The growing impact of satellite megaconstellation launch and re-entry emissions on radiative forcing and stratospheric ozone depletion

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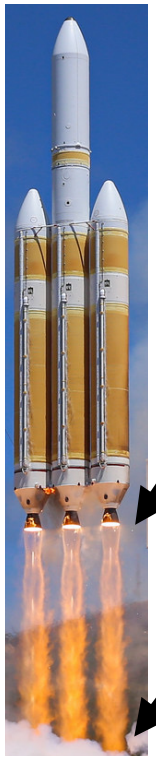
The environmental impacts of SMC emissions

Launches (all atmospheric layers)



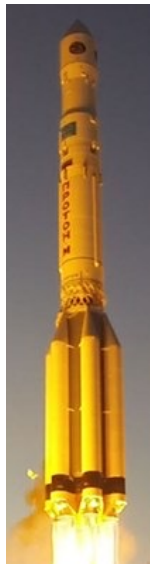
Hydrogen
Delta IV Heavy
LOX / LH_2
H_2O
Thermal NO_x

1º fuel burn emissions

2º afterburning emissions

Kerosene
Falcon 9
LOX / RP1
H_2O
CO
CO_2
BC
Thermal NO_x

Methane
Zhuque-2
LOX / CH_4
H_2O
CO
CO_2
BC
Thermal NO_x



Hypergolic
Proton-M
N_2O_4 / UDMH
H_2O
CO
CO_2
BC
Thermal NO_x
Fuel NO_x

Solid
Long March 11
Al / NH_4ClO_4 / HTPB
H_2O
CO
CO_2
BC
Thermal NO_x
Fuel NO_x
Chlorine
Al_2O_3

SMC Launches

Reentries (60-80 km)

Payload/Rocket
Thermal NO_x
Al_2O_3

Stratospheric ozone depletion
Climate forcing

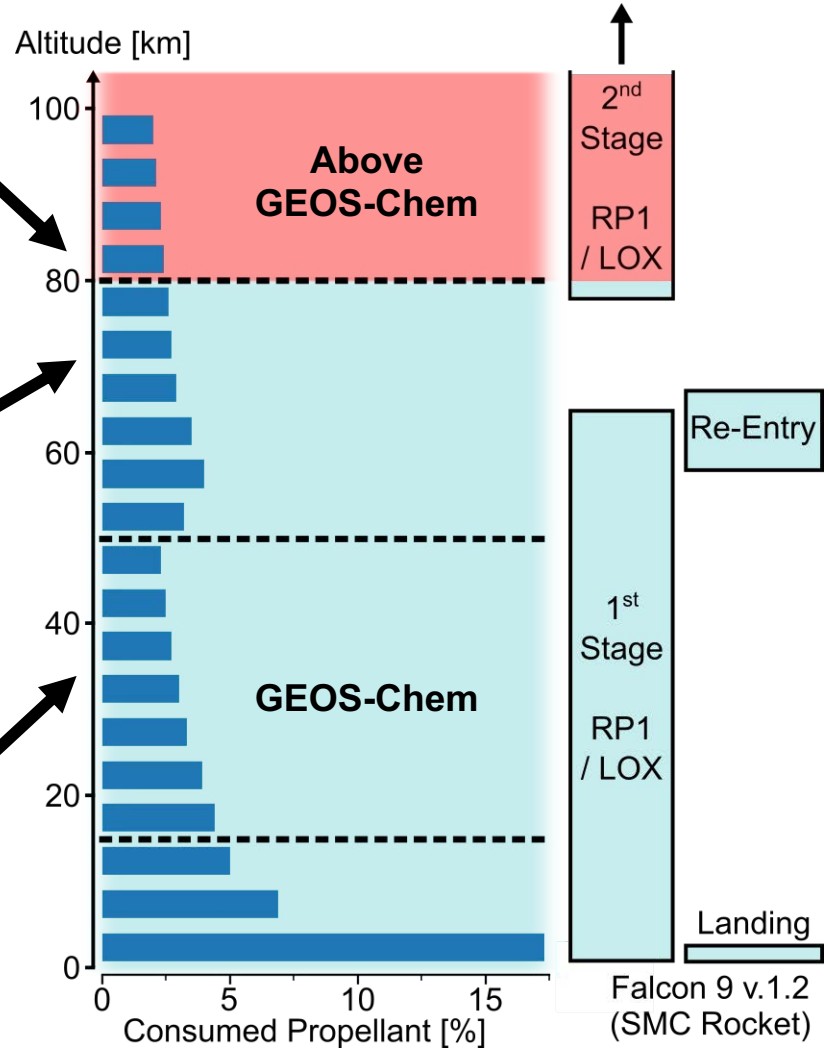
Developing 3D emission inventories of rocket launches and re-entries

