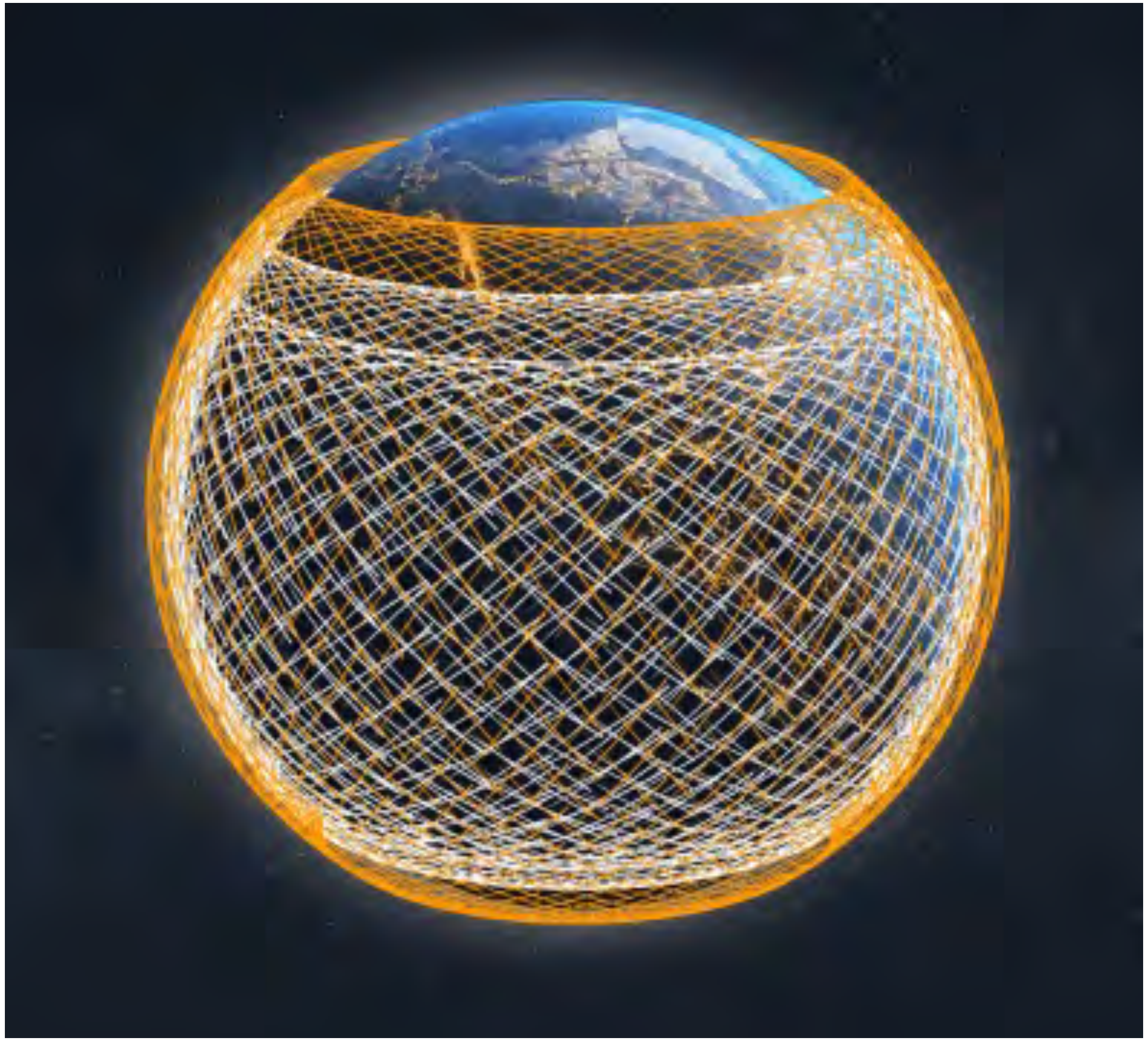
Developing satellite megaconstellation emission inventories to determine the impact on stratospheric ozone and climate.



