Deleterious effects of space sector air pollutant emissions on climate and stratospheric ozone

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GAQC, Peking U. Eloise Marais (e.marais@ucl.ac.uk) 23 Sep 2022

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LAB EXPERIMENTS

GEOS Chem

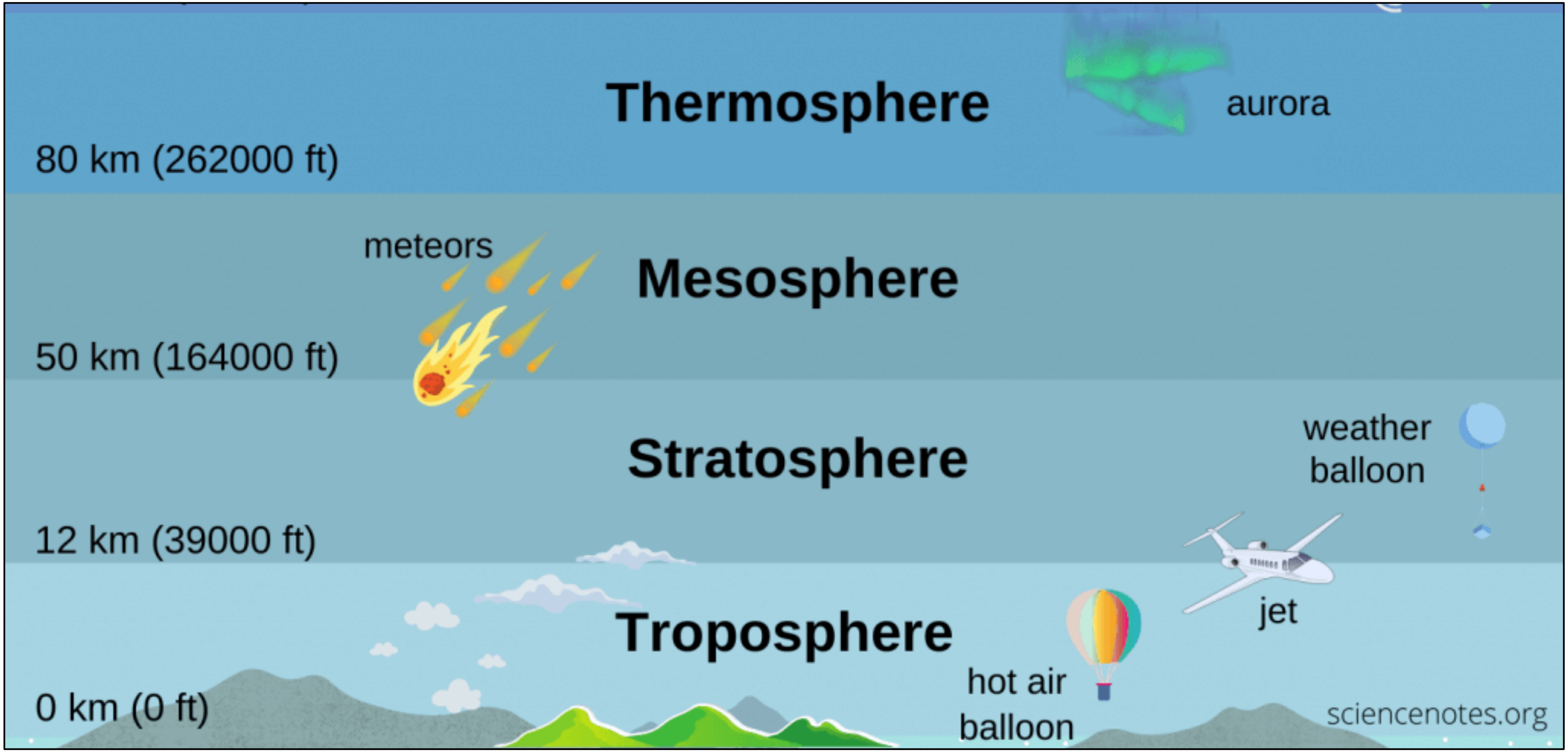
3D ATMOSPHERIC CHEMISTRY MODEL

SATELLITES

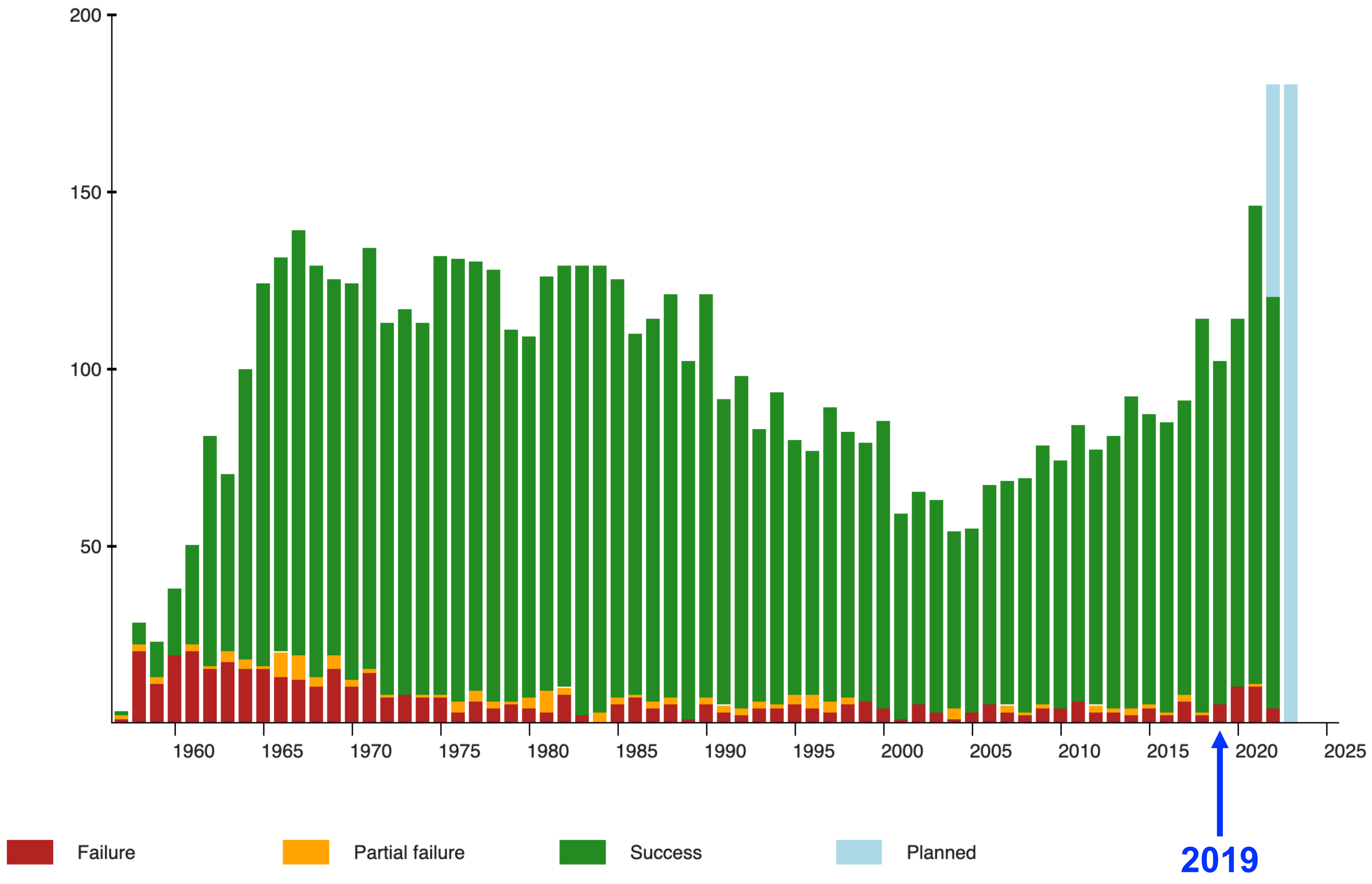
IN SITU

We use and develops state-of-science datasets and tools to inform policy.