Launch emissions (all atmospheric layers)

79% propellant burned within GEOS-Chem altitude range.

33-98% pollutants emitted within GEOS-Chem altitude range.

Altitude-dependent emission factors included.



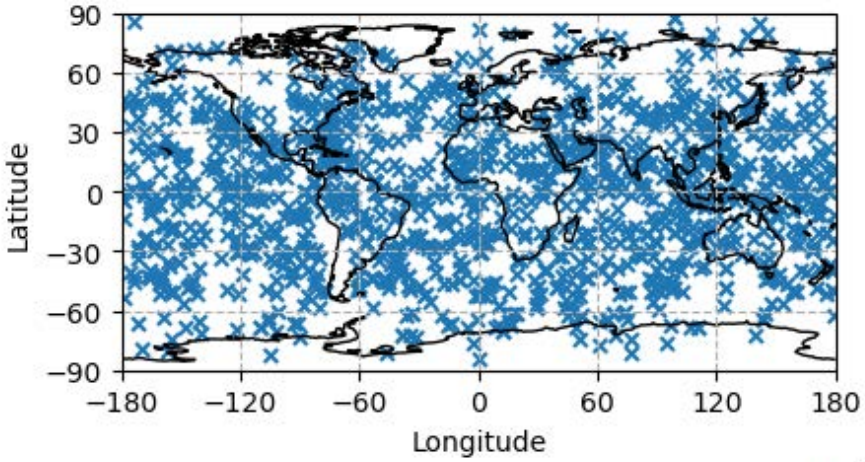
Annual propellant consumption has increased from 38-67 Gg.

[Ross *et al.* 2014]

Re-entry emissions (60-80 km)

