Developing inventories of by-products from satellite megaconstellation launches and disposal to determine the influence on stratospheric ozone and climate

UCL EGU General Assembly 2024 erc

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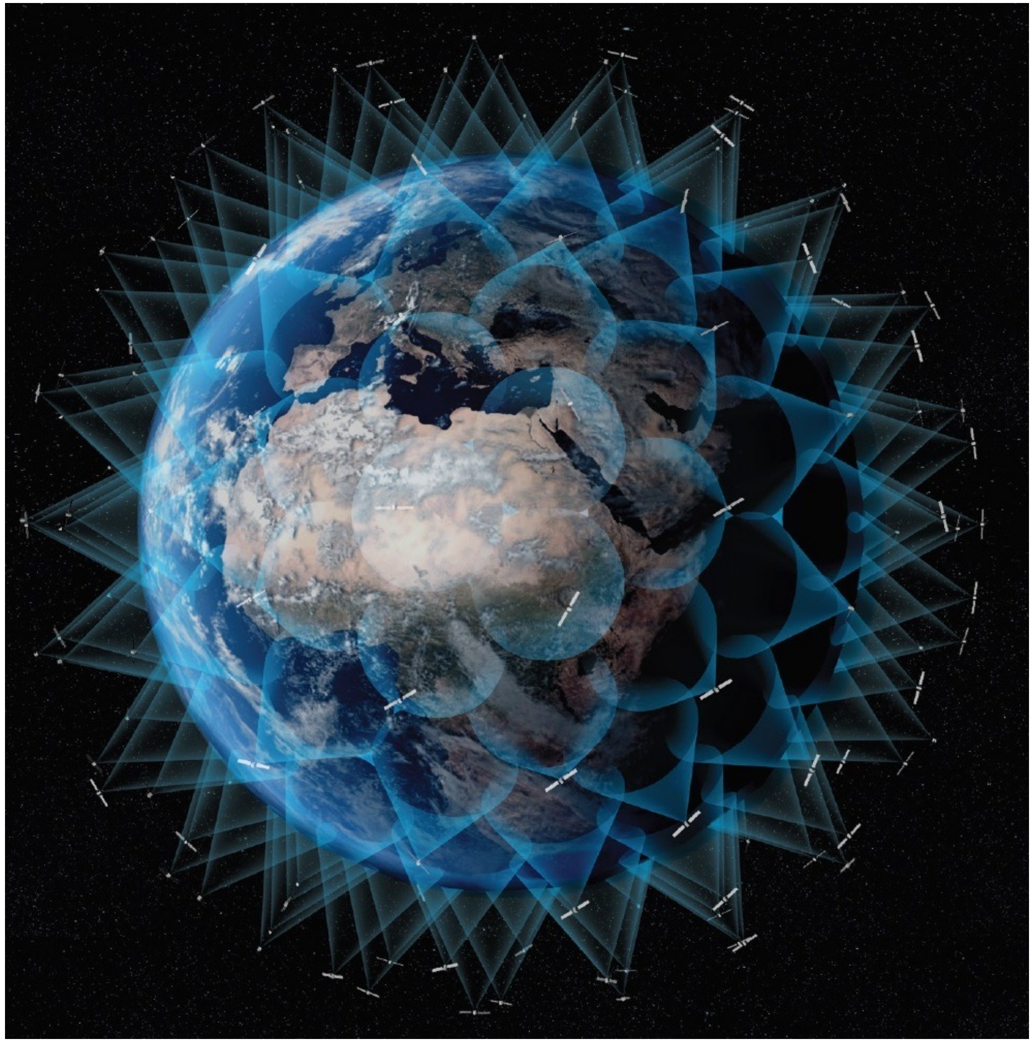
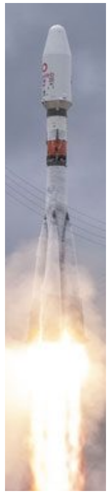
The rise of satellite megaconstellations (SMCs)



SpaceX Starlink

6166

401



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.

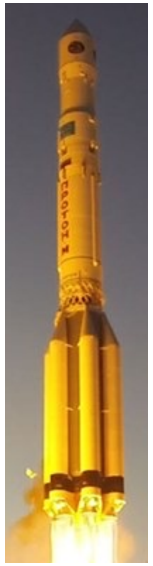
Air pollutant emissions from satellite megaconstellations

Launches (all atmospheric layers)

Hydrogen
Delta IV Heavy
LOX / LH_2
H_2O
Thermal NO_x

Kerosene
Falcon 9
LOX / RP1
H_2O
CO
BC
Thermal NO_x

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



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

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

Reentries (upper atmosphere)

Payload/Rocket
Thermal NO_x
Al_2O_3

Pollutants released in all atmospheric layers.

