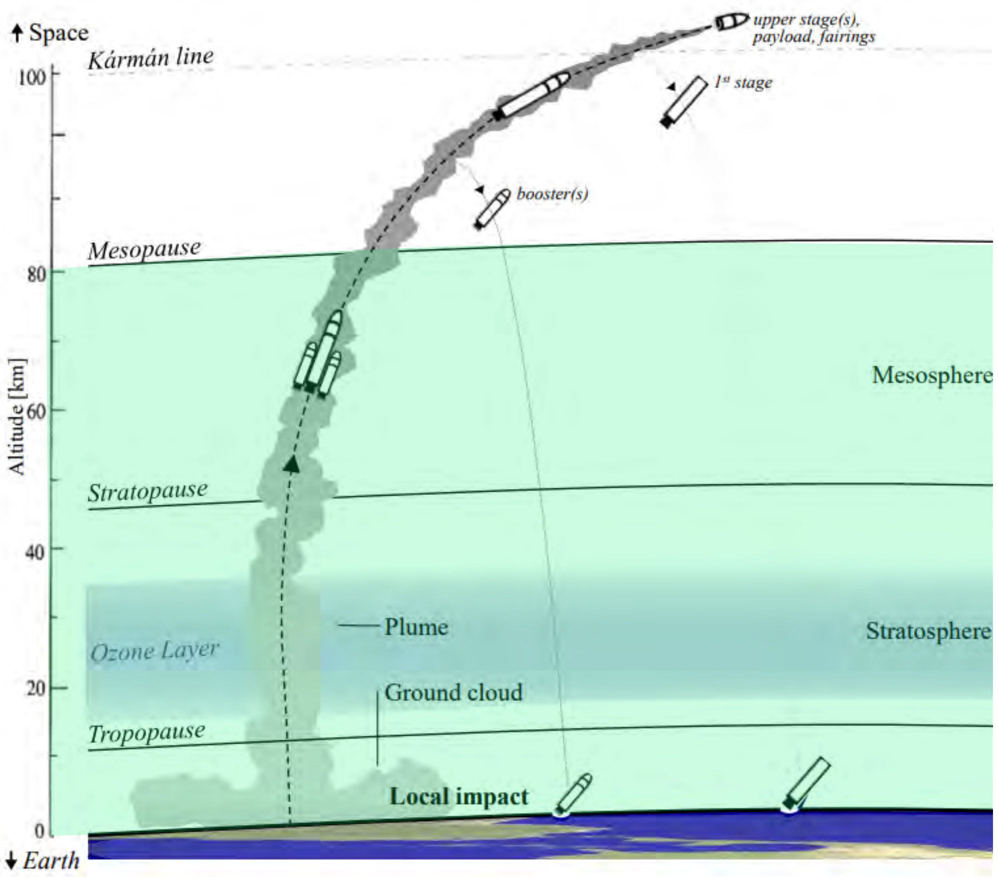
>1,000,000 satellites

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

SMCs are driving the post-2019 surge in launches and re-entries, mostly with the SpaceX Falcon rocket (54% of launches in 2025) launching the Starlink constellation.

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

Air Pollutant Emissions from Rocket Launches

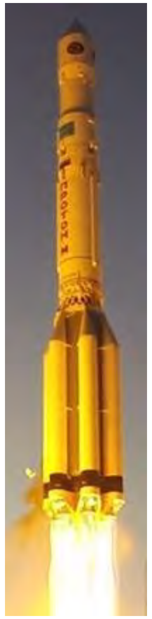


Launch emissions are injected throughout all atmospheric layers, with altitude-dependent plume chemistry

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)

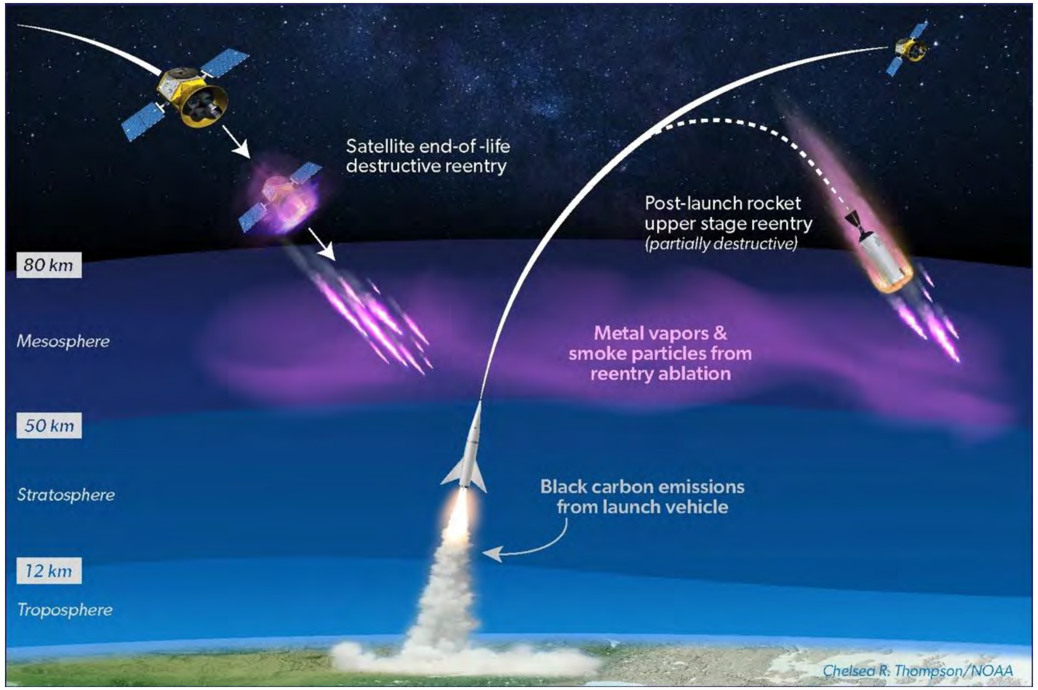
Kerosene
Falcon 9
LOX / RP1
H_2O
CO
CO_2
Black Carbon
Thermal NO_x



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

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

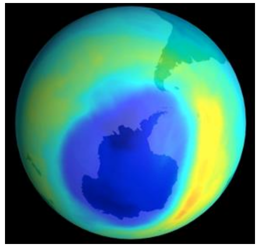
[NOAA, ESA]

Environmental impacts of the space industry

Launches (0 km to orbit)

Reentries (60-80 km)