Reusable

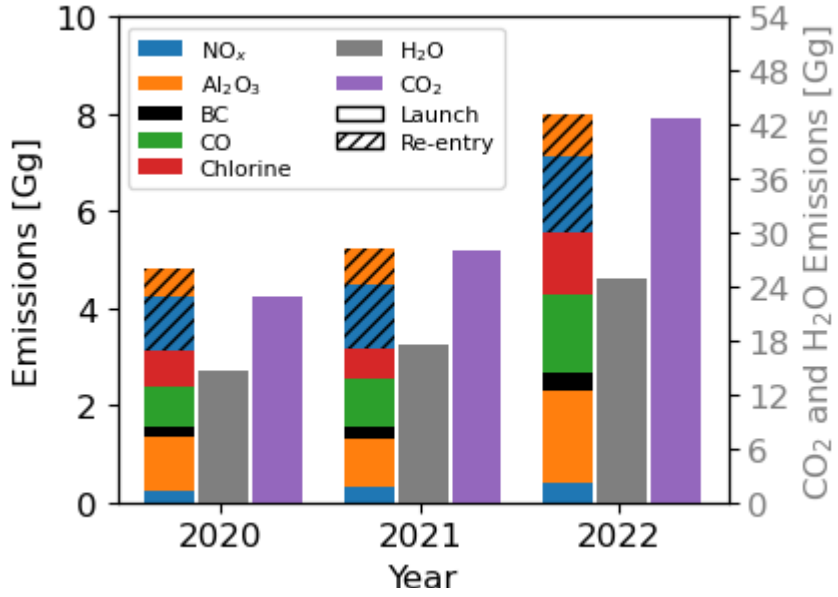
Expendable

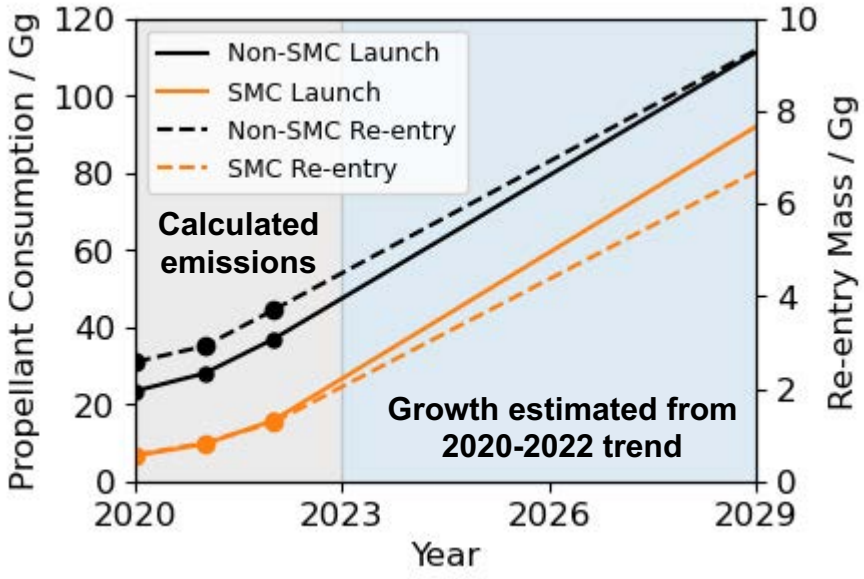


Annual re-entry mass (5 Gg) is now ~40% of natural influx (26% SMC). 2 kt unablated mass returns to Earth.

Implementing annual emissions into GEOS-Chem

64-99% increase in annual emissions.





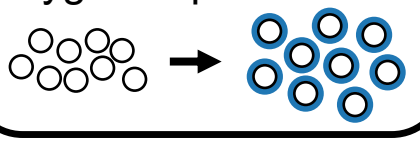
GEOS-Chem
v14.3.0
4° x 5° x 47 layers

+ RRTMG
Radiative Transfer Model

→ **Atmospheric Composition Radiative Forcing**

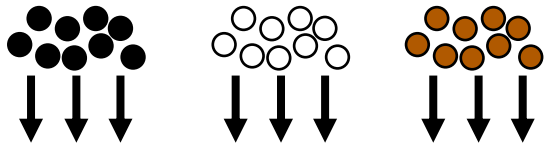
Stratospheric adjustment added to GCClassic/RRMTG.