Rocket launch and re-entry emissions affect ozone and climate

Stratospheric Ozone Depletion

NO_x

$NO + O_3 \rightarrow NO_2 + O_2$

$NO_2 + O \rightarrow NO + O_2$

$O_3 + O \rightarrow 2O_2$

Cl_y

$Cl + O_3 \rightarrow ClO + O_2$

$ClO + O \rightarrow Cl + O_2$

$O_3 + O \rightarrow 2O_2$

Al_2O_3

Surface for chlorine activation

TOA Radiative Forcing

BC

Absorbs solar

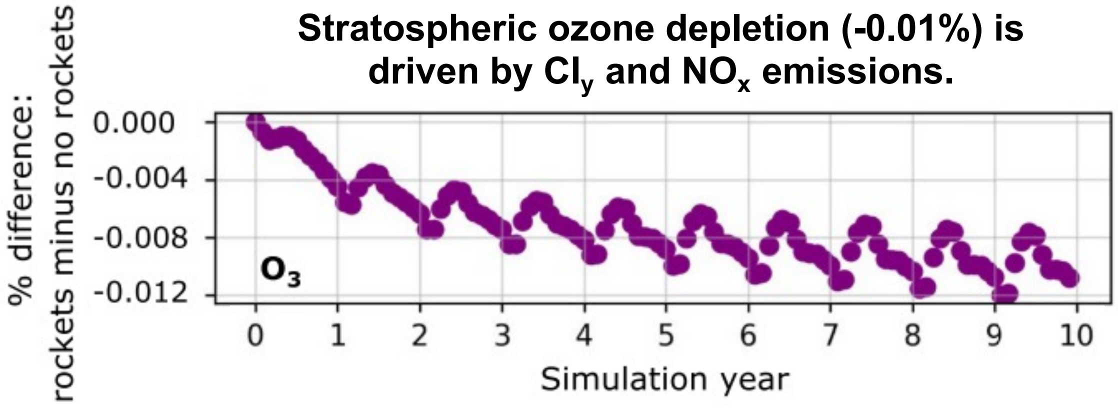
Al_2O_3

Absorbs terrestrial

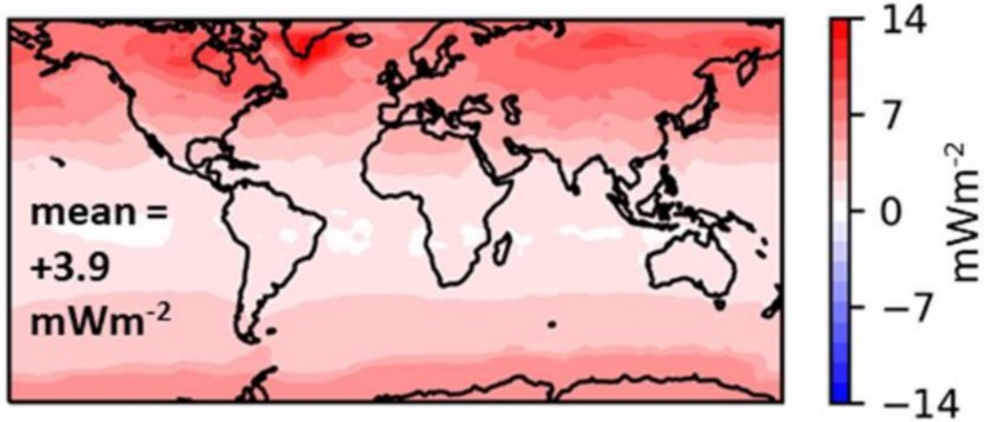
Reflects solar

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

Stratospheric ozone depletion (-0.01%) is driven by Cl_y and NO_x emissions.