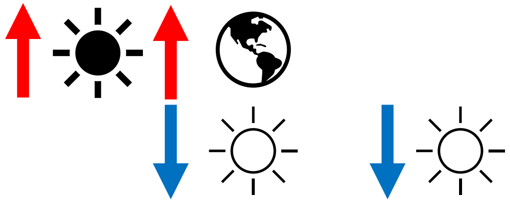
Stratospheric O_3 depletion



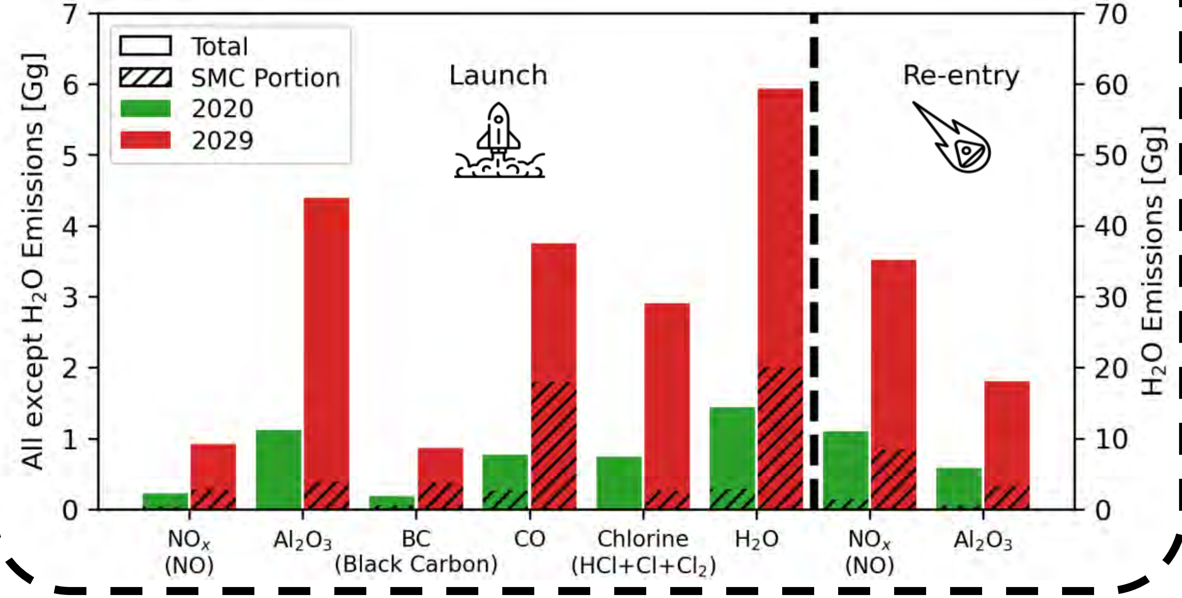
Driven by NO_x and Cl_y

Instantaneous Climate Forcing

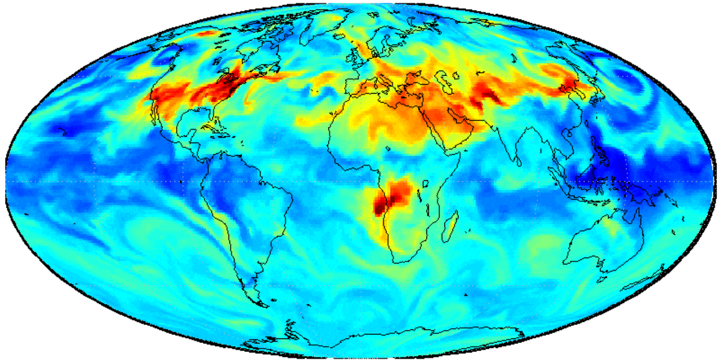
BC Al_2O_3 Strat. Aerosol



Global, 3D, hourly rocket launch and re-entry emission inventory for 2020-2022, extrapolated to 2029



GEOS-Chem + RRTMG



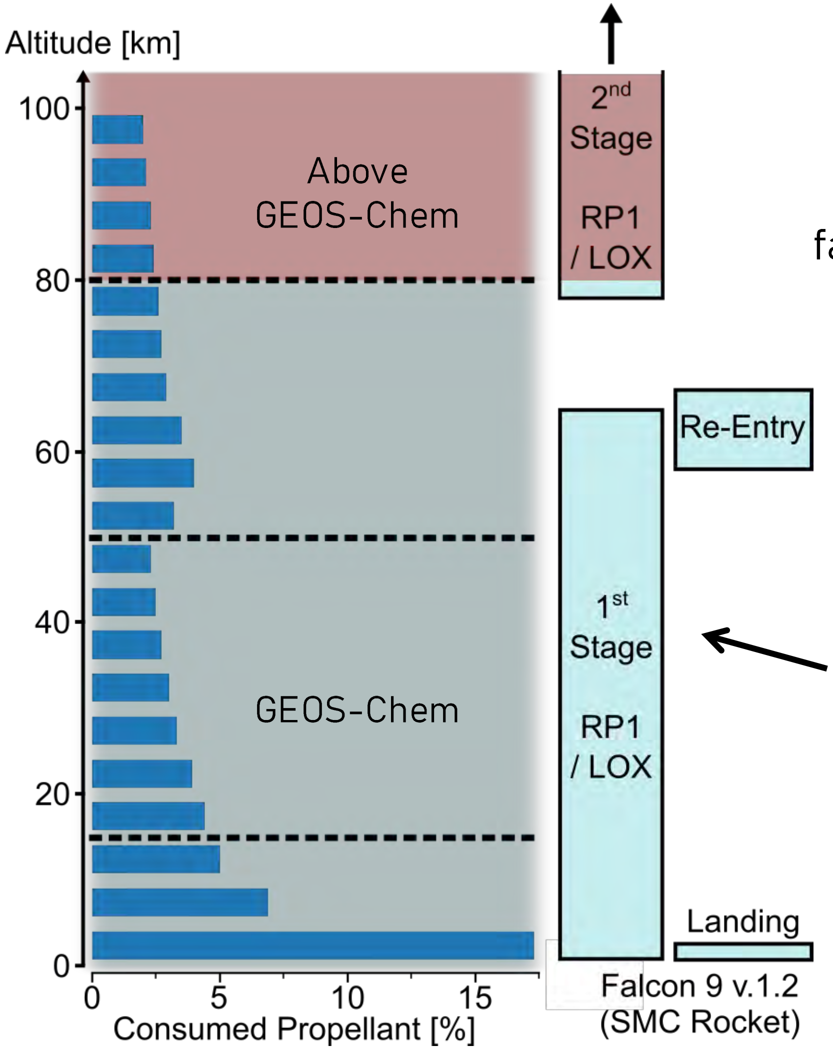
1. No missions
2. All missions
3. SMC missions only

2020-2029
4° x 5° x 47 layers
0-80 km

Atmospheric Composition Radiative Forcing

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.