Al_2O_3 added as ozone-depleting hygroscopic aerosol



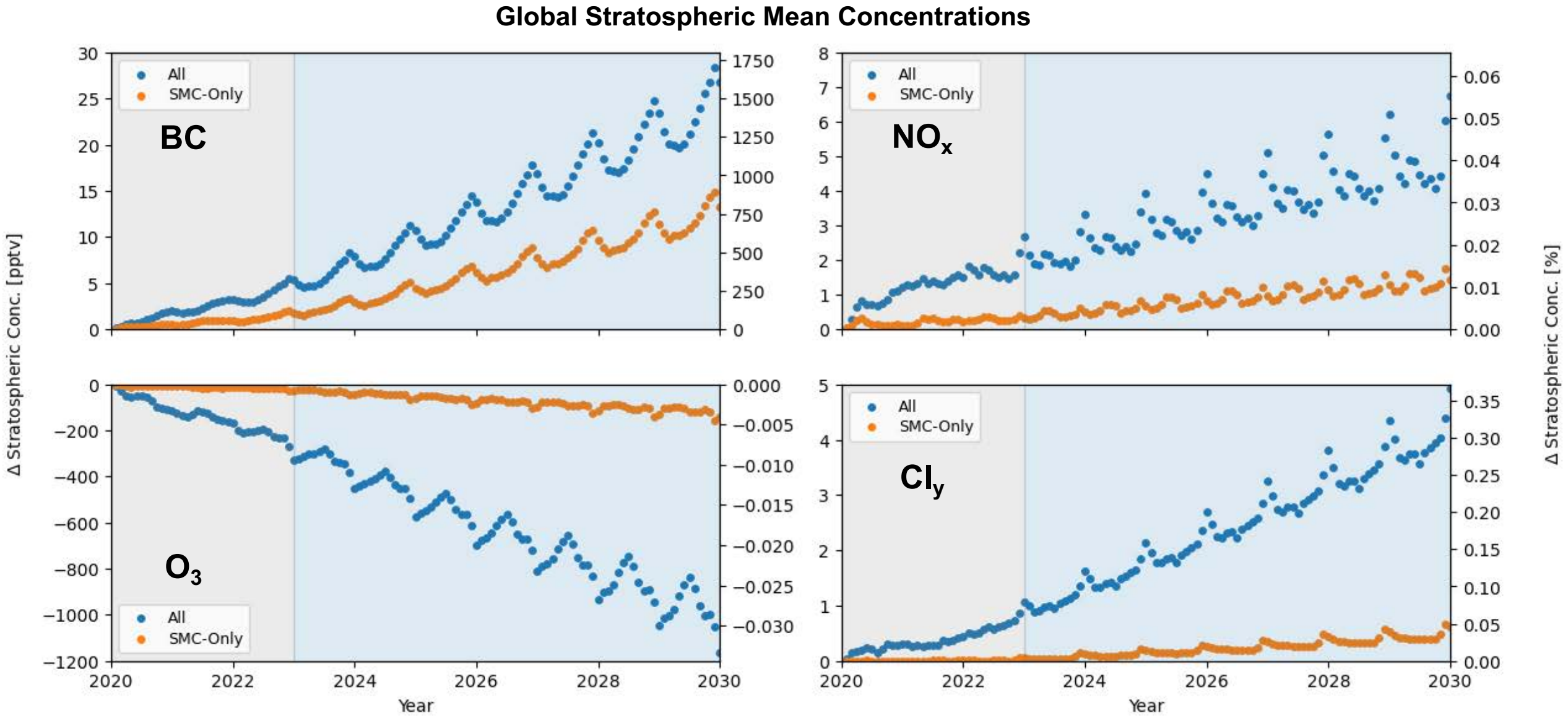
Updated gravitational settling

BC Al_2O_3 Dust



[IPCC 2007]

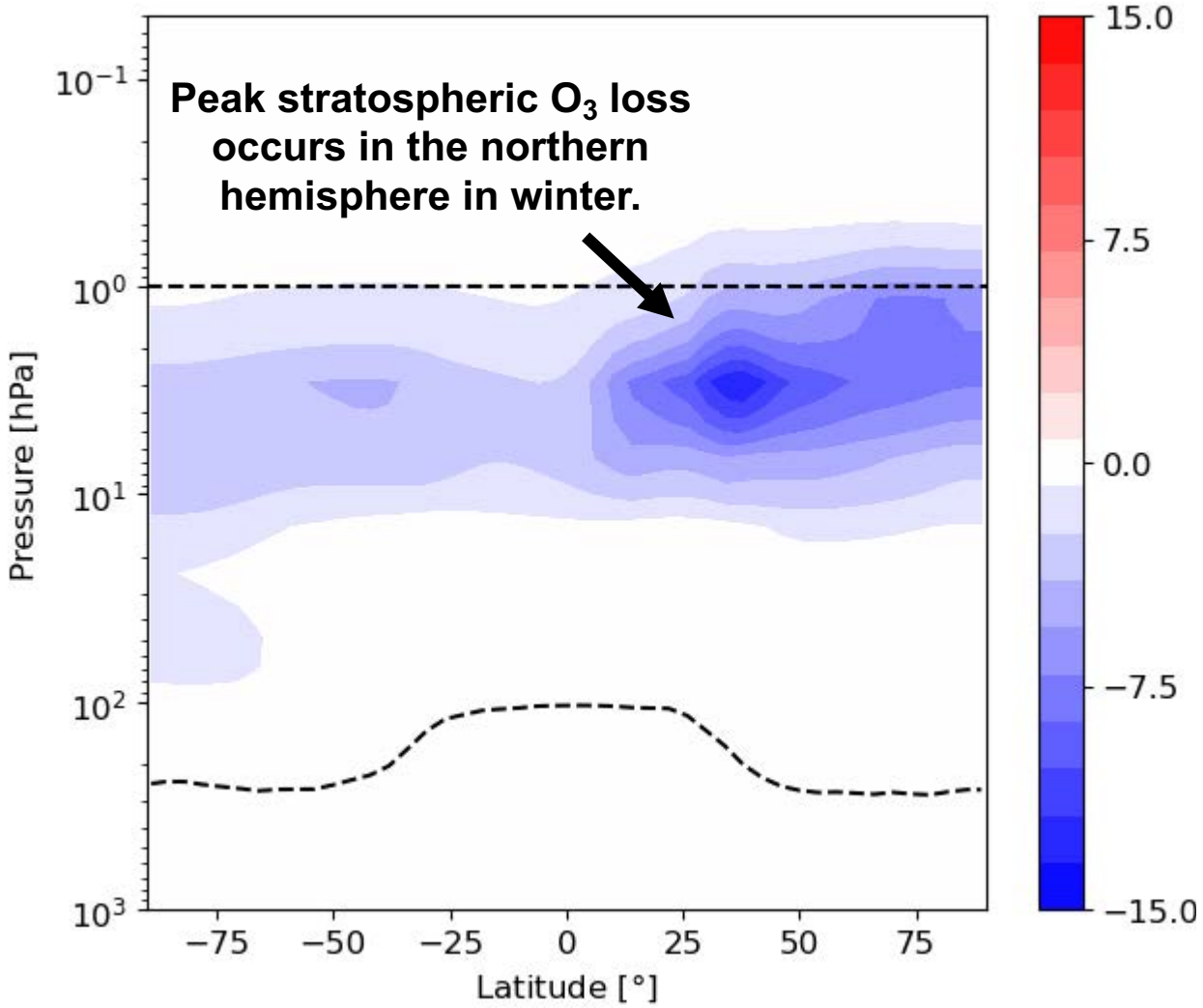
Impact of space industry emissions on stratospheric concentrations