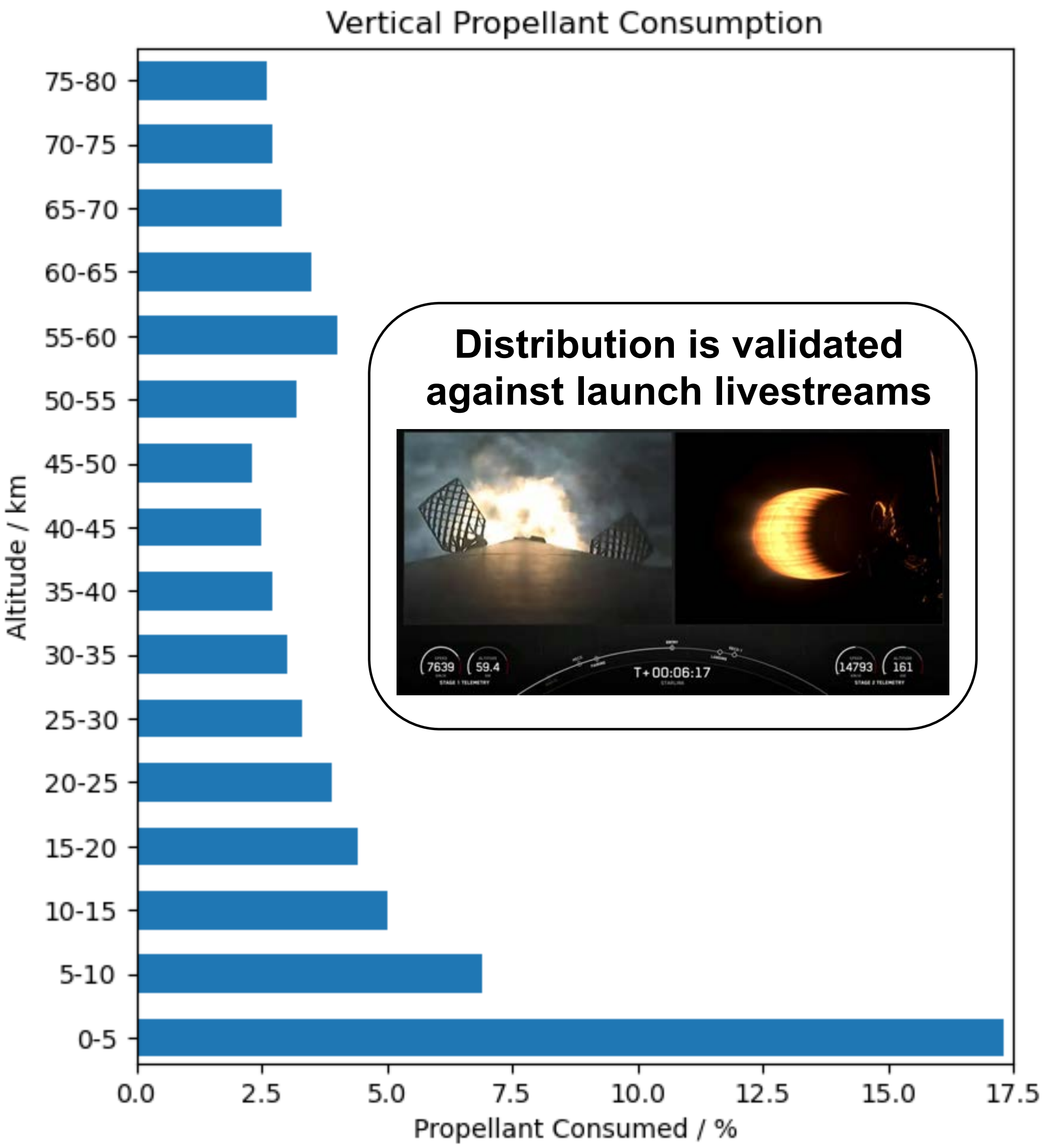


Global climate forcing at TOA is driven by BC emissions.