Layers in the atmosphere relevant to the space industry

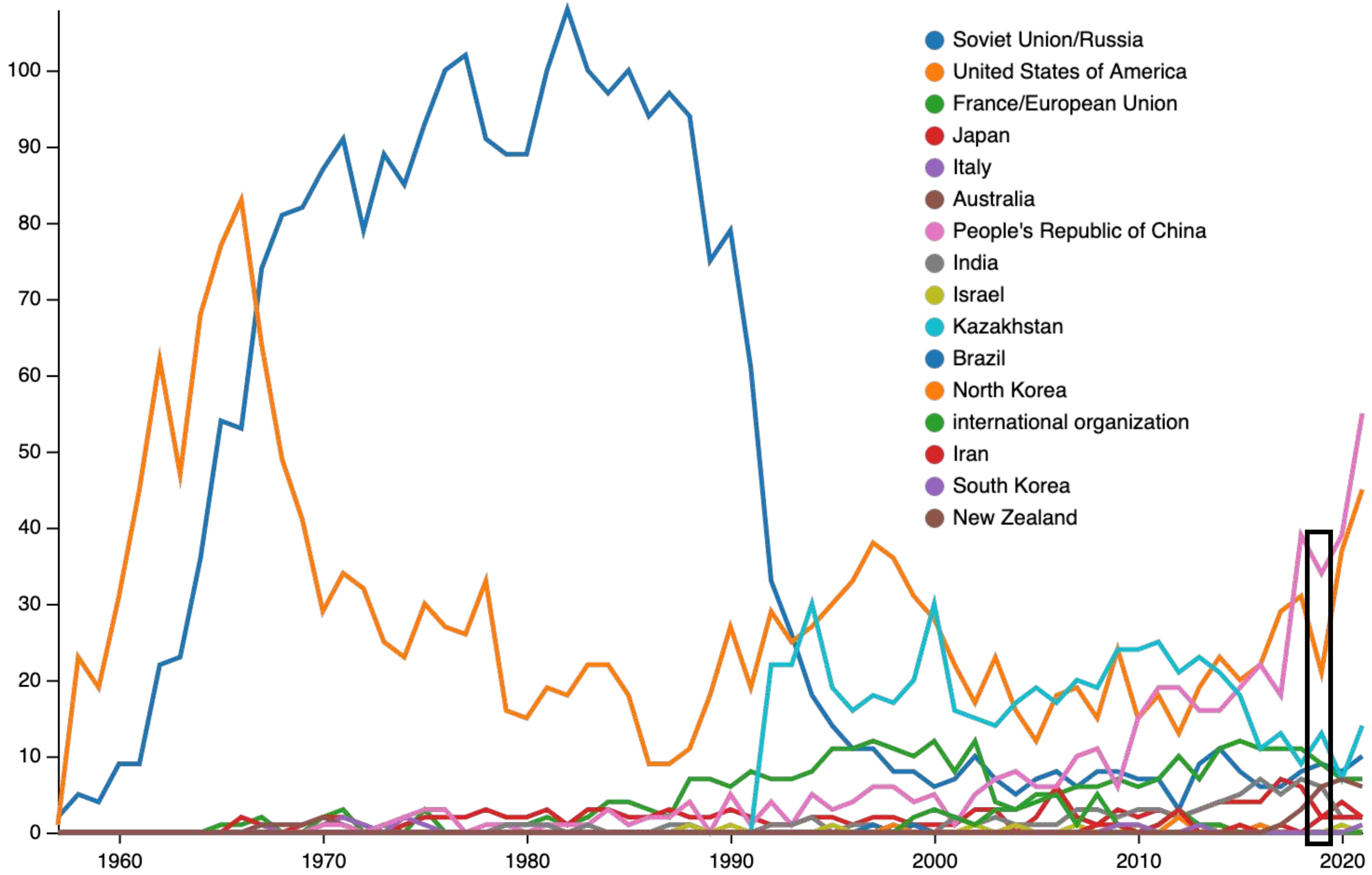


Recent rapid increase in rocket launches



A more diverse space sector than the first space race

Number of rocket launches per country in each year



Even the UK is joining the race:

Dominant propellants and associated pollutants

Ariane V

Solid:
Al_2O_3, HCl, NO_x, BC, H_2O

Falcon 9

Kerosene:
NO_x, BC, H_2O

New Shephard

Cryogenic:
H_2O, NO_x

Proton M

Hypergolic:
H_2O, NO_x, BC

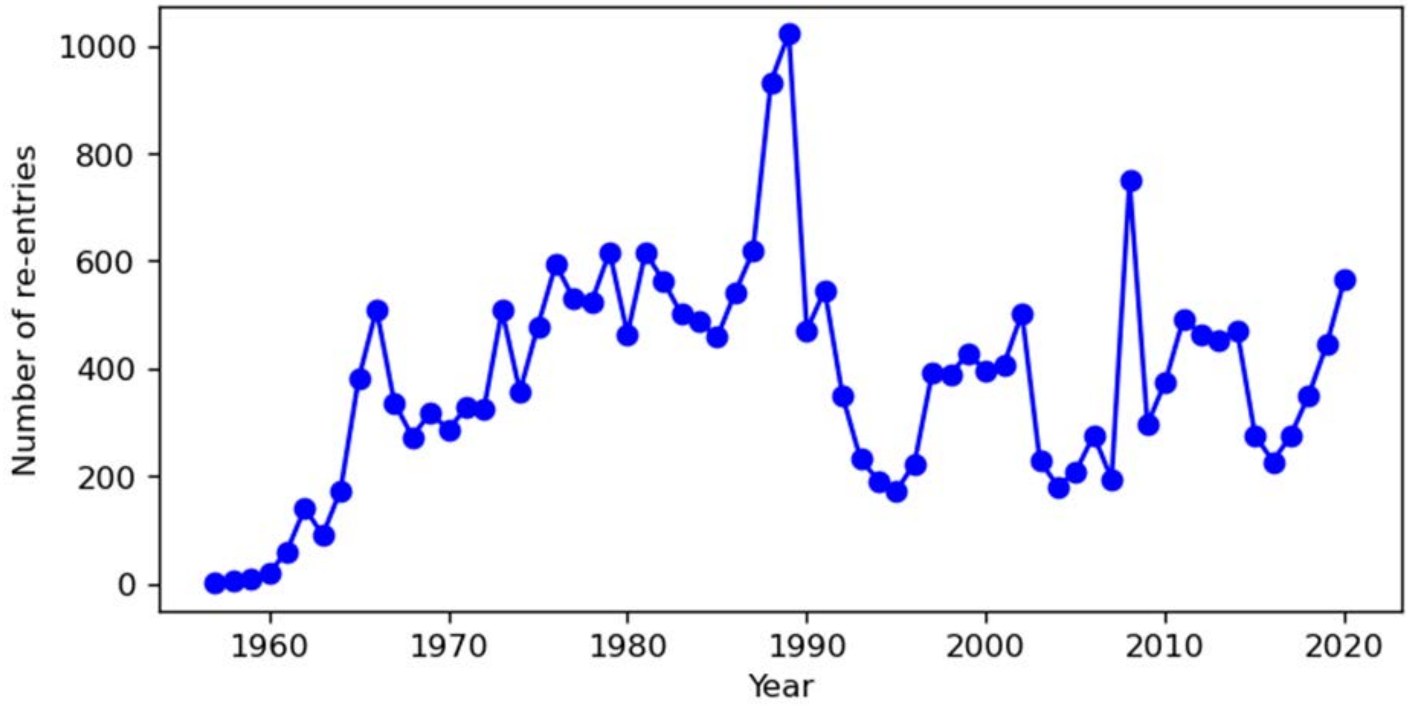
BC: black carbon (soot)
Al_2O_3: alumina particles

NO_x: NO + NO_2
HCl: hydrochloric acid

Surge in returning space junk and reusable rockets

Re-entry burn produces ~17.5 mass % NO_x for heat shields of reusable components and 100% for complete burn-up

