Air pollution and environmental impacts of megaconstellation satellite missions

Air Quality in the 21st Century
ROYAL SOCIETY OF CHEMISTRY

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erc

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

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Environmental impacts of the space industry

Launches (0-80 km)

Hydrogen
Kerosene
Methane
Hypergolic
Solid

H_2O
CO
CO_2
BC
Thermal NO_x
Fuel NO_x
Chlorine
Al_2O_3

Reentries (60-80 km)

Payloads
Components
Capsules
Rocket Bodies
Debris

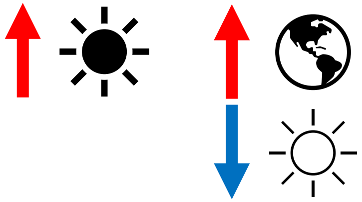
Thermal NO_x
Al_2O_3

Stratospheric O_3 depletion

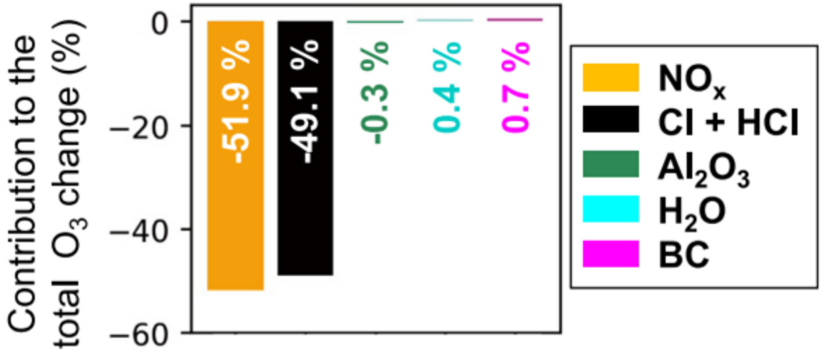
Driven by **NOx, Cly, and Al_2O_3**

Climate forcing

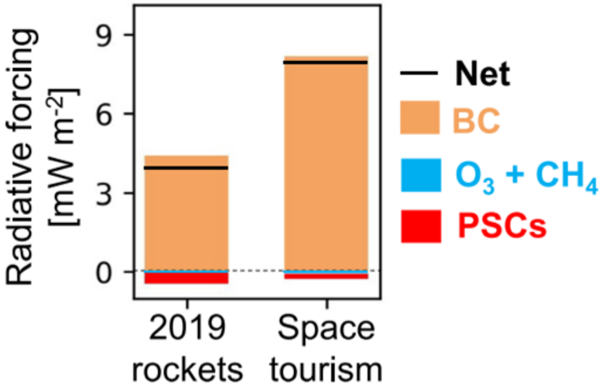
BC Al_2O_3



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



O_3 loss over 60-90°N is ~10% of recovery from Montreal Protocol.



BC emissions drive positive radiative forcing (375x more efficient than surface sources).

[Ryan *et al.* 2022]

Recent developments in the space industry

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Onset of the satellite megaconstellation (SMC) era

SpaceX Starlink

↑ 7001

↓ 607

Eutelsat OneWeb

↑ 640

↓ 6

SMCs are contributing to rapidly increasing launch rates and re-entry mass.

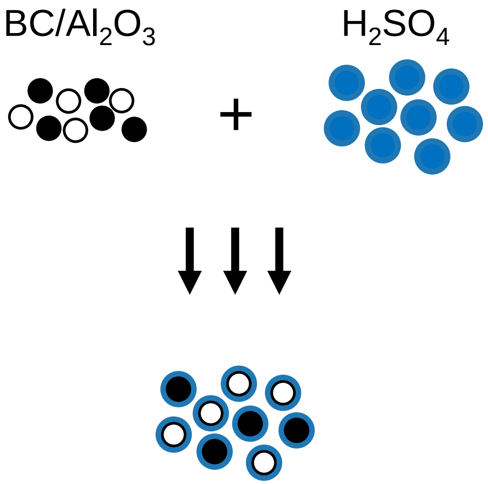
[JSR, 11/09/24]

Understanding of emission chemistry has developed

1º fuel burn emissions (altitude-independent)