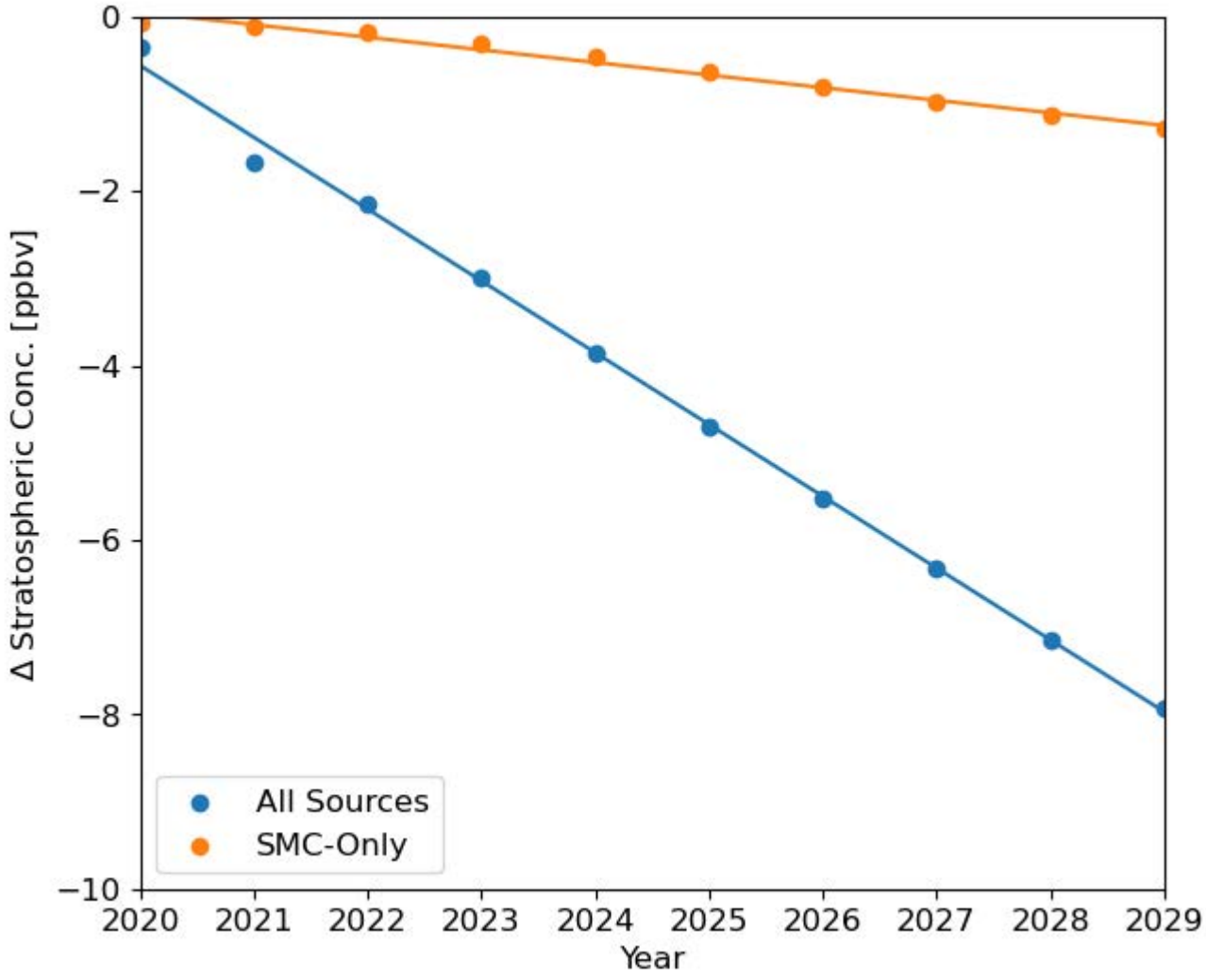
Minimal O_3 loss from SMCs but significant BC emissions.