Spent satellites and space debris (as old as the space race), discarded boosters and rocket stages, reusable rockets stages, space capsules/shuttles/pods/planes



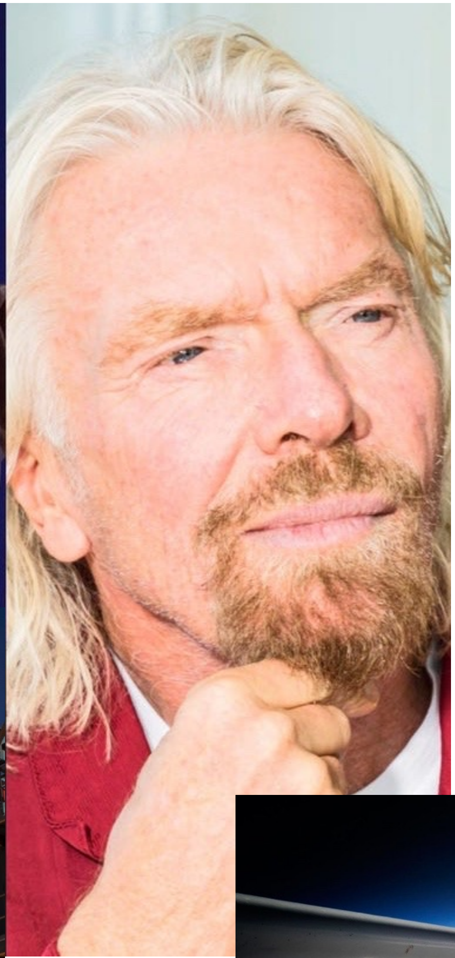
Data Source: ESA (https://discosweb.esoc.esa.int/)

Reusable boosters and vehicles transporting people

The NASA Space Shuttle

SpaceX Reusable Booster

The advent of the billionaire space tourism industry



SpaceX

kerosene

Blue Origin

Cryogenic (hydrogen)

Virgin Galactic

Rubber fuel (HTPB)

Space Tourism

Each rocket uses a different propellant

Virgin Galactic

Hybrid:
solid fuel (HTPB) +
liquid oxidizer (N_2O)

Carbon-based fuel

Blue Origin

Cryogenic:
liquid fuel (H_2) +
liquid oxidizer (O_2)