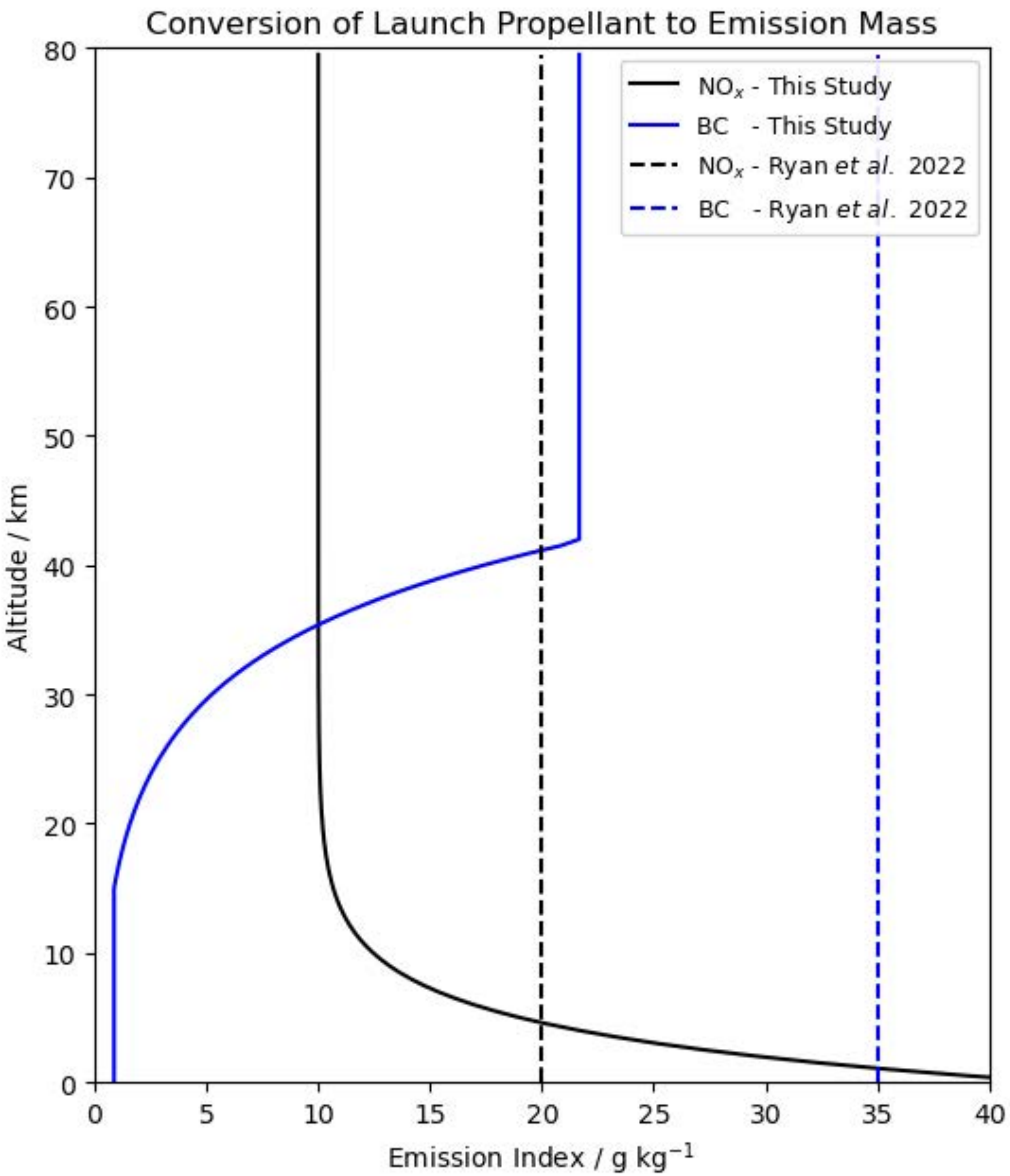


[Ryan *et al.* 2022]

Creating a vertical distribution of launch emissions



Distribution is validated against launch livestreams



[Ross *et al.* 2014]

Conversion of re-entry mass to upper atmosphere emissions

Reusable Objects

17.5%

0%

NO_x

Al_2O_3

Expendable Objects

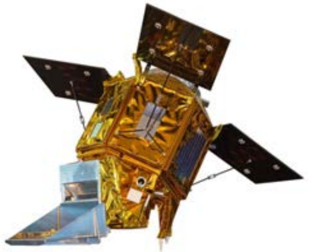
Composition:

Rocket Stages
70% Al

Survivability:

70% Core
35% Upper

Payloads
40% Al



0% SMC
20% Non-SMC

40%

Variable %

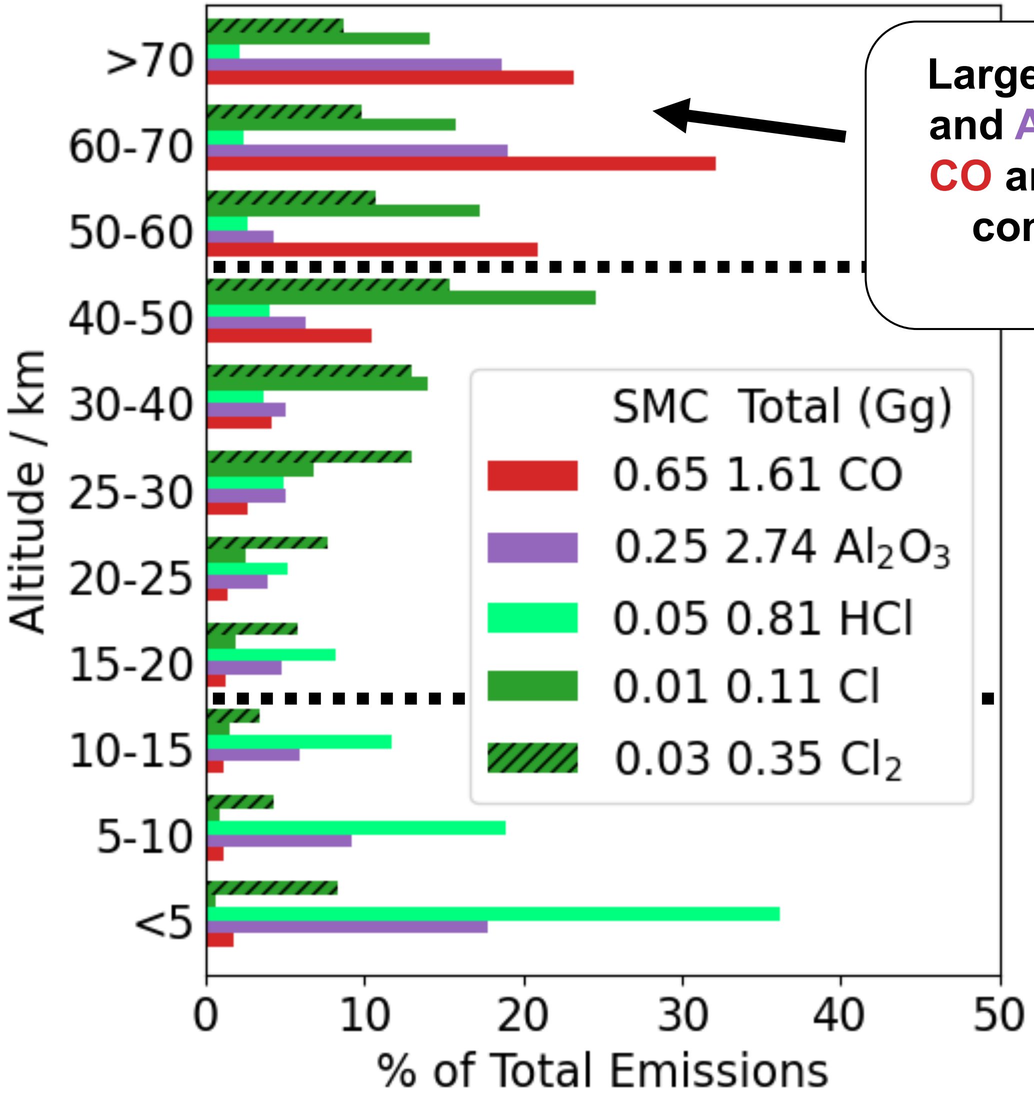
NO_x

Al_2O_3

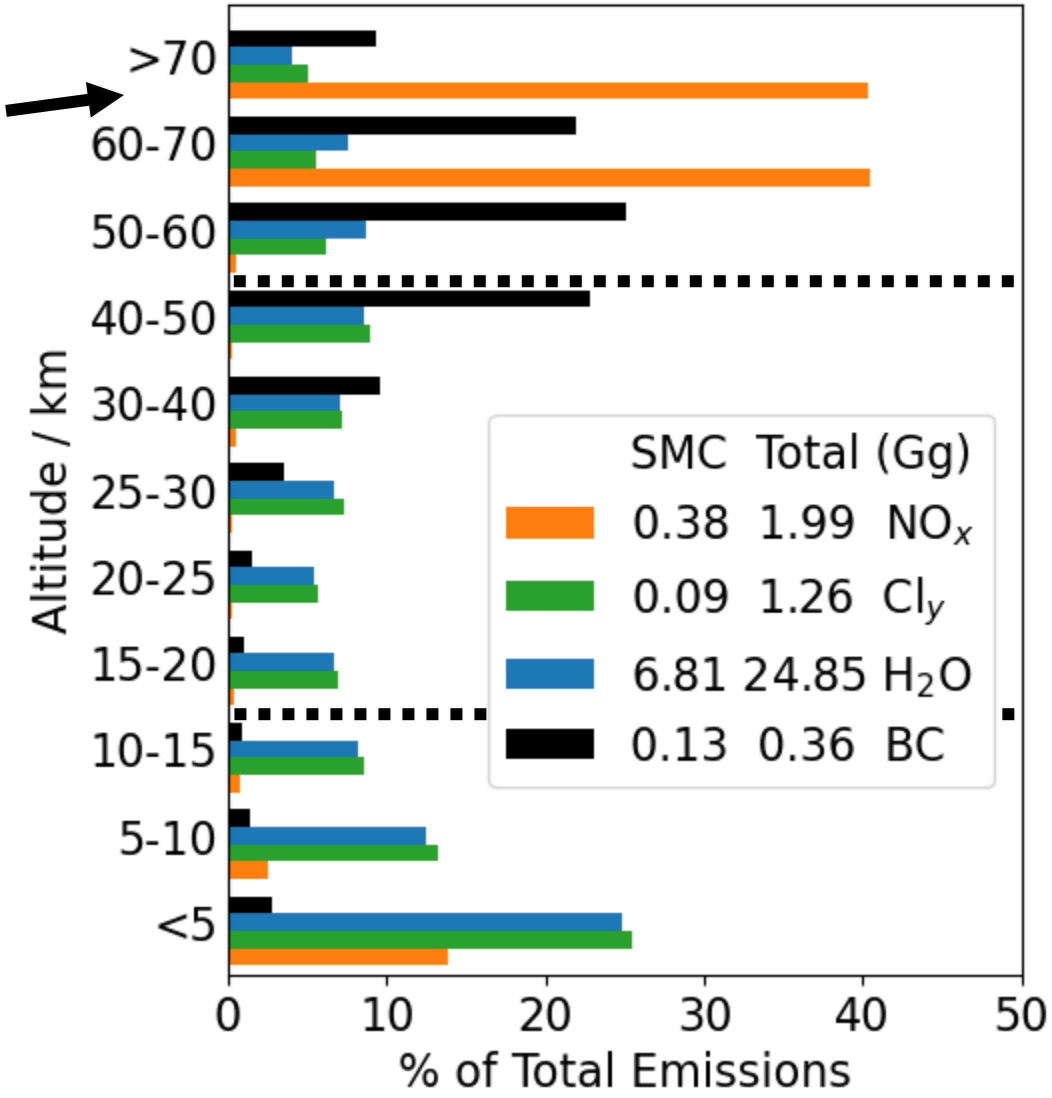
Re-entry mass has increased since 2020 (3.27-5.59 Gg, 878-1650 objects), partly driven by satellite megaconstellations (17-23%). Conversion to emissions requires broad assumptions on ablation and chemical composition.