Minimal increases in ozone depleting emissions from SMCs.

Stratospheric ozone depletion in the context of the Montreal Protocol



Peak O_3 loss coincides with maximum increases in Cl_y.



Peak O_3 loss is a reversal of 10% of Montreal recovery (2% for SMCs).

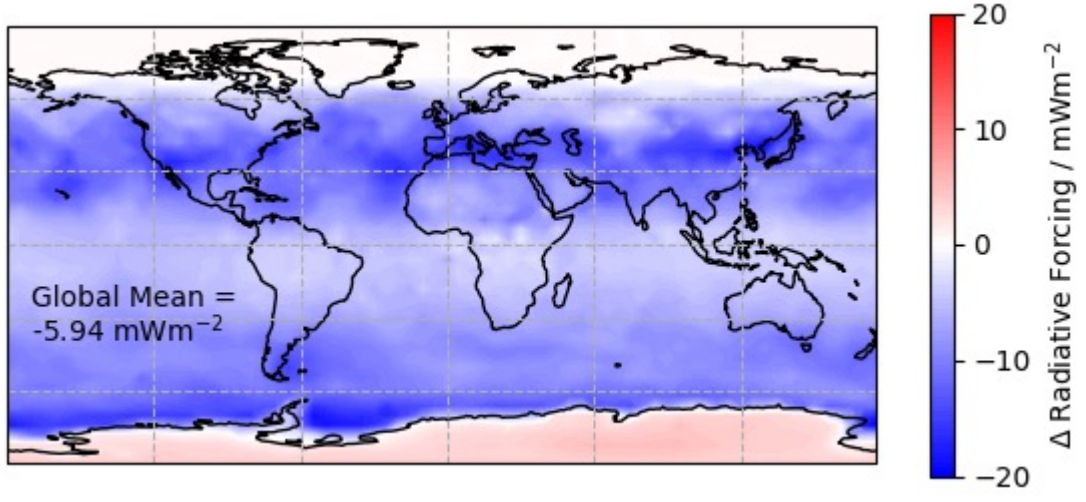
Impact of space industry emissions on radiative forcing