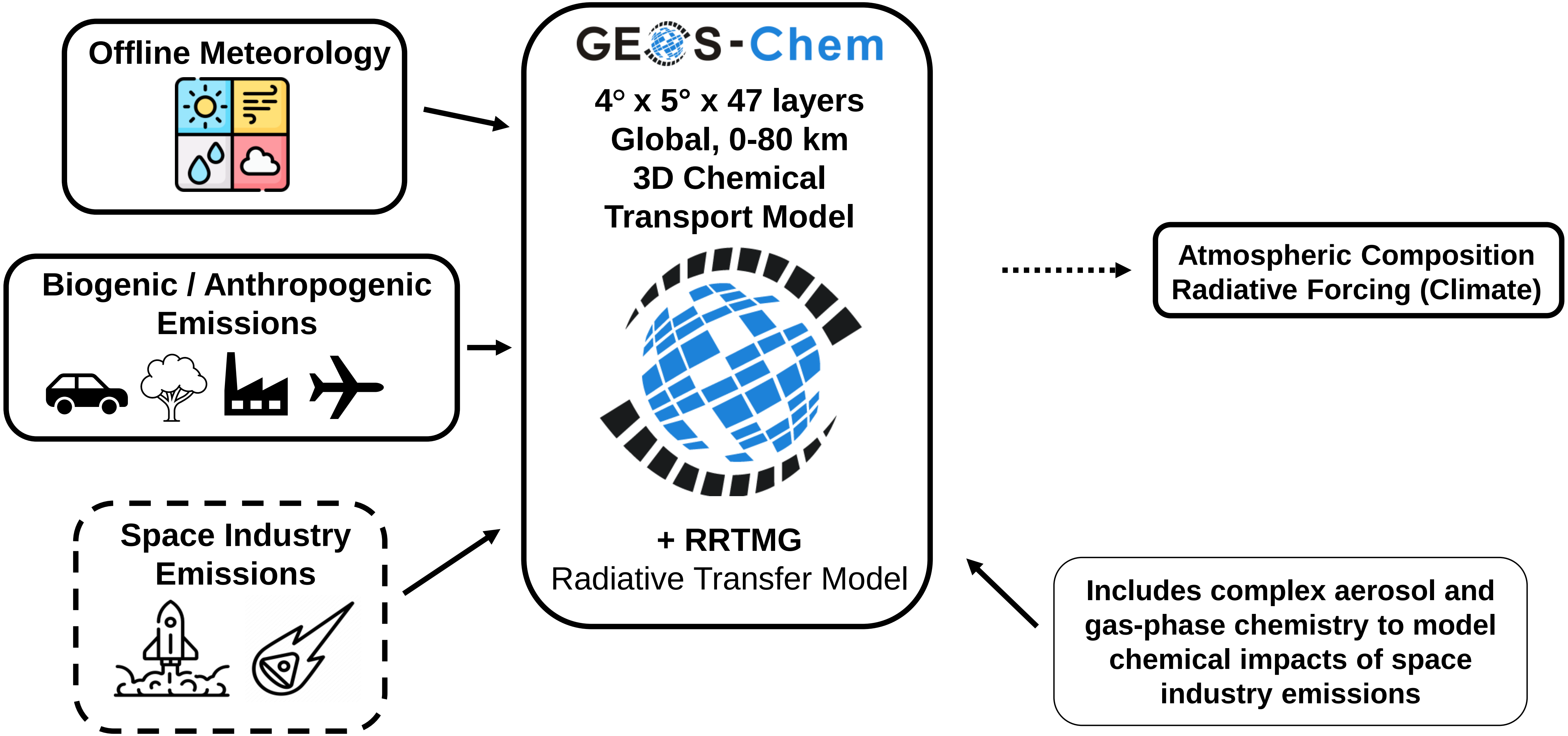
2º afterburning emissions (altitude-dependent)

Launch emissions change with altitude depending on oxygen availability



Aerosol emissions condense into stratospheric sulfate, changing chemical pathways

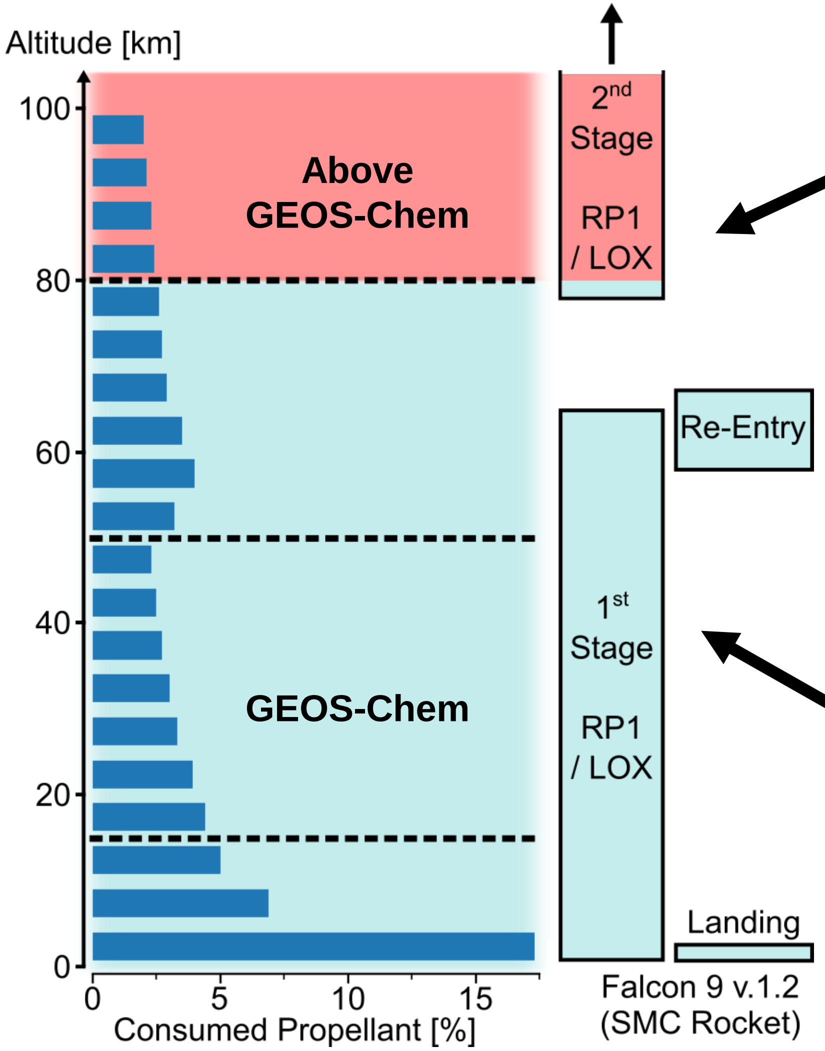
Modelling space industry emissions in a 3D atmospheric chemistry model