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

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

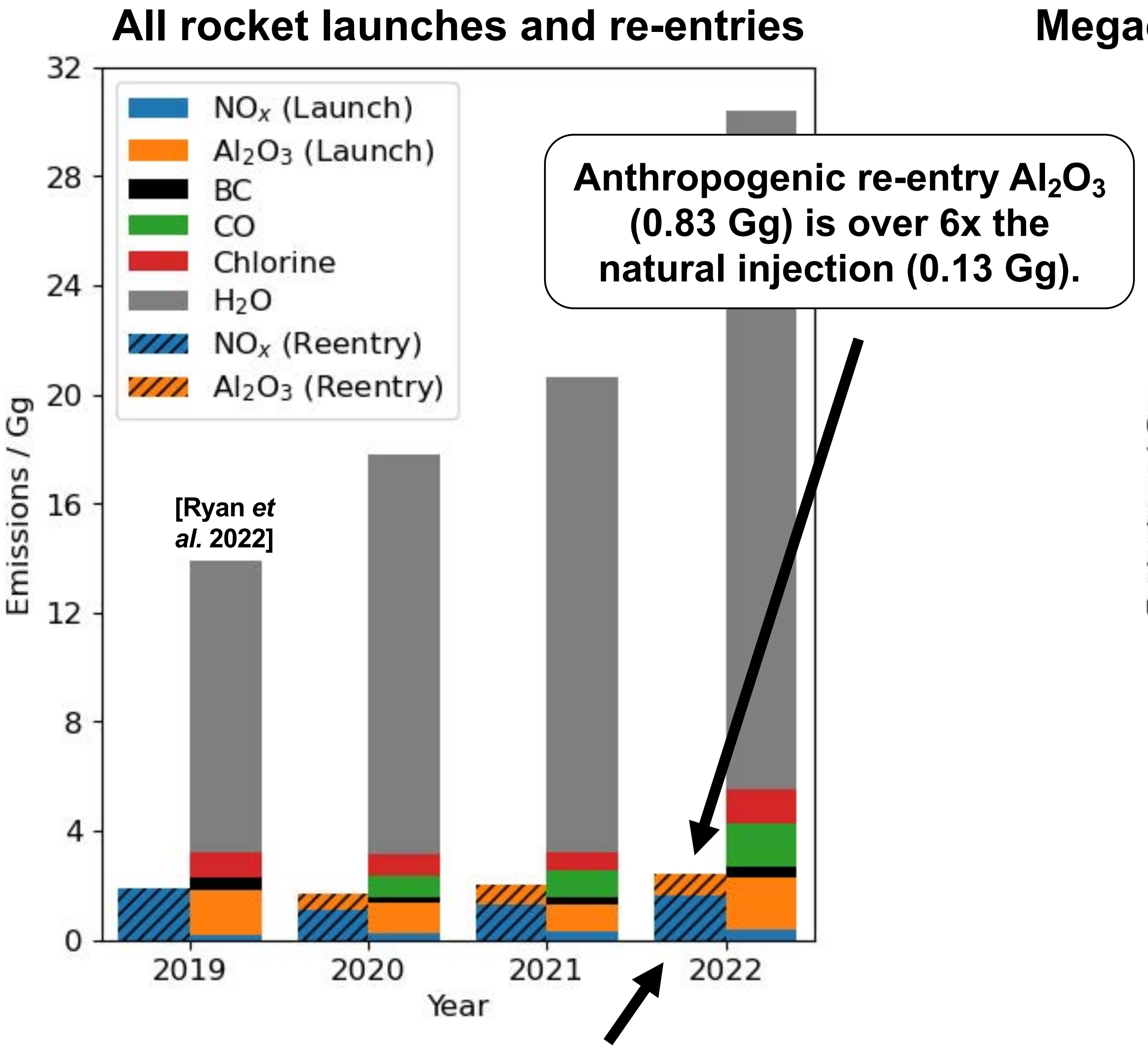


Large emissions of NO_x and Al_2O_3 (re-entry) and CO and BC (incomplete combustion) above stratopause.