Preliminary Results

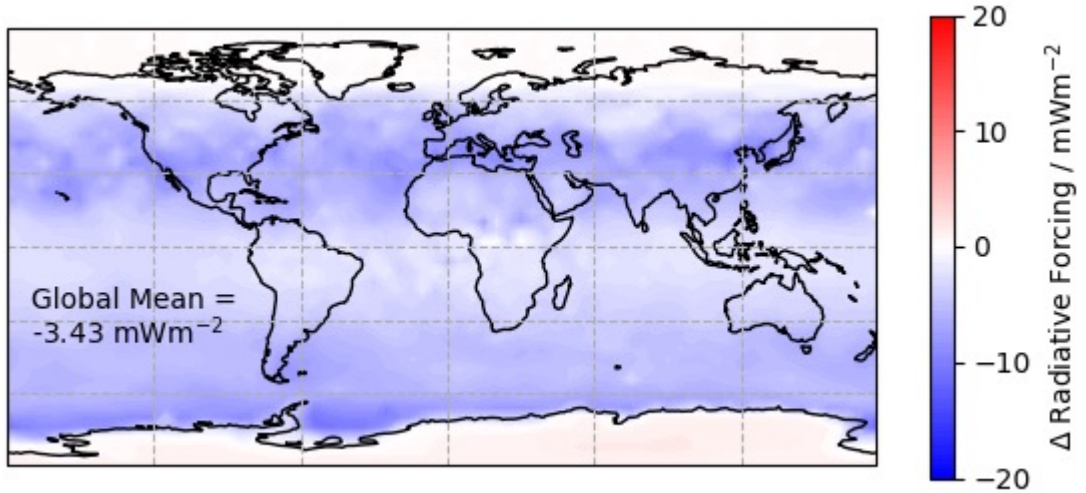
UCL

Stratospherically-adjusted radiative flux at tropopause (2030)

All Sources

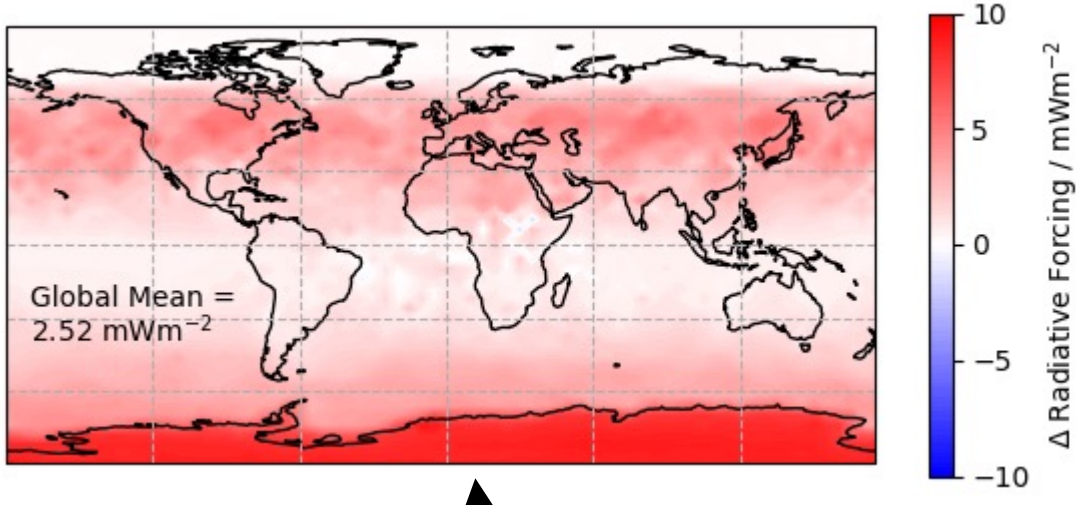


SMC



Increased stratospheric BC burden drives forcing through absorption of SW radiation.

Instantaneous radiative flux at top of atmosphere (2023)



Net increase at the top of atmosphere attributable to BC SW absorption.

Negative flux at tropopause, likely due to BC absorption above the tropopause.

Summary

- **Developed SMC and non-SMC emission inventories for 2020-2022.**
- **Preliminary results demonstrate immediate environmental impacts.**
  - A decade of increasing rocket launch and re-entry emissions reverse 10% of Montreal Protocol gains.
  - SMCs cause negligible O_3 depletion but lead to large increases in stratospheric BC.
  - Increasing rocket launch and re-entry emissions cause decrease in stratospherically-adjusted tropopause flux and increase in instantaneous TOA flux.
  - SMCs affect climate through significant emissions of BC above the tropopause.

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