[IPCC 2007]

Developing 3D emission inventories of rocket launches and re-entries

Launch emissions (all atmospheric layers)



Within model range:
- **79% propellant burn**
- **33-98% emissions**

Altitude-dependent emission factors included.

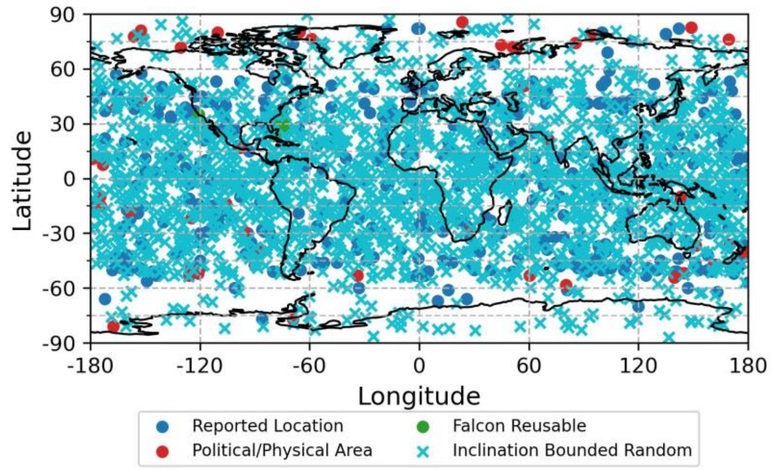
We model the specific altitude range of each rocket stage burn.

Annual propellant consumption increased from 38-67 Gg in 2020-2022.

Re-entry emissions (60-80 km)

Reusable | **Expendable**

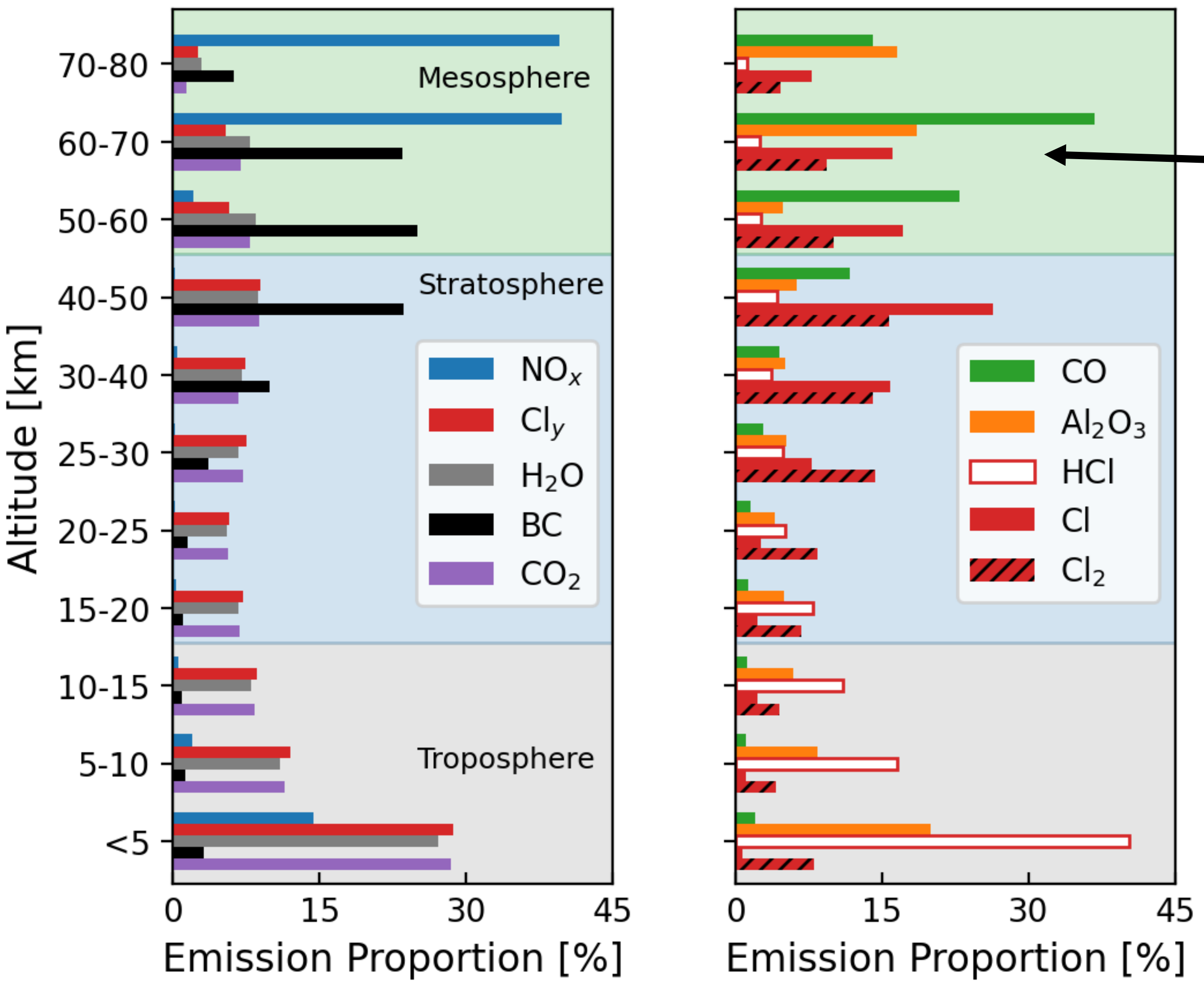
Re-entering Objects (2020-2022)



Annual re-entry mass (5 Gg) is now ~40% of natural influx (18-26% SMC). 2 kt unablated mass returns to Earth.

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

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.

Much lower emissions than surface sources, but mostly injected above the tropopause

[Barker *et al.*, 2024]

Modelling space industry emissions in a 3D atmospheric chemistry model

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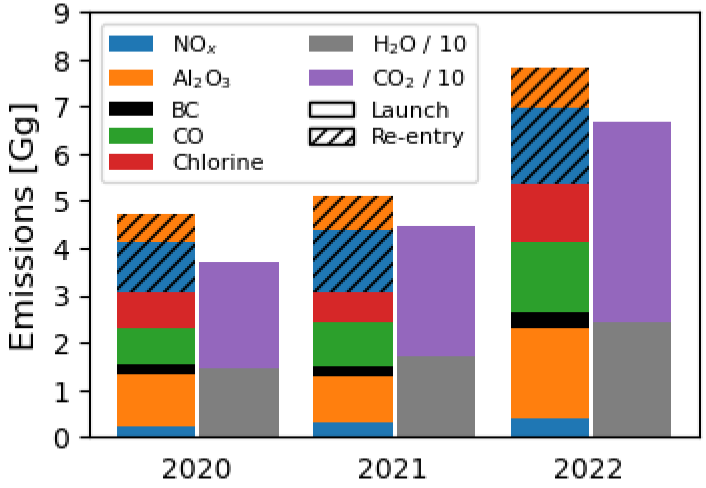
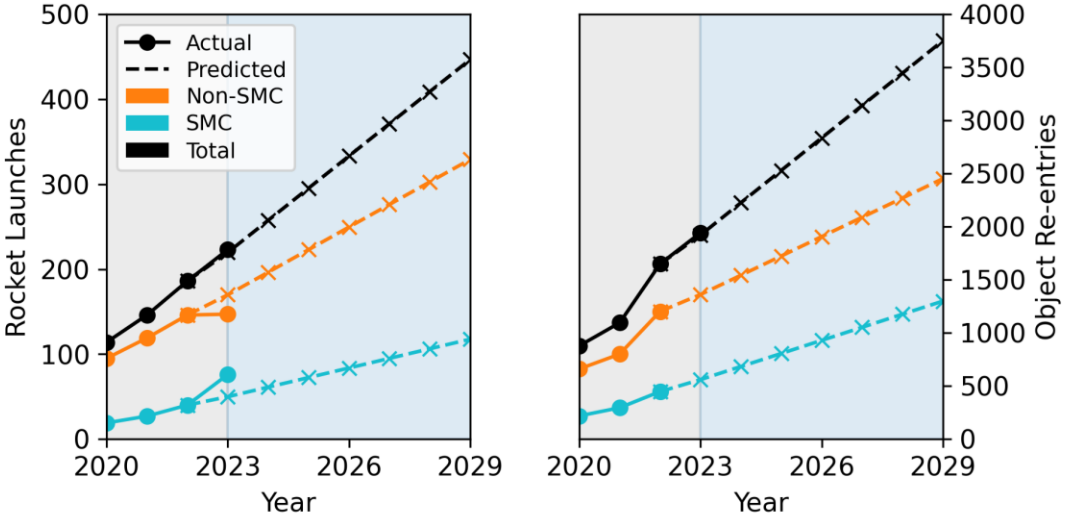
42-91% increase in annual emissions in 2020-2022



Emissions projected to 2029



GEOS-Chem

+ RRTMG

2020-2029

1. No missions

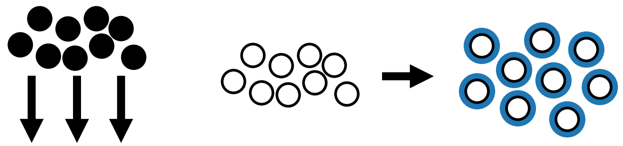
2. All missions

3. SMC missions only

Atmospheric Composition Radiative Forcing

Updated radiative forcing

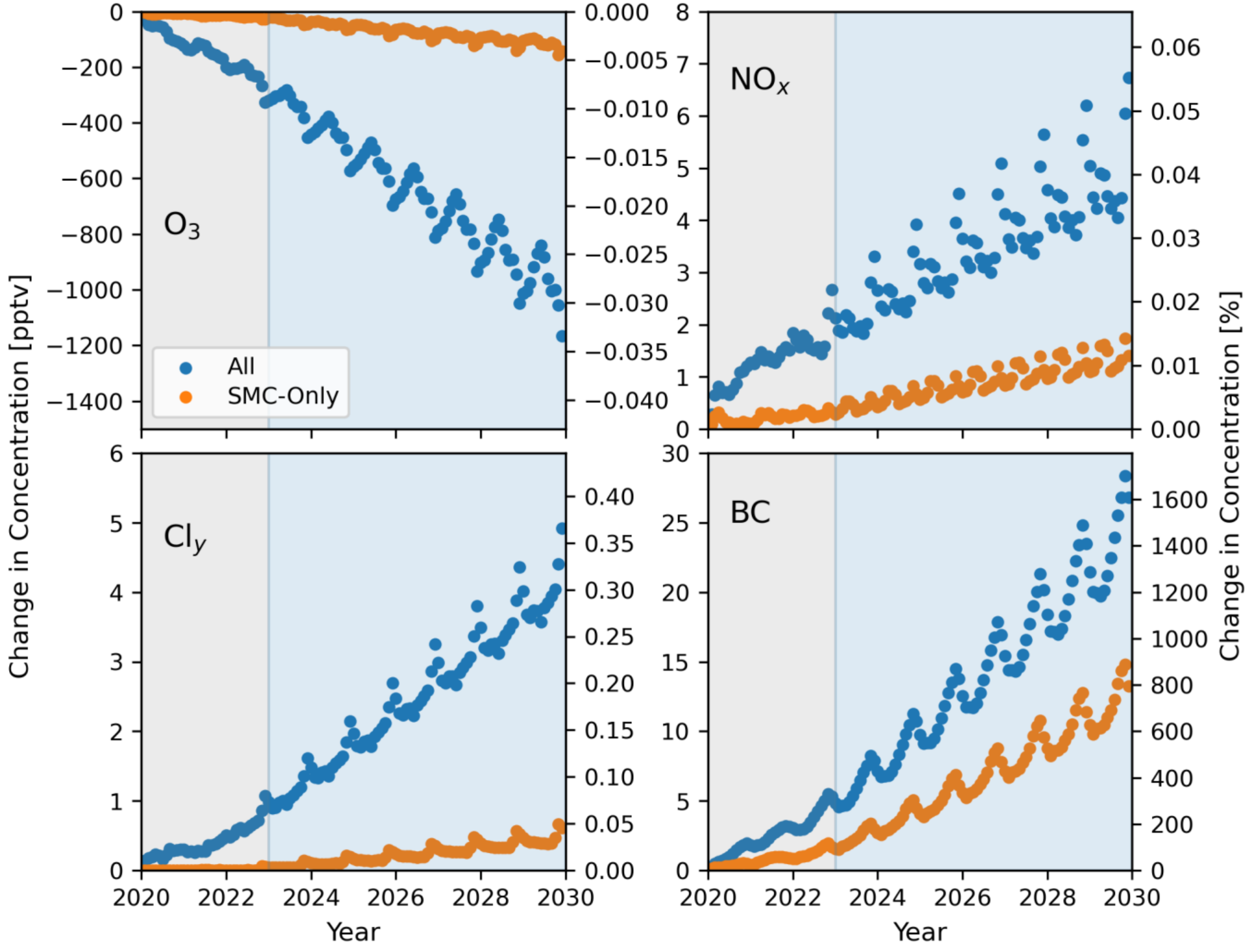
Updated aerosol physics and chemistry



[Barker *et al.*, 2024, IPCC 2007]

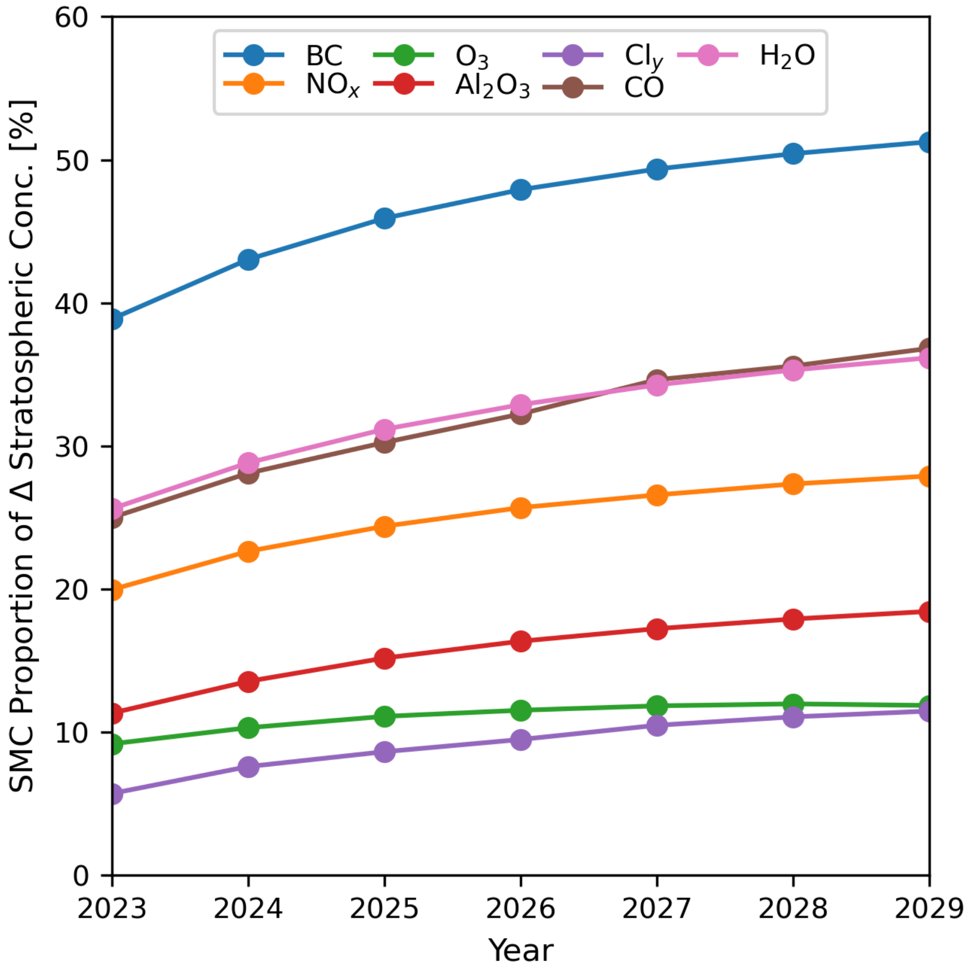
Impact of space industry emissions on stratospheric composition

Impact of space industry air pollution on the stratosphere



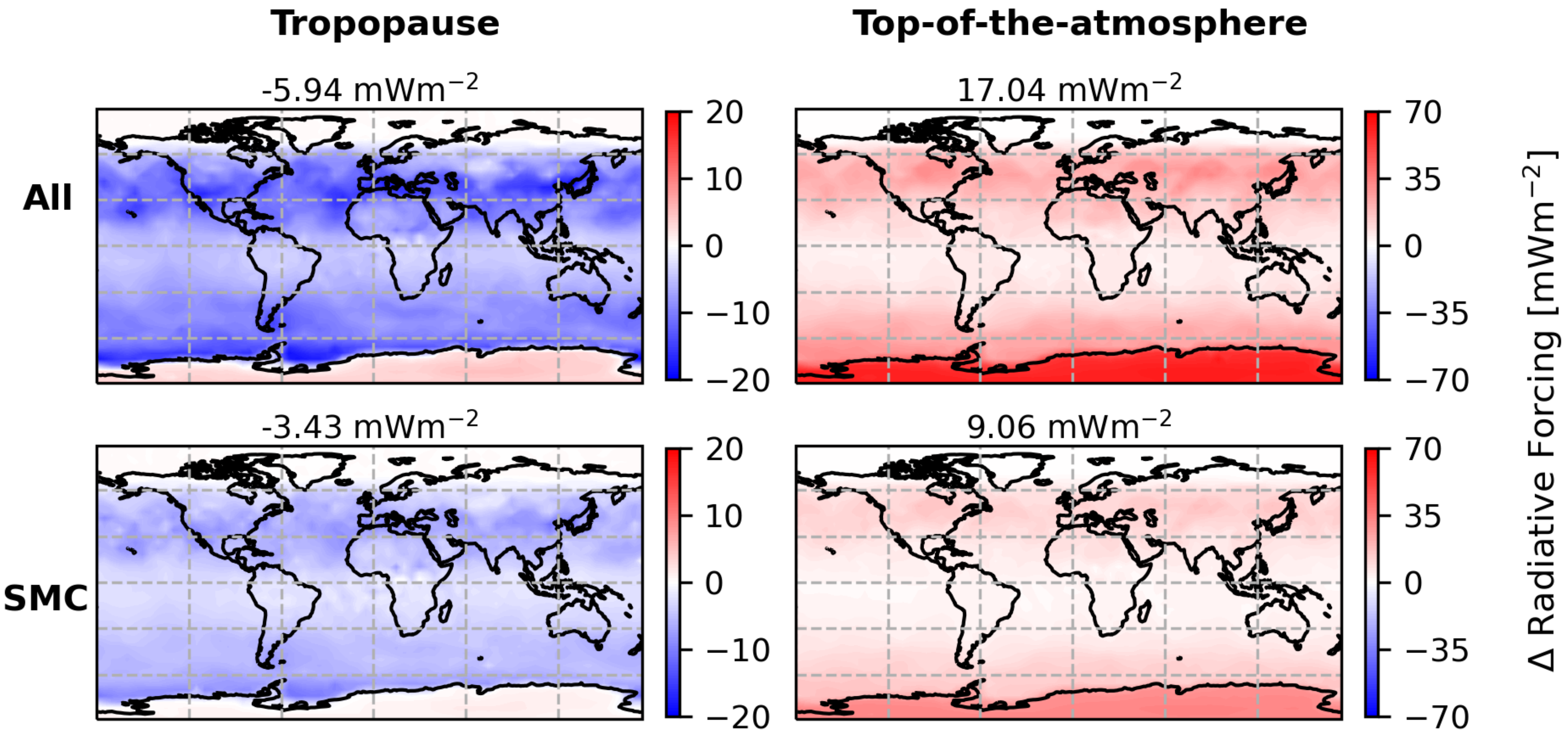
Minimal O_3 loss or increases in ozone depleting emissions (Cl_y, NO_x) from SMCs.

Annual SMC contribution to stratospheric concentration change



SMCs contribute >50% of BC increases in the stratosphere, but only 12% of O_3 depletion.

Impact of space industry emissions on radiative forcing



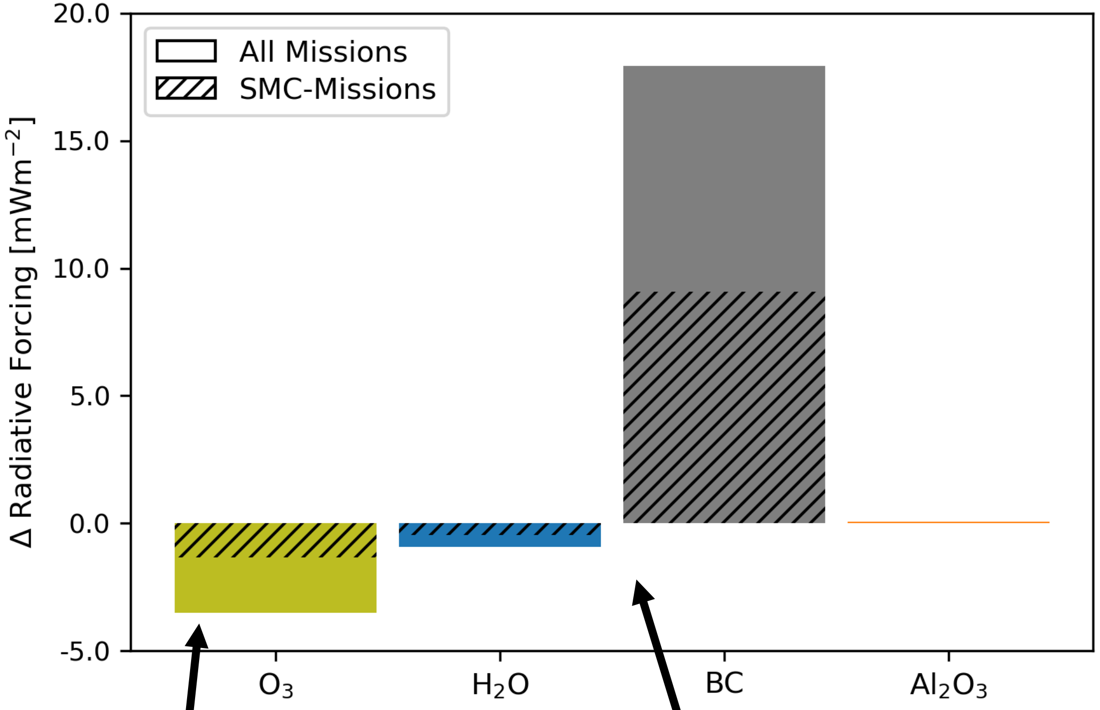
SMCs contribute >50% of the radiative flux

Negative flux at tropopause due to BC SW absorption above the tropopause.

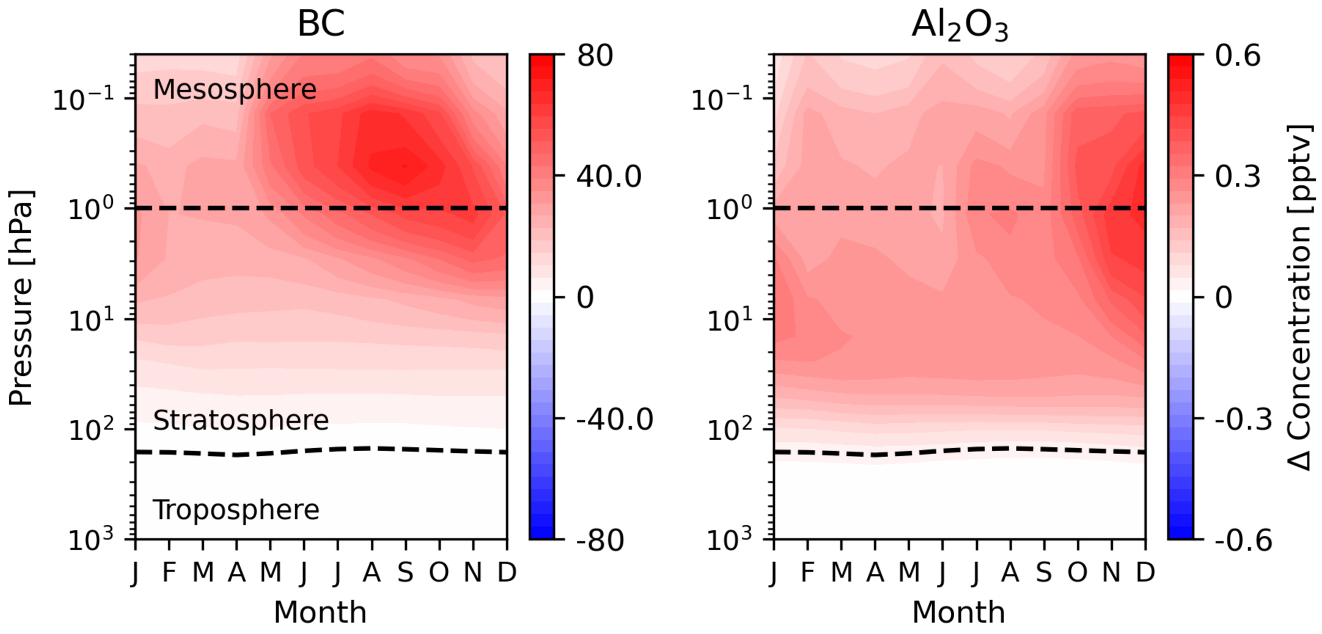
Rocket launch and re-entry emissions affect radiative forcing throughout the atmosphere.

Instantaneous radiative forcing from each emission species

Top-of-atmosphere radiative forcing (Dec 2029)



Multi-year mean aerosol concentrations



Ozone depletion leads to negative forcing

~50% of radiative forcing for H_2O and BC is from SMC-missions

BC remains in mesosphere whereas Al_2O_3 rapidly settles

We need greater understanding of the optical, chemical, and physical properties of particle-phase re-entry emissions.

Summary

- **Global, 3D, hourly rocket launch and spacecraft re-entry emissions quantified for 2020-2022.**
- **Preliminary simulations demonstrate immediate impacts on ozone and climate (in draft).**
  - SMCs cause negligible O_3 depletion compared to non-SMC emissions (~12% of total) but contribute >50% of radiative forcing.
  - Increasing rocket launch and re-entry emissions cause cooling at tropopause flux and warming at top-of-atmosphere.
- **Upcoming sensitivity simulations:**
  - Model resolution.
  - Aerosol size distribution.
  - Suborbital re-entry mass filter.
  - Additional re-entry emissions.
- **Upcoming chemistry changes:**
  - Adding stratospheric BC and Al_2O_3 to sulfate surface area.

Read our study in Nature Scientific Data!

Download our emission inventory here:

Contact: Connor Barker (connor.barker@ucl.ac.uk)

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