No carbon in fuel

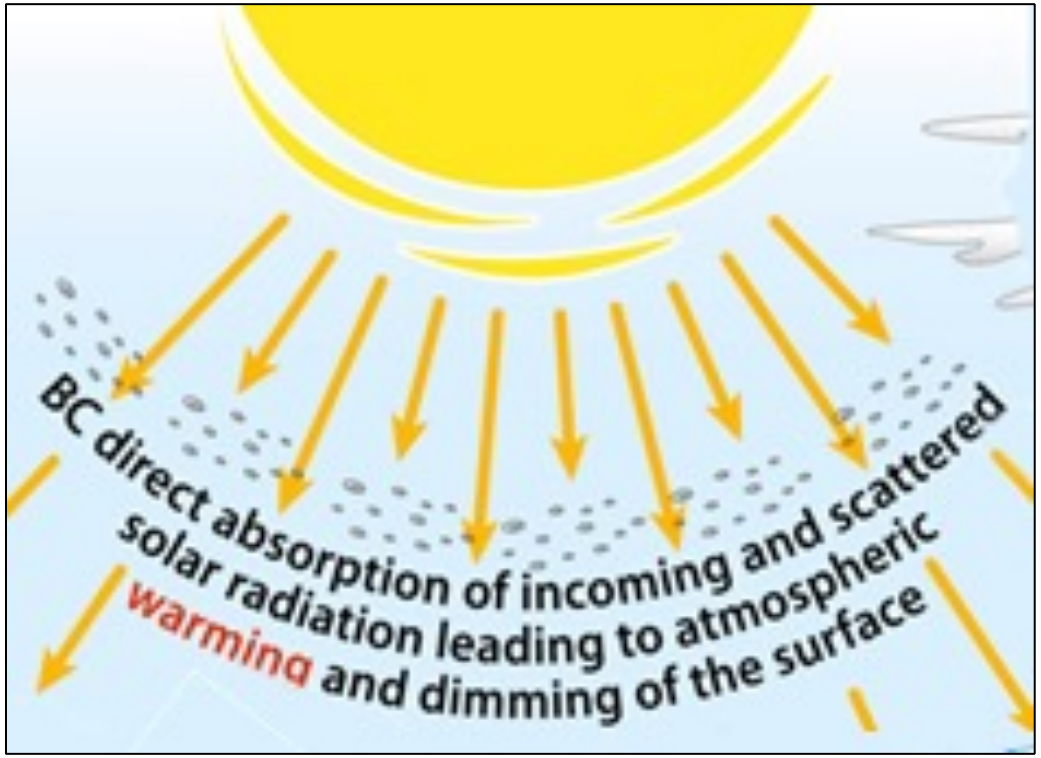
SpaceX

Liquid:
kerosene +
liquid oxidizer (O_2)