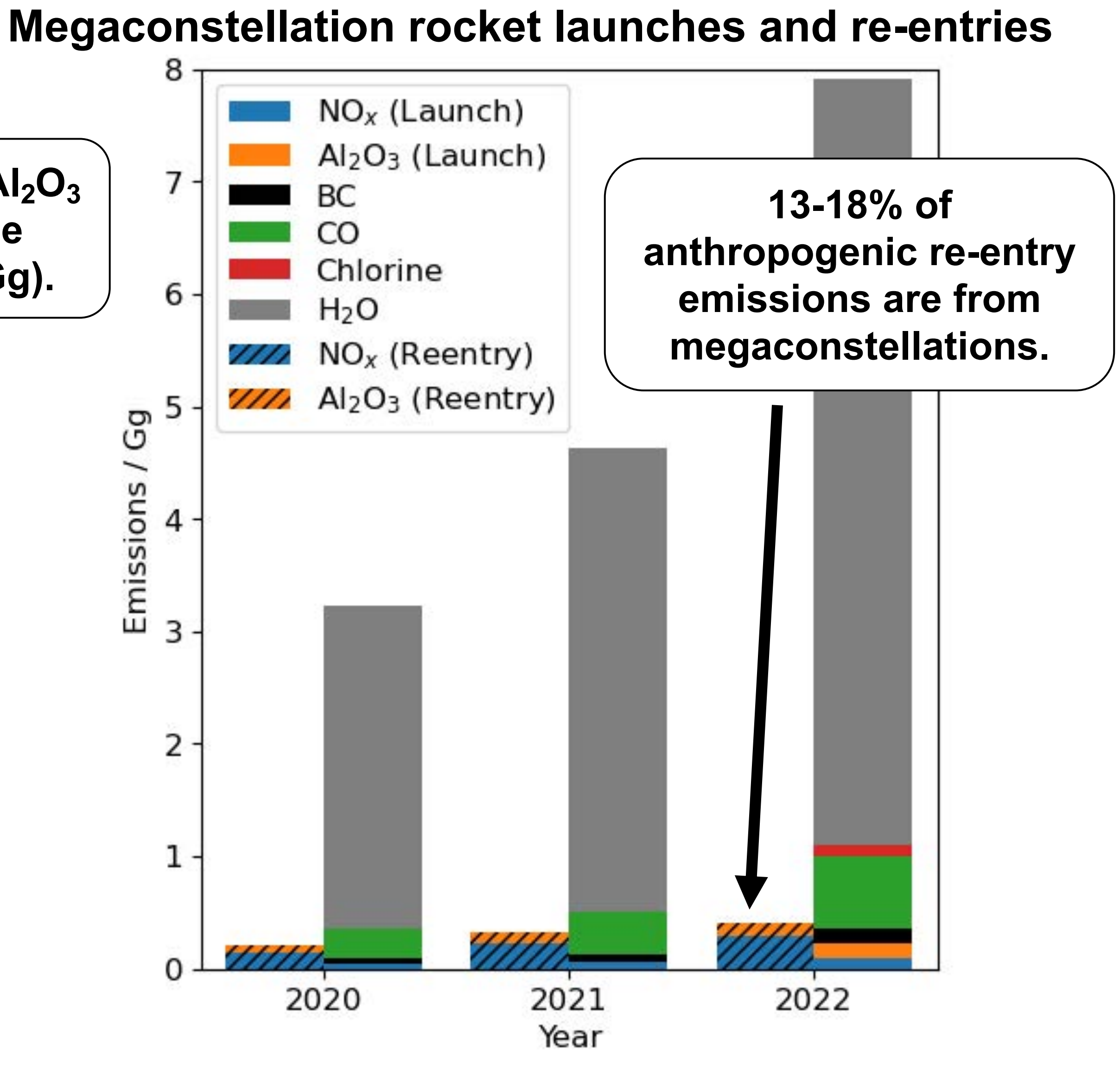


Most BC, NO_x, H_2O, CO, Cl_y, and Al_2O_3 emissions are injected above the tropopause.

Satellite launch and re-entry emission inventory



Anthropogenic re-entry NO_x (1.60 Gg) is approaching the natural injection (2-40 Gg).

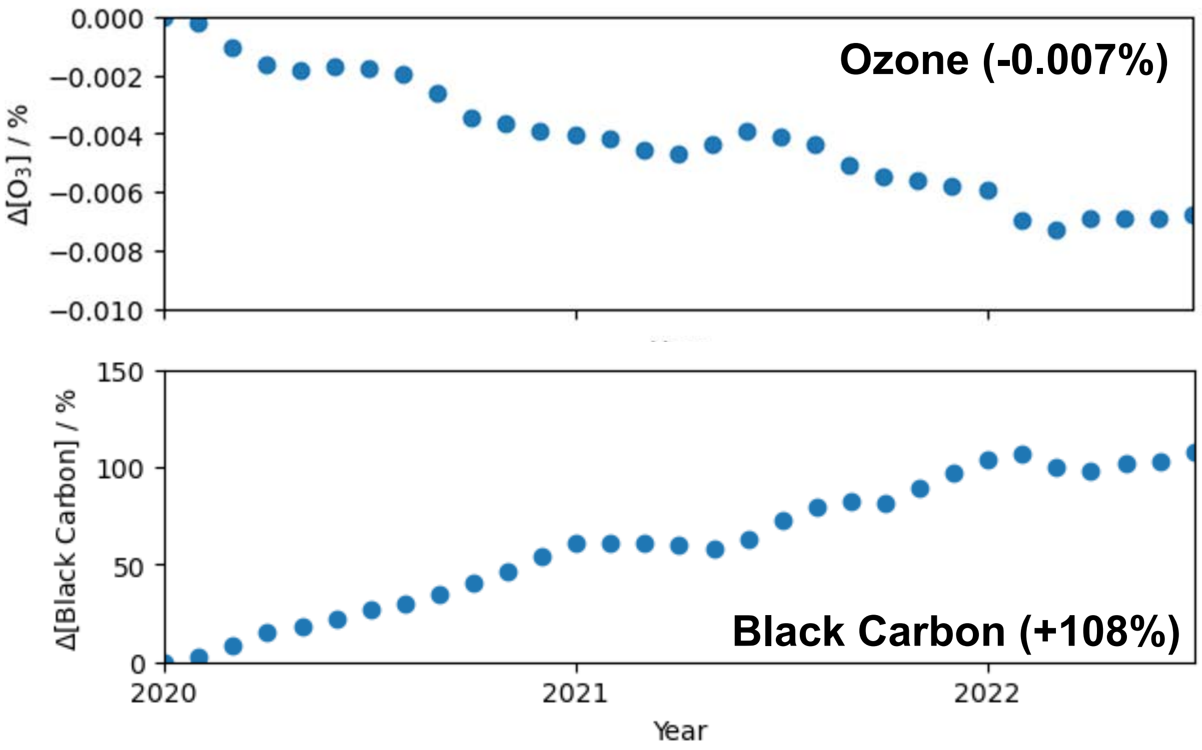


Kerosene fuel dominates megaconstellation launches, reducing harmful Cl_y and Al_2O_3 emissions.