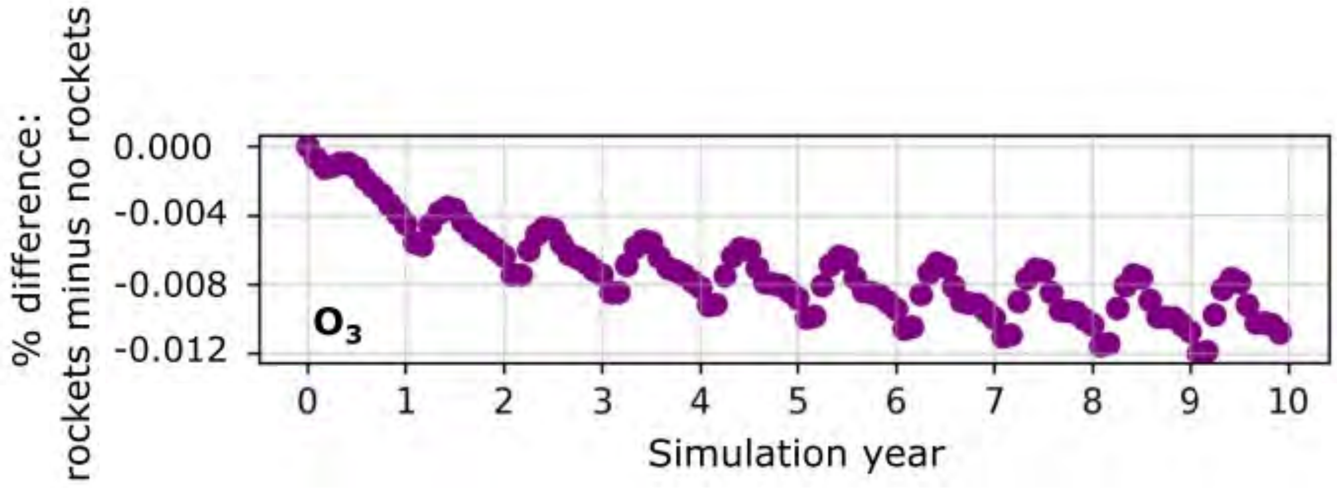
ESTEC Workshop

10th January 2024

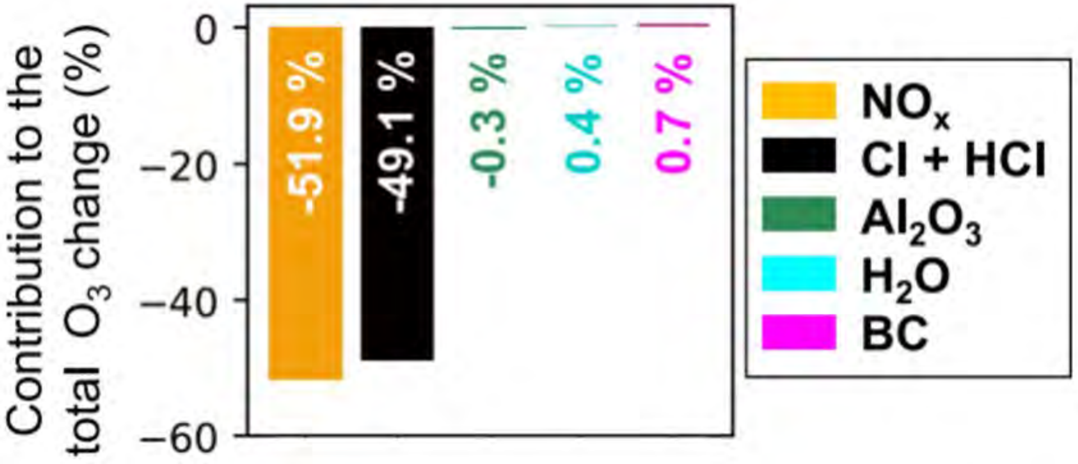
Connor Barker (connor.barker@ucl.ac.uk), Eloise Marais, Jonathan McDowell

Impact of rocket launch and re-entry emissions on stratospheric ozone

Impact of a decade of increasing 2019 rocket launch and re-entry emissions on stratospheric ozone depletion.



Contribution of individual pollutants to stratospheric O_3 depletion.