Carbon-based fuel

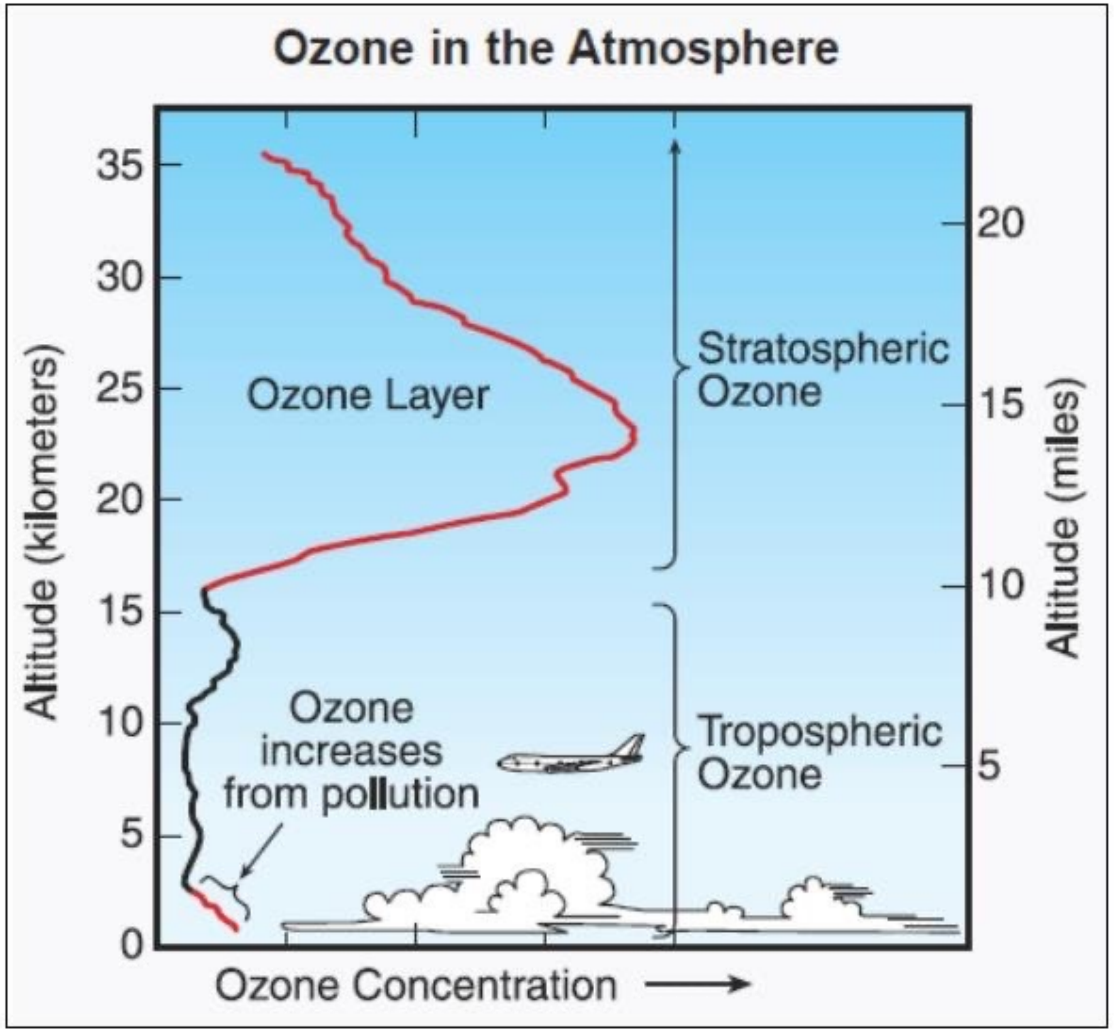
Most Concerning Atmospheric Impacts

Black carbon (**soot**) very efficient at absorbing incoming sunlight



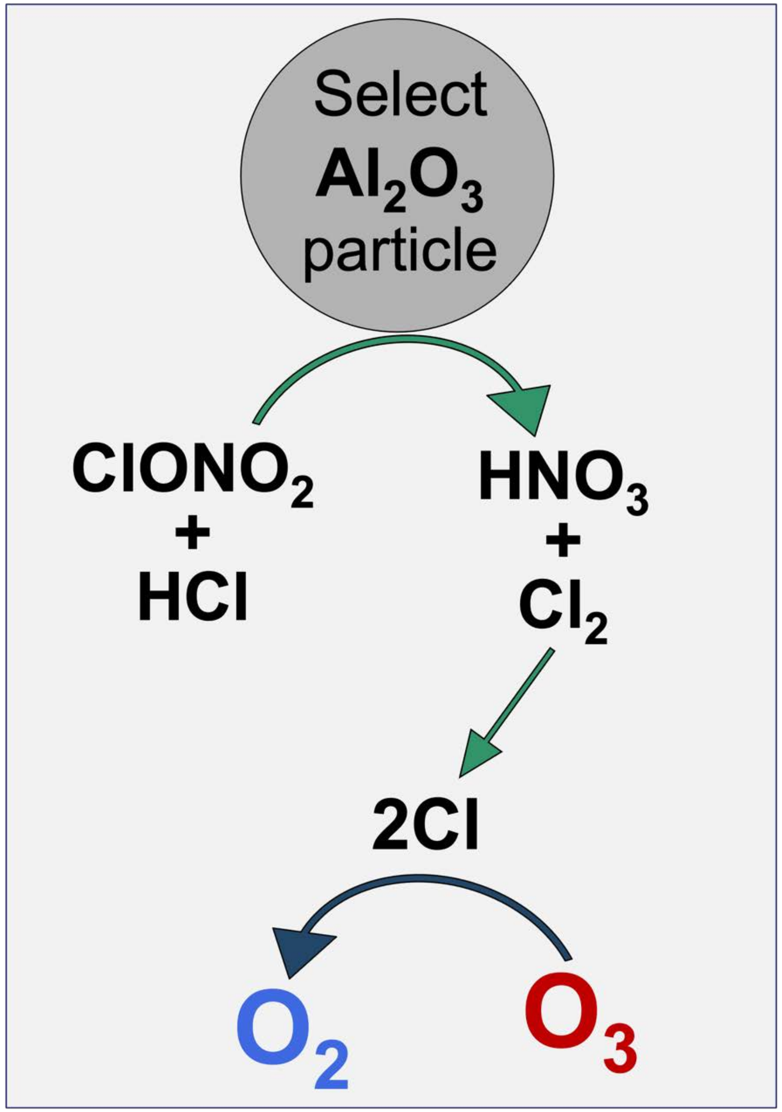
3rd largest climate warming (radiative forcing) after CO_2 and CH_4

H_2O, **NO_x** and **Al_2O_3** deplete stratospheric ozone by promoting conversion of O_3 to O_2



Most Concerning Atmospheric Impacts

Al_2O_3 particles provide a surface for rapid ozone depletion