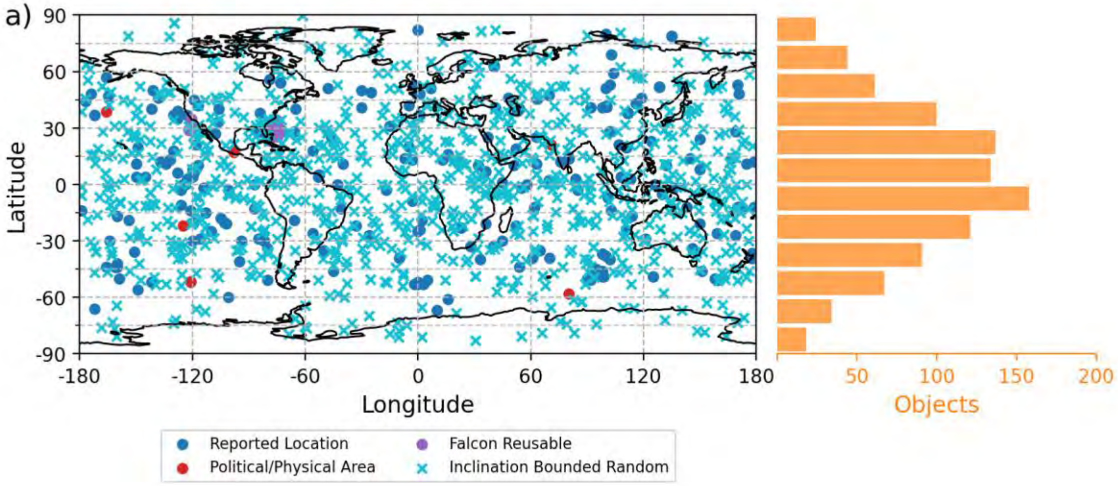
Annual propellant consumption increased from 36-63 Gg in 2020-2022.

Re-entry

Reusable

Expendable

Re-entering Objects in 2022

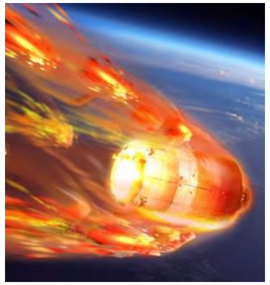


Annual re-entry mass has increased (3-5 kt), and the SMC portion is increasing too (18-26%)

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

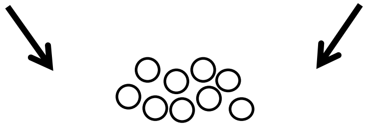
Updating GEOS-Chem to represent stratospheric aerosol injection

Alumina (Al_2O_3) added as advected chemically-active tracer

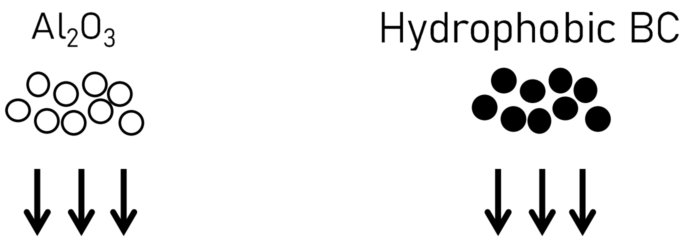


Re-entry ablation

Solid rocket fuel

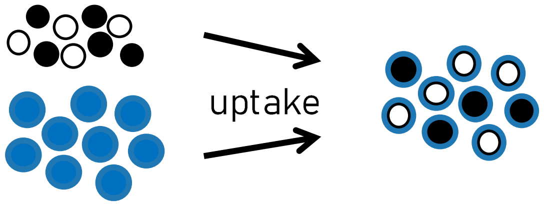


Gravitational settling updated



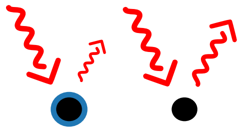
Added prompt uptake of BC and Al_2O_3 to stratospheric sulfate

BC + Al_2O_3 emissions



Stratospheric H_2SO_4

Added enhanced shortwave absorption from lensing effect

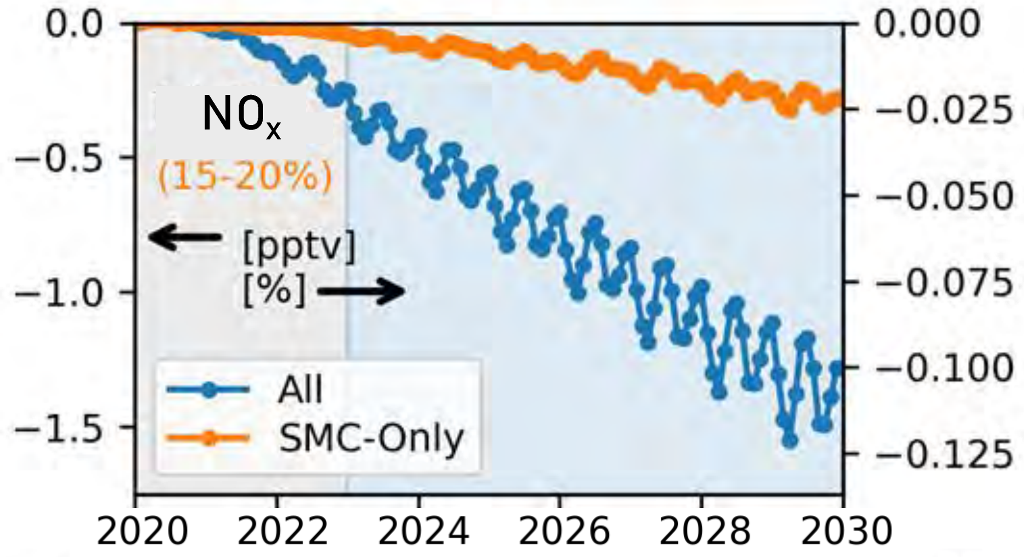


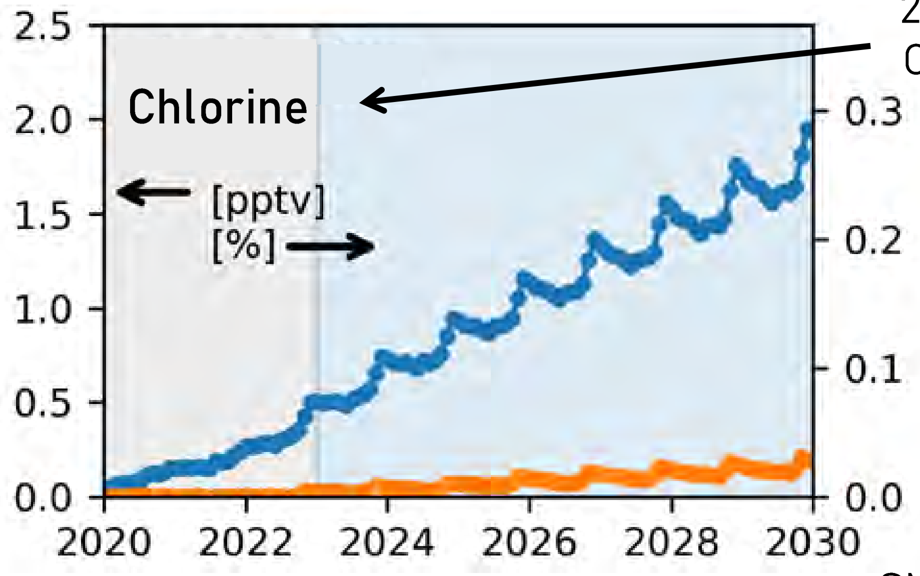
Non-absorbing shell focusses light onto absorbing core

[Barker *et al.*, in review]

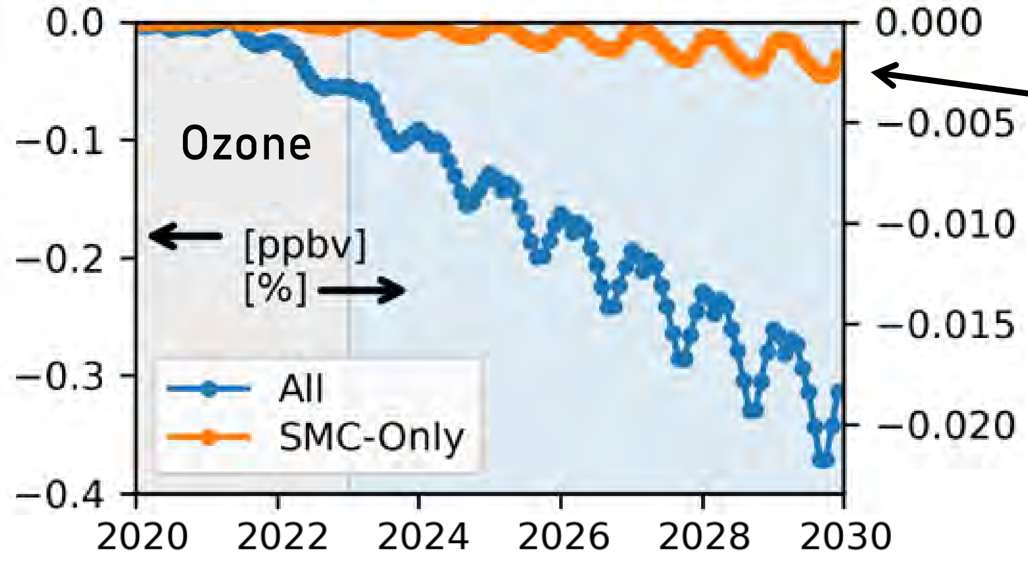
Stratospheric ozone depletion by the space industry

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	15%	20%
Chlorine	5%	9%
Ozone	3%	9%

Global stratospheric ozone depletion by the space industry is small (0.02%) compared to surface sources (~2%).

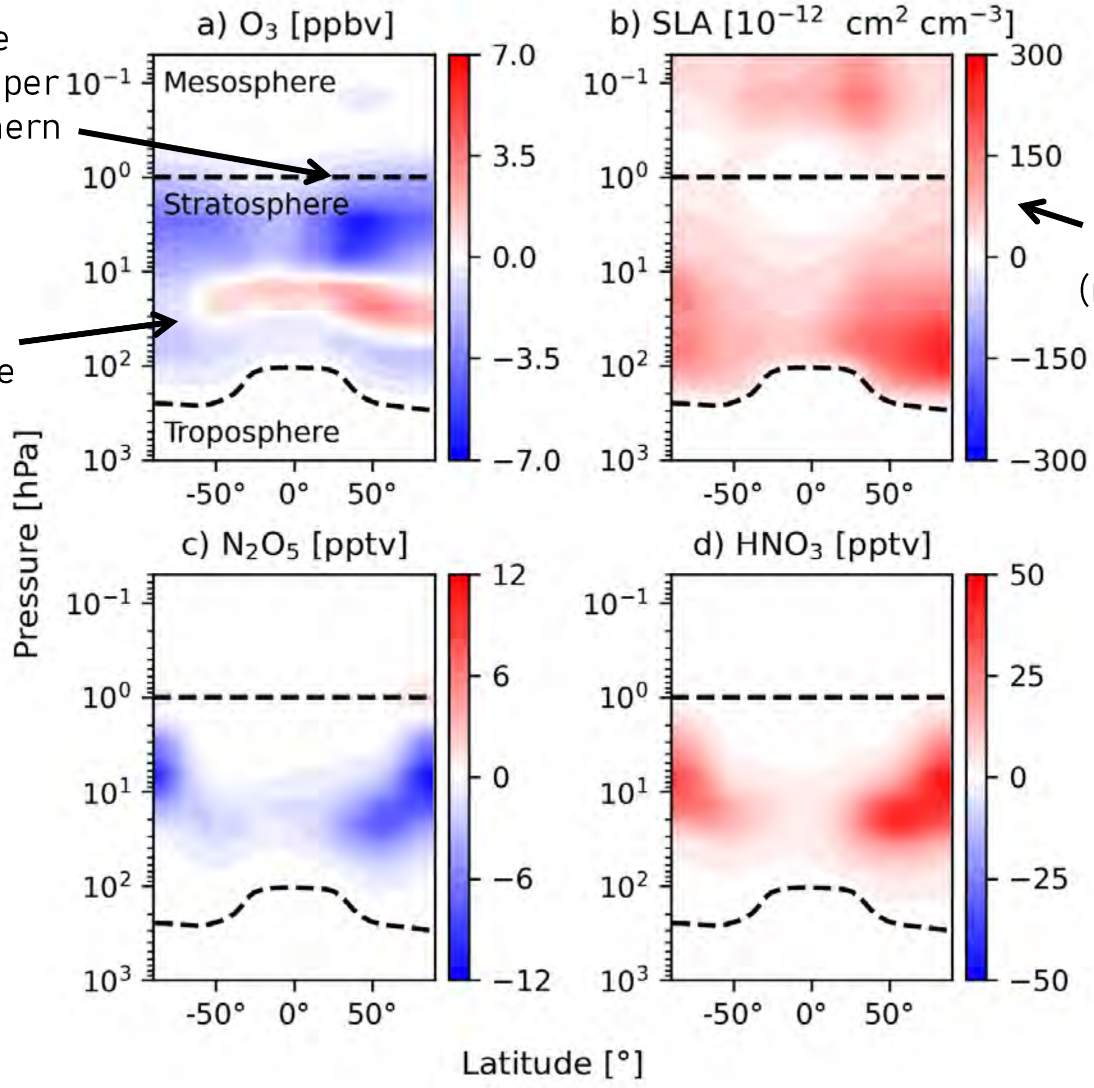
[Barker *et al.*, in review]

Stratospheric ozone depletion by the space industry

Annual mean changes in vertical profile (2029)

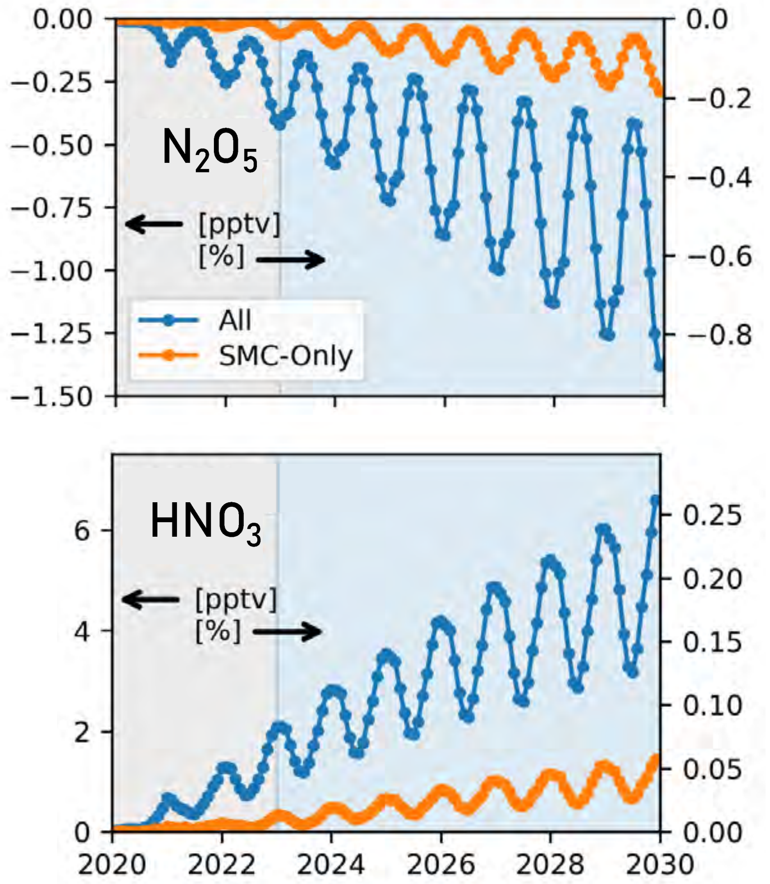
Maximum ozone depletion in the upper stratosphere northern hemisphere

Maximum ozone production in middle stratosphere



SLA: stratospheric liquid aerosol (mostly sulfate

Monthly mean change in stratospheric composition



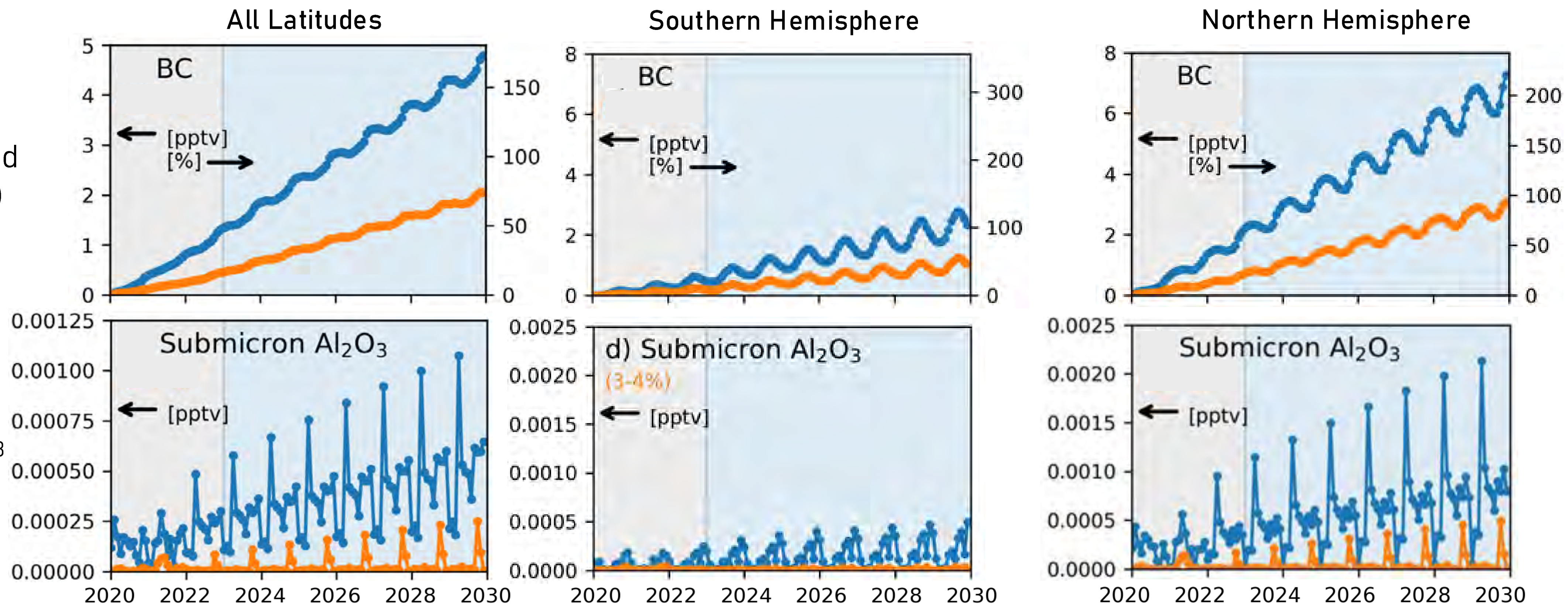
Uptake of aerosols to SLA increases surface area, increasing rate of hydrolysis of N_2O_5 to form HNO_3. This suppresses NO_x recycling.

Stratospheric aerosol chemistry

Monthly mean change in stratospheric concentration

Total BC (coated and uncoated)

Uncoated Al_2O_3



SMC Contribution

	2020	2029
BC	36%	43%
Al_2O_3	5%	7%

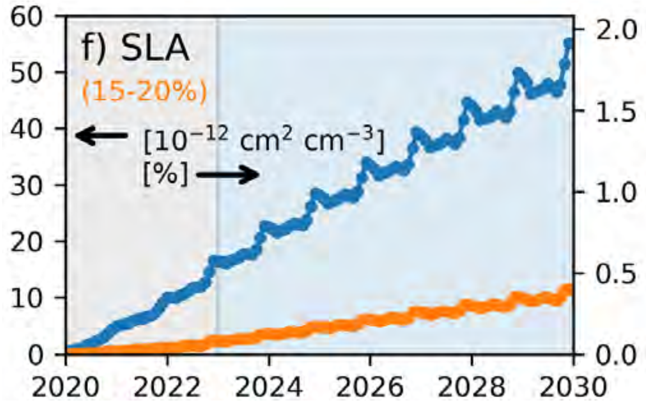
Aerosol seasonality is dominated by the northern hemisphere (launches).

[Barker et al., in review]

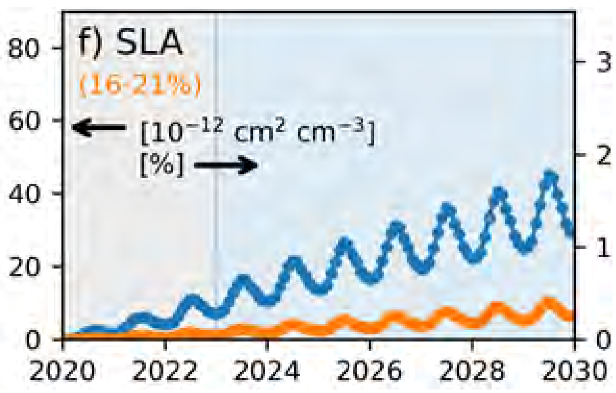
Stratospheric aerosol chemistry

Monthly mean change in stratospheric surface area concentration

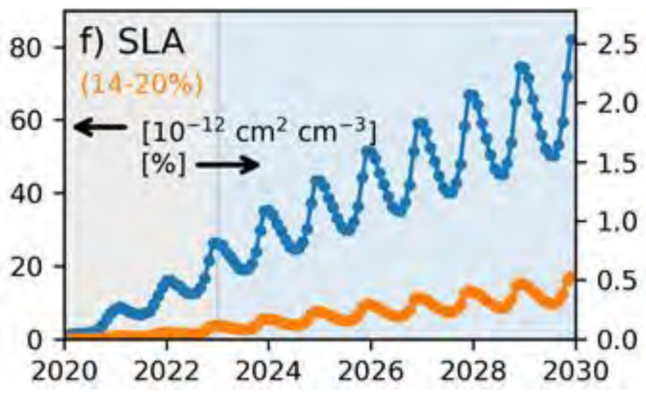
All Latitudes



Southern Hemisphere



Northern Hemisphere



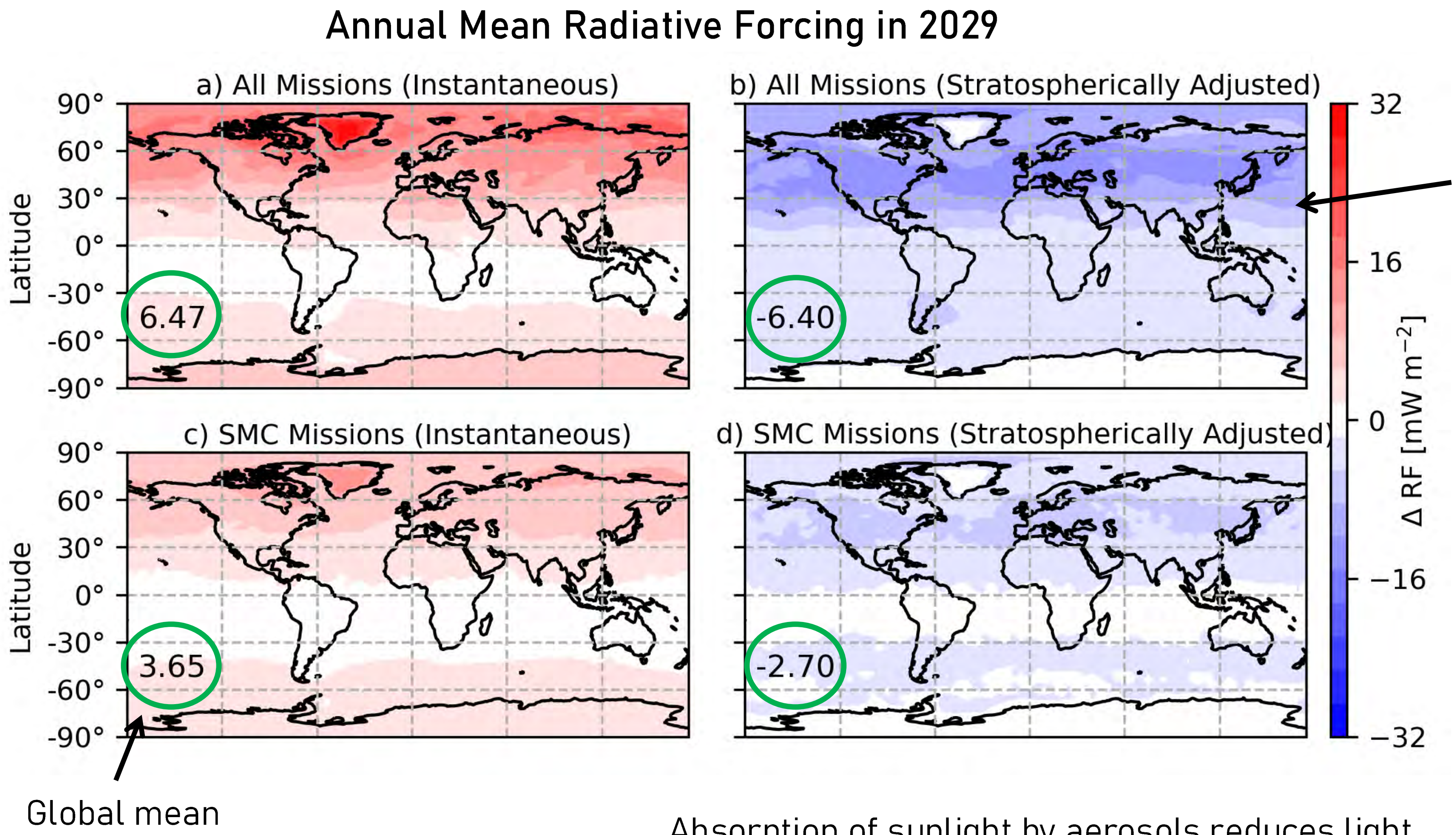
This increase is primarily due to uptake of Al_2O_3 rather than BC.

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.

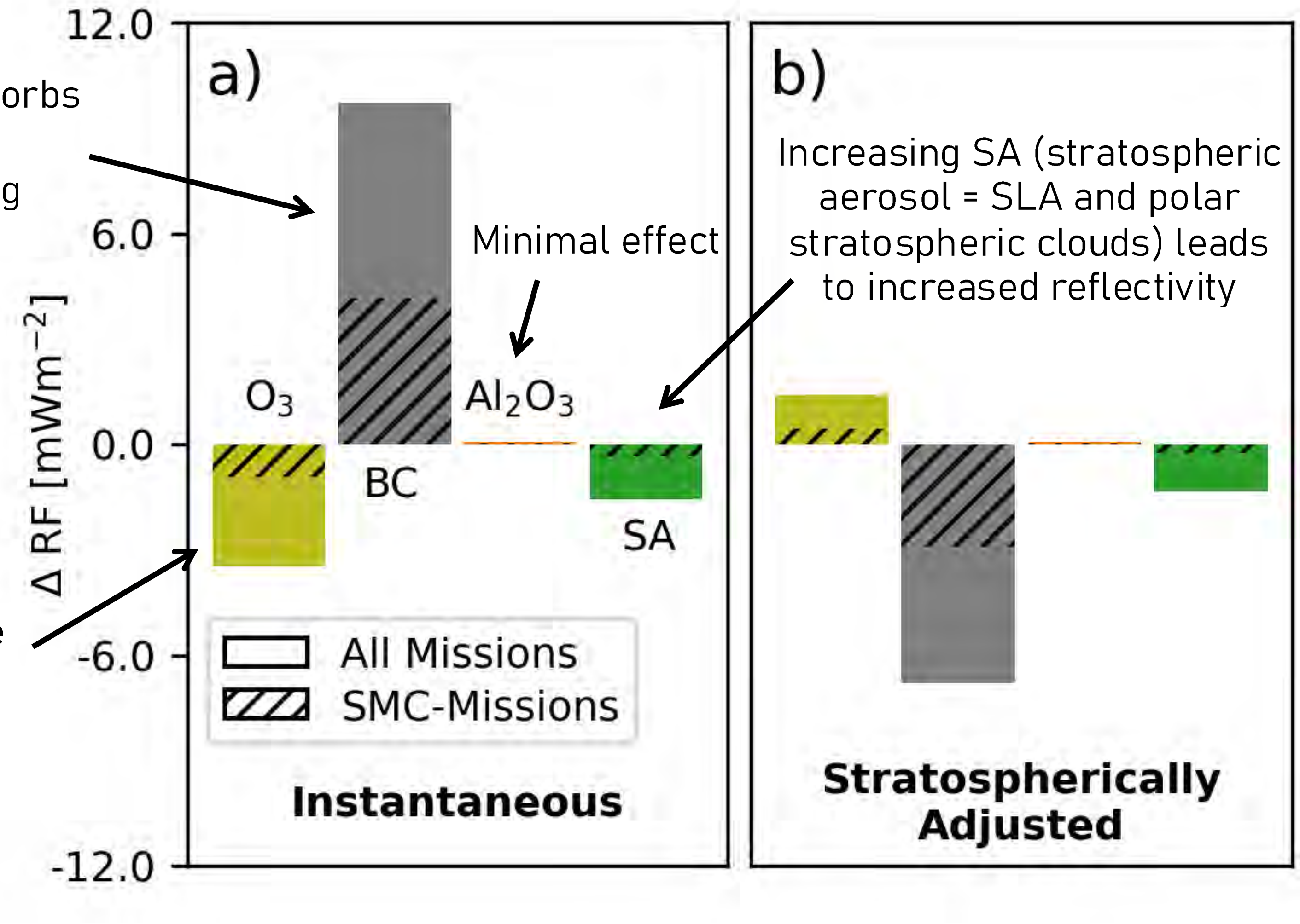
Absorption of sunlight by aerosols reduces light reaching the troposphere, leading to negative stratospherically adjusted radiative forcing.

[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



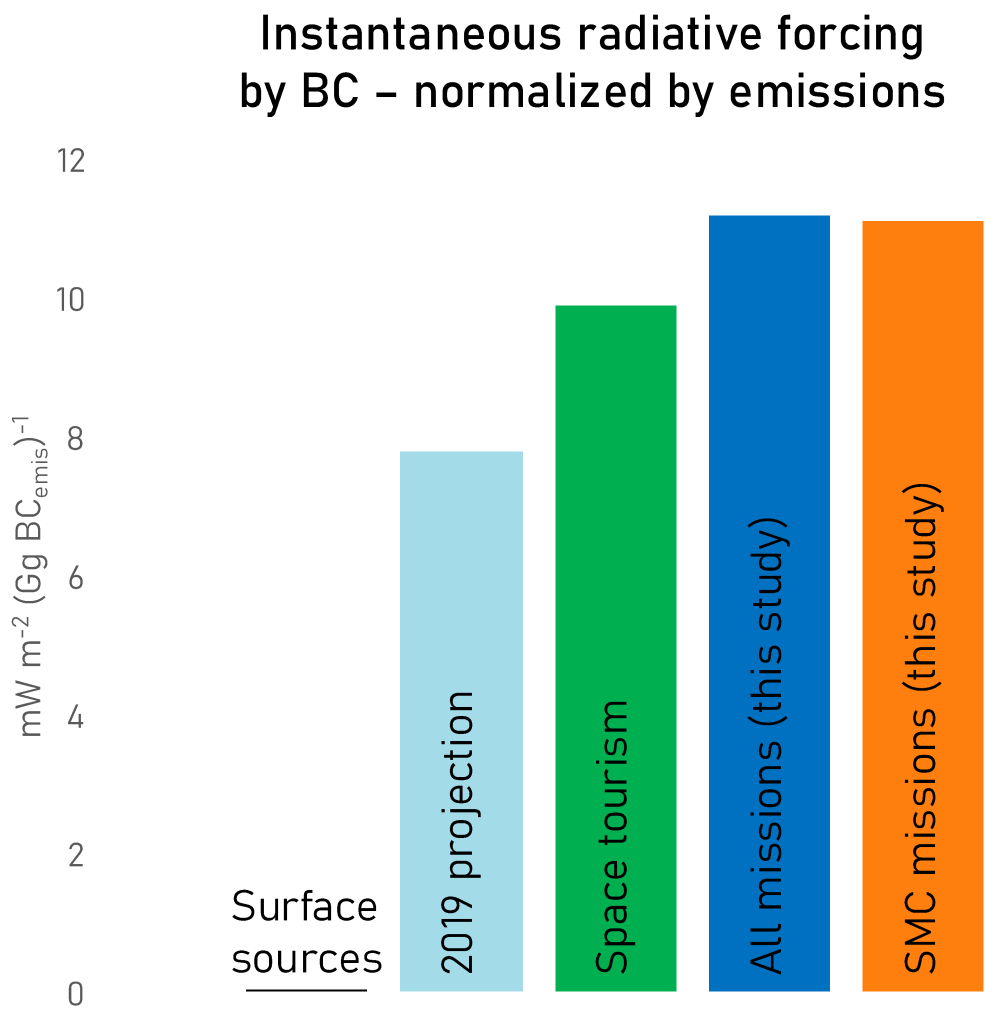
Ozone is a greenhouse gas, so a reduction means a cooling effect

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

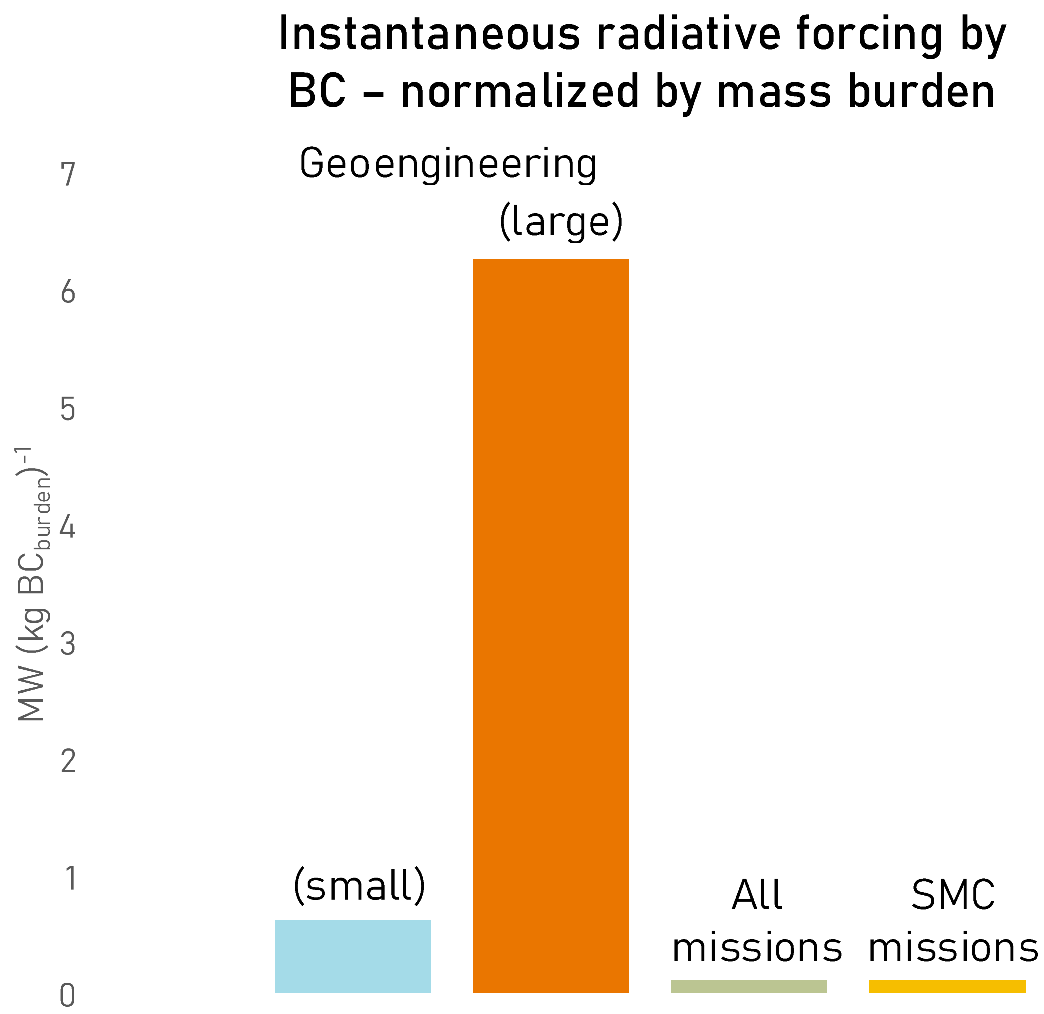
Radiative forcing is dominated by BC absorption of incoming sunlight by sulfate-coated BC above the tropopause

[Barker et al., in review]

Putting the radiative forcing into context



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

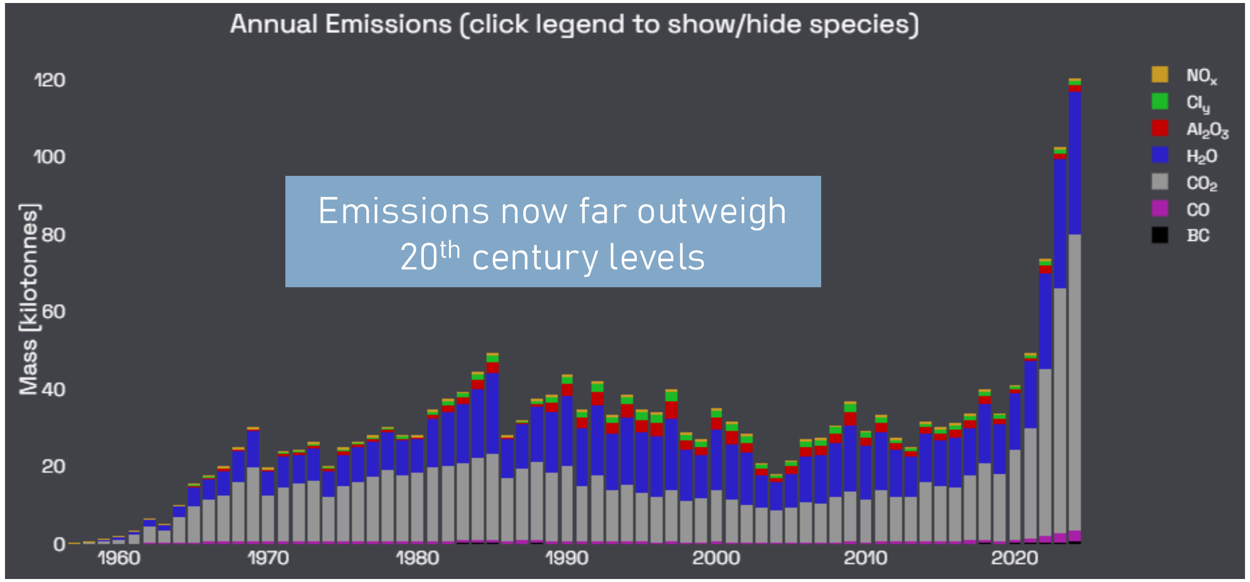


The normalized forcing is smaller than similar geoengineering studies.

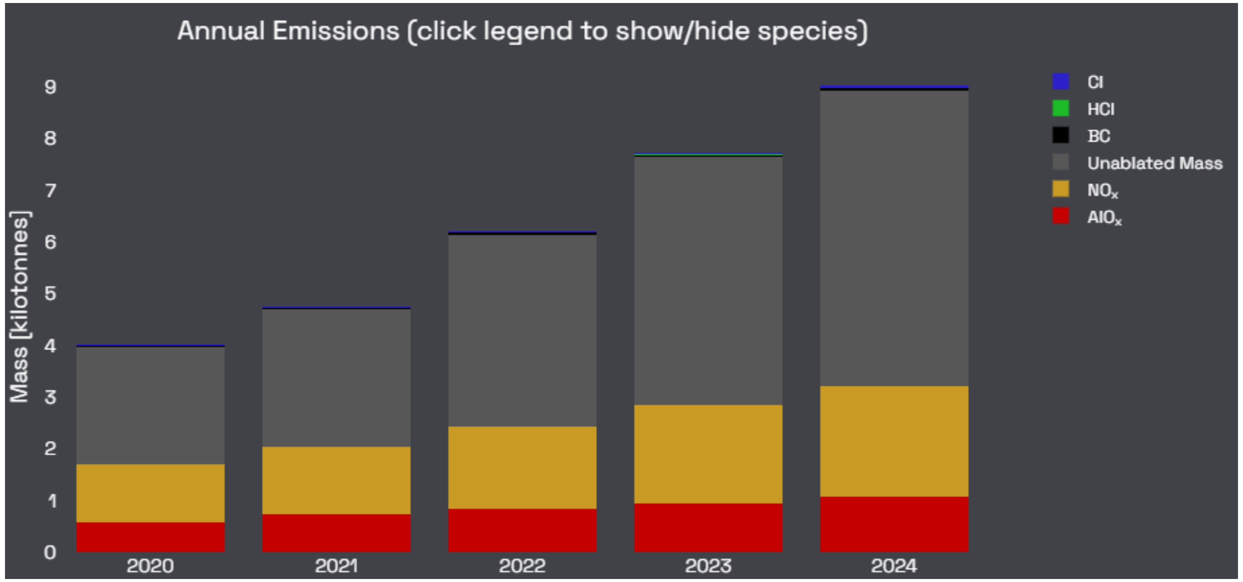
[Barker *et al.*, in review, Ryan *et al.* 2022, Dong *et al.* 2019, Kravitz *et al.* 2012]

Space Emissions Tracker

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



Re-entry emissions from 2020-2024



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

Exponential increase in emissions since 2020

Re-entry emissions are increasing, but delay between launch and re-entry means exponential rise is delayed

Full link: https://cbarker211.github.io/. Extended with help from UCL Astrophysics summer research student, Eric Tan.

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 0.02% 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.

Contact: Connor Barker
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Launch 🚀 Re-entry 🛰

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