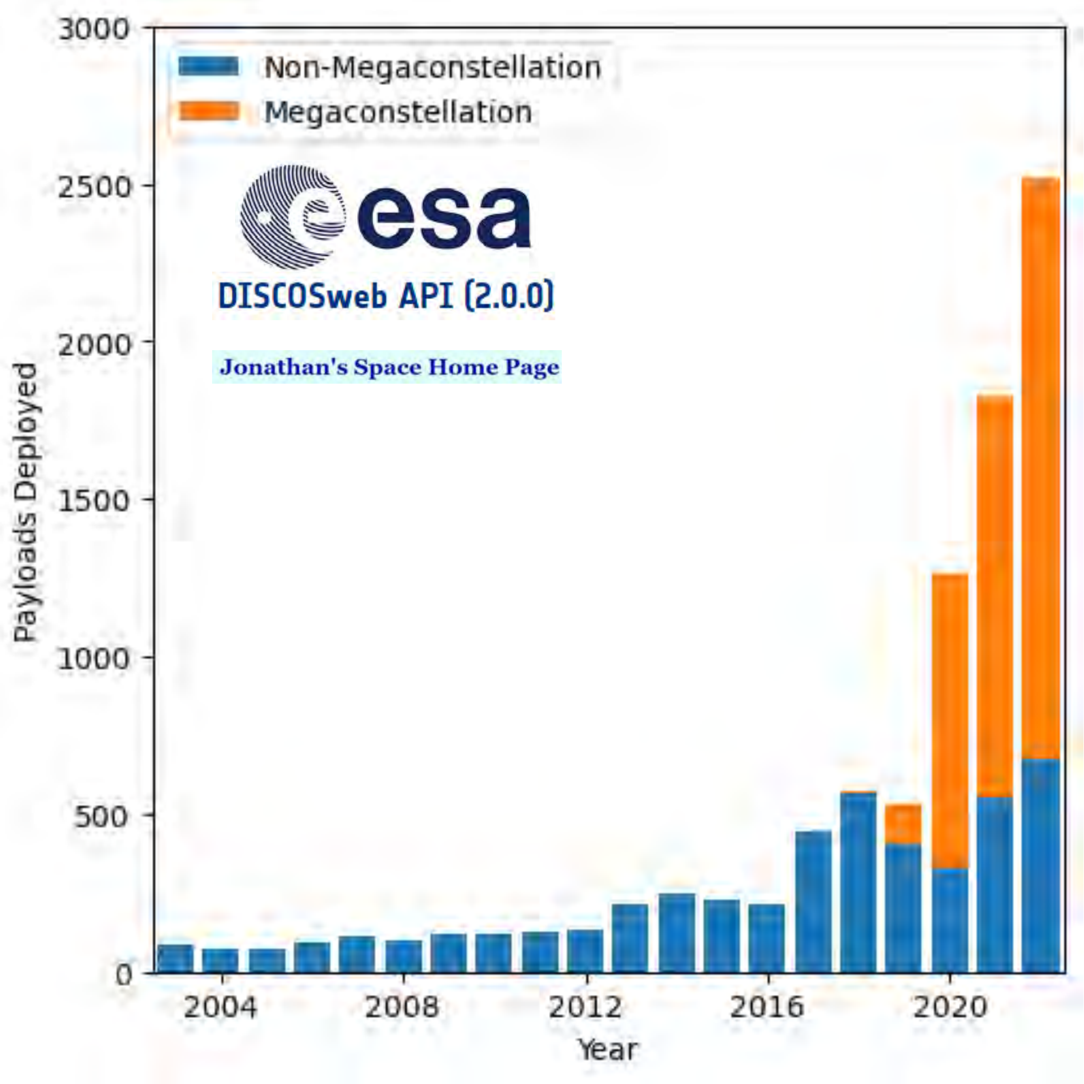
[Ryan *et al.* 2022]

Space industry emissions cause a 0.01% decrease in global stratospheric O_3.

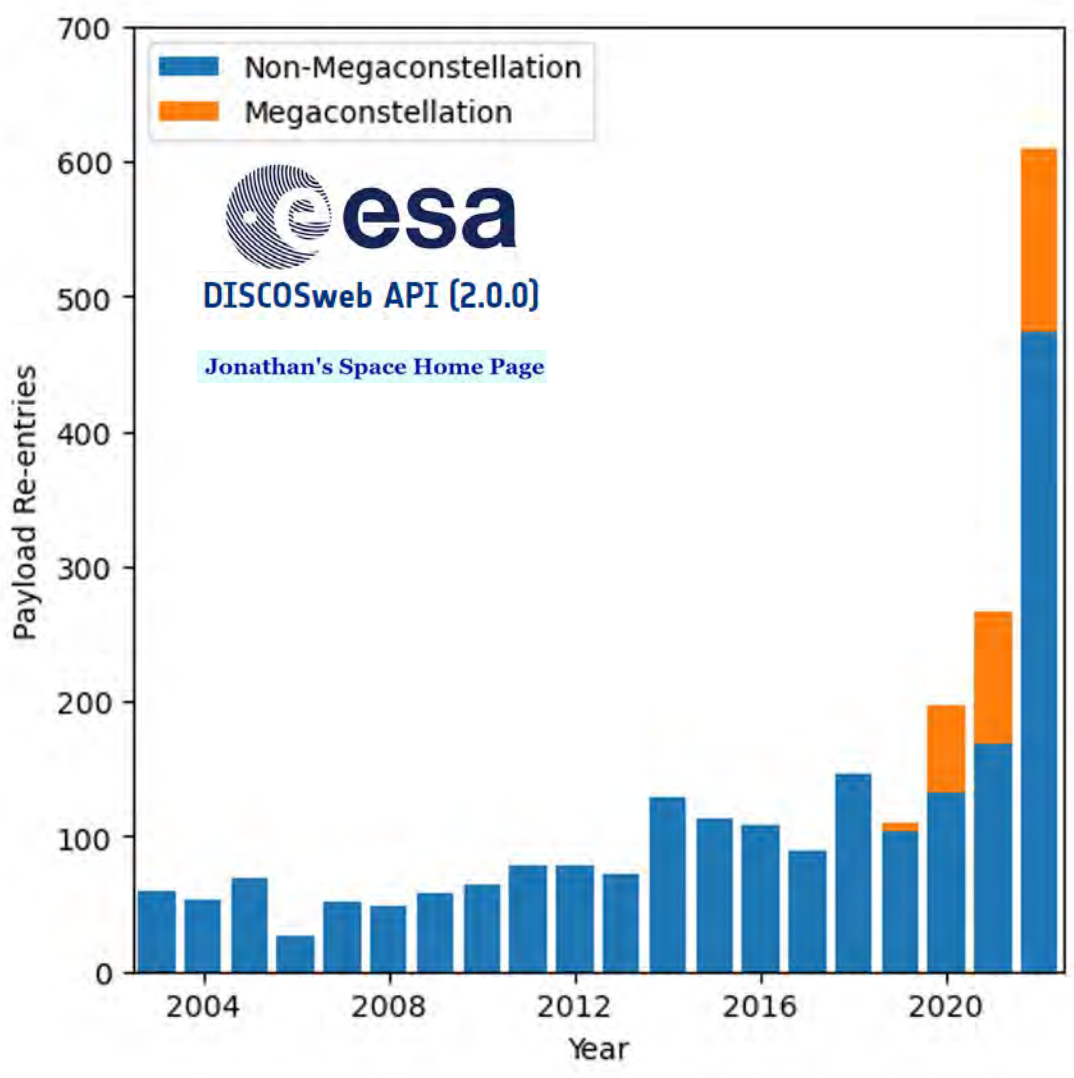
Most space industry stratospheric O_3 depletion is from atmospheric re-entry NO_x (2.45 Gg in 2019).

Rapid increases in payload launch and re-entry rates

Annual payloads deployed to orbit



Annual payload re-entries



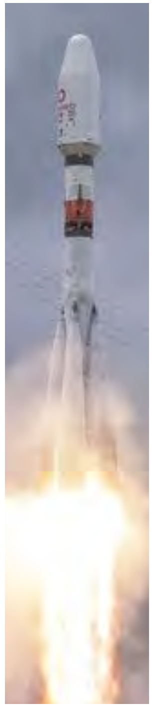
Most payloads deployed to orbit are megaconstellation satellites.
Short lifespan (<2 years) is already leading to increasing re-entry rates.

The rise of satellite megaconstellations (SMC)

SpaceX Starlink

Launched by SpaceX Falcon 9
Up to 60 satellites / launch
5671 launched, 383 re-entered

Eutelsat OneWeb



Launched by Soyuz, Falcon 9 and GSLV Mk III
Up to 40 satellites / launch
640 launched, 6 re-entered

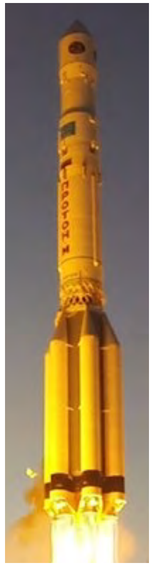
~ 540,000 extra SMC satellites planned for LEO, impacting astronomy, overcrowding and pollution.
Environmental impacts remain under-investigated and under-regulated.

Air pollutant emissions from satellite megaconstellations

Launches (all atmospheric layers)

Kerosene
Falcon 9
LOX / RP1
H_2O
CO
Thermal NO_x
BC

Hydrogen
Delta IV Heavy
LOX / LH_2
H_2O
CO
Thermal NO_x



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

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

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

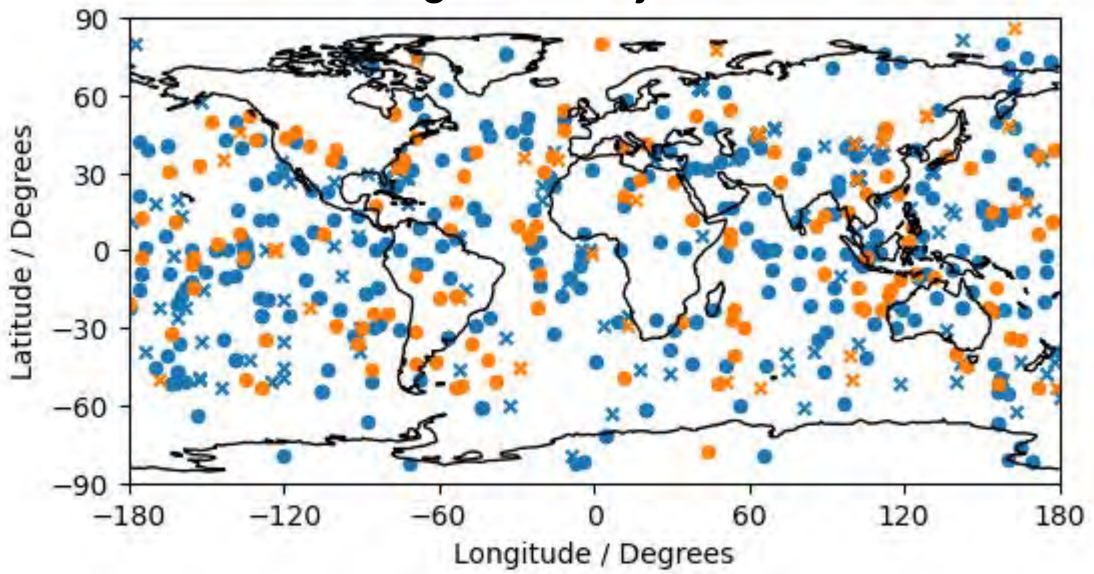
Reentries (upper atmosphere)

Payload/Rocket
Thermal NO_x
Al_2O_3
Other Metal Oxides?

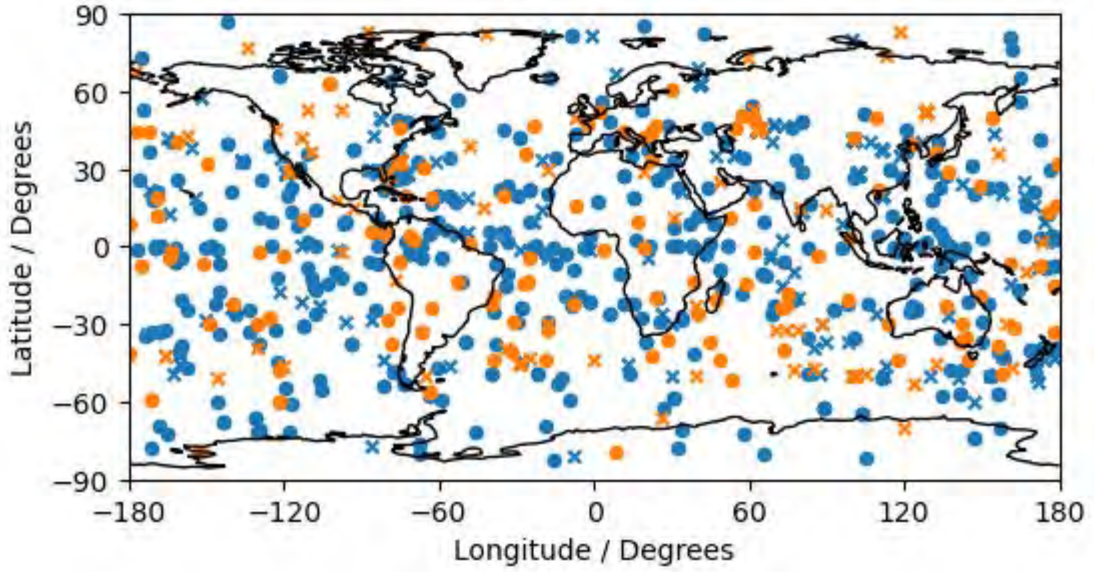
Most megaconstellation satellites launch using kerosene propellant.
Determining re-entry mass for each object is key to calculating thermal NO_x and Al_2O_3 emissions.

Contribution of megaconstellations to re-entry mass

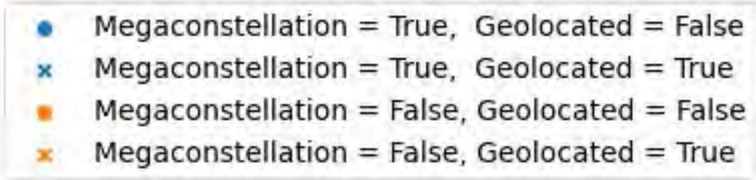
2020 - 3.27 Gg **-** 878 objects – 16.4% SMC



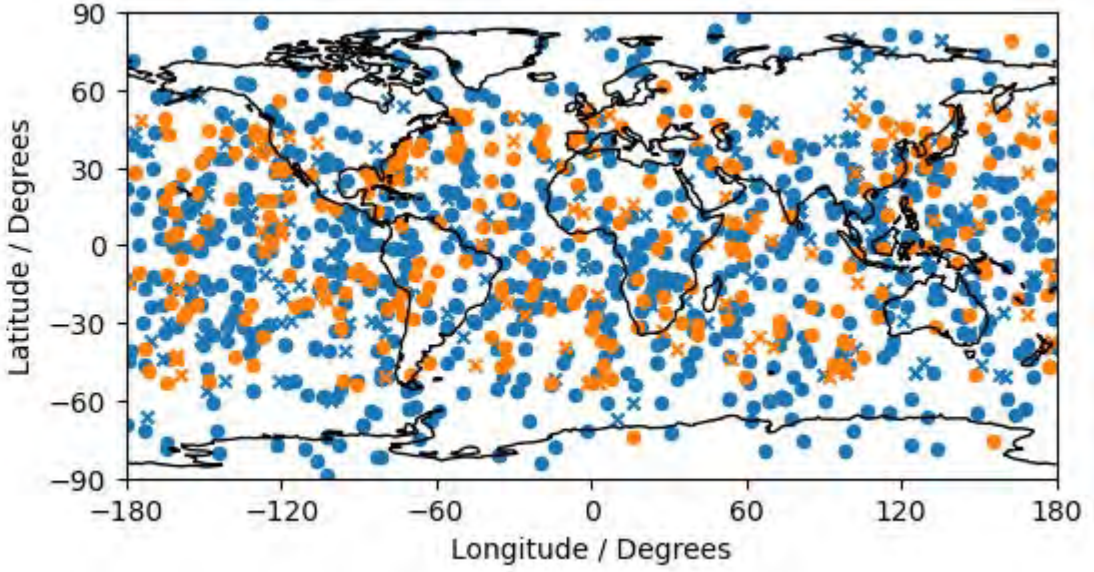
2021 - 4.02 Gg - 1095 objects – 20.6% SMC



Spatial distribution of annual object re-entries



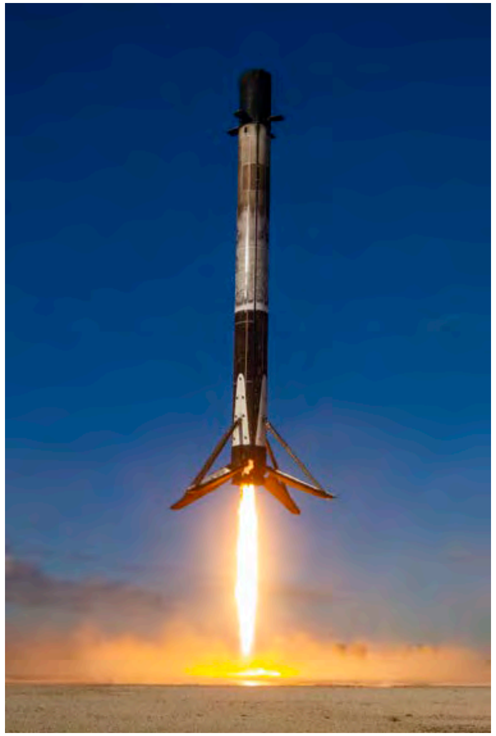
2022 - 5.58 Gg - 1650 objects – 20.9% SMC



Near doubling of re-entry mass since 2020 is partly driven by increasing contributions from satellite megaconstellations.

Conversion of re-entry mass to upper atmosphere emissions

Reusable Objects



17.5% of re-entry mass converted to NO_x.
No Al_2O_3 emissions.

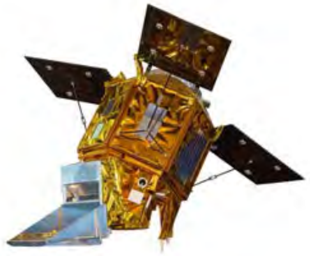
Expendable Objects

Rocket Bodies – 70% Aluminium

Survivability:

70% Core Stage
35% Upper Stage

Payloads – 40 % Aluminium



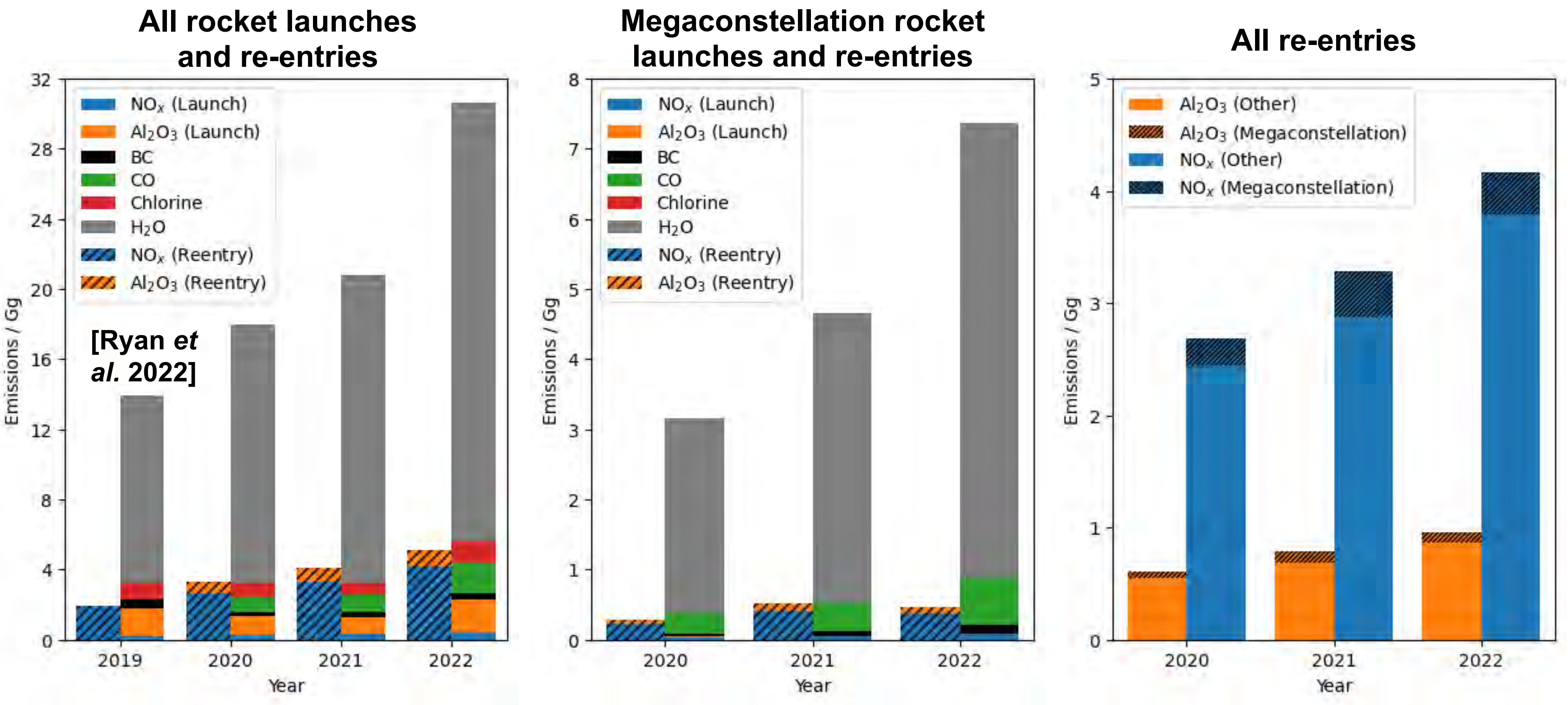
0% SMC Payload
20% Non-SMC Payload

100% of re-entry mass converted to NO_x.
Al_2O_3 emissions dependent on object type.

NO_x emissions for reusable components are still based on Space Shuttle studies.
Broad assumptions for expendable object ablation and survivability.

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

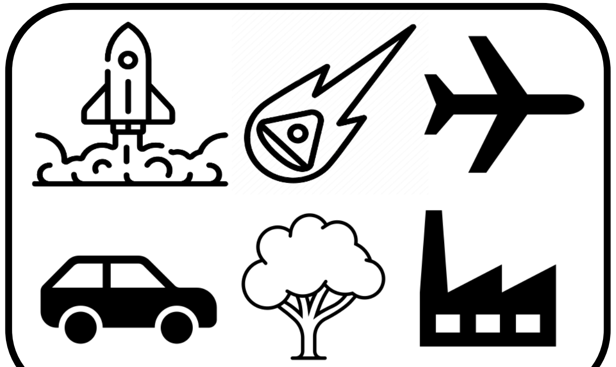
Annual emission totals for satellite megaconstellations.



Similar re-entry emissions in 2021 and 2022, additional re-entries are offset by changing launch rockets. Megaconstellations contribute 9% of re-entry emissions, approaching natural injection of Al_2O_3 and NO_x.

Implementation of space industry emissions in GEOS-Chem

Emissions



Meteorology

NASA GMAO MERRA-2

GEOS-Chem

3D Atmospheric Chemistry Transport Model

+ RRTMG
Radiative Transfer Model

Differences between simulations

1. No rocket/re-entry emissions
2. All rocket/re-entry emissions
3. SMC rocket/re-entry emissions only

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.

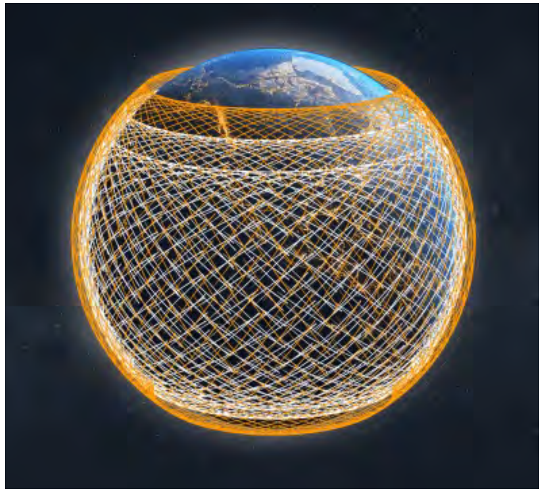
More information is needed on emission indices and the properties of Al_2O_3 aerosol from object re-entry.

Conclusions, Uncertainties and Next Steps

- **Emission inventories for SMC and non-SMC emissions have been compiled for 2020-2022.**
  - 0.94 and 4.00 Gg of Al_2O_3 and NO_x were released into the upper atmosphere in 2022.
  - Megaconstellations contribute ~ 9% of total re-entry Al_2O_3 (0.09 Gg) and NO_x (0.38 Gg) emissions in 2022.
  - Increased rocket stage reusability has mitigated the impact of increasing megaconstellation re-entries.

- **More research/data is needed to address large uncertainties:**
  - Mass of Al_2O_3 / NO_x emissions from reusable re-entries.
  - % survivability and chemical composition for each re-entering object.
  - Geolocation and timestamp information for every re-entering object.
  - Increased data availability from rocket manufacturers to aid research.
  - Particle size, mass distribution and optical properties of Al_2O_3 aerosol from object re-entry for modelling.

- **Next steps:**
  - Build the 2023 emission inventory.
  - Use the 2020-2022 growth rate and list of proposed constellations to predict future satellite megaconstellation emissions.
  - Simulate the impact of a decade (2020-2029) of megaconstellation emissions on stratospheric ozone and climate.



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