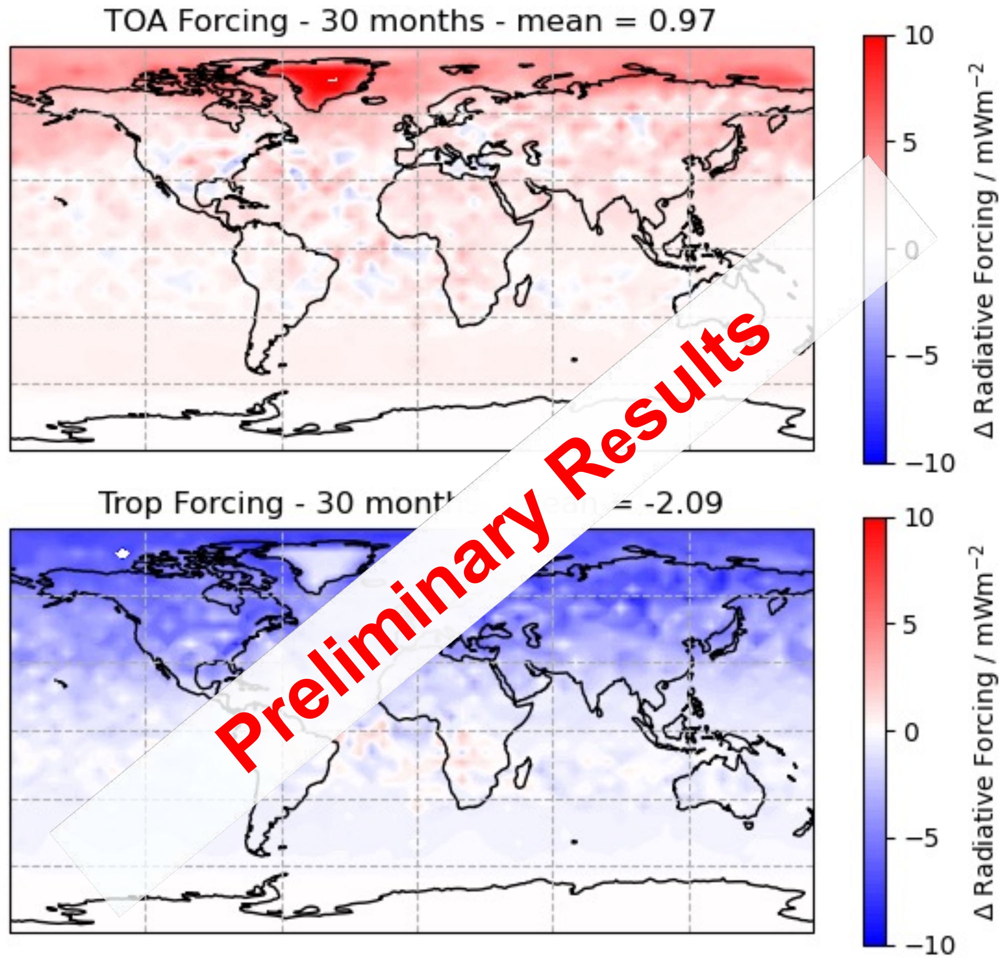
Rocket launch and re-entry emissions deplete ozone and affect climate

UCL

Impact of improved 2020-2022 emissions on stratospheric concentration.



Global stratospheric ozone depletion after 2.5 years is approaching 10-year loss in Ryan *et al.* 2022 (-0.01%).



Increased stratospheric BC burden drives cooling at tropopause and heating at top of atmosphere, dominated by SW.

GEOS-Chem + RRTMG

Conclusions, uncertainties and next steps

- **Compiled emission inventories for 2020-2022 SMC and non-SMC emissions.**
  - Launch and re-entry have risen from 2020-2022 for megaconstellation and non-megaconstellation sources.
  - Anthropogenic alumina re-entry emissions have exceeded the natural meteoritic injection.
- **Preliminary results demonstrate immediate environmental impacts.**
  - 2.5-years of increasing rocket launch and re-entry emissions result in global stratospheric ozone depletion of -0.007%.
  - Large increase in stratospheric black carbon burden (+108%).
  - Increasing rocket launch and re-entry emissions cause cooling at tropopause and heating at top of atmosphere.
- **More research/data is needed to address uncertainties:**
  - Experimental data for launch and re-entry emission indices at varying altitudes.
  - % survivability and chemical composition for each re-entering object.
  - Increased data availability from rocket manufacturers to aid research.
  - Particle size, mass distribution and optical properties of BC/Al_2O_3 aerosol emissions.
- **Next steps:**
  - Finish simulating the impacts of a decade of all launch and re-entry emissions on stratospheric ozone and climate.
  - Simulate the megaconstellation emissions only to see the individual environmental impact of SMCs.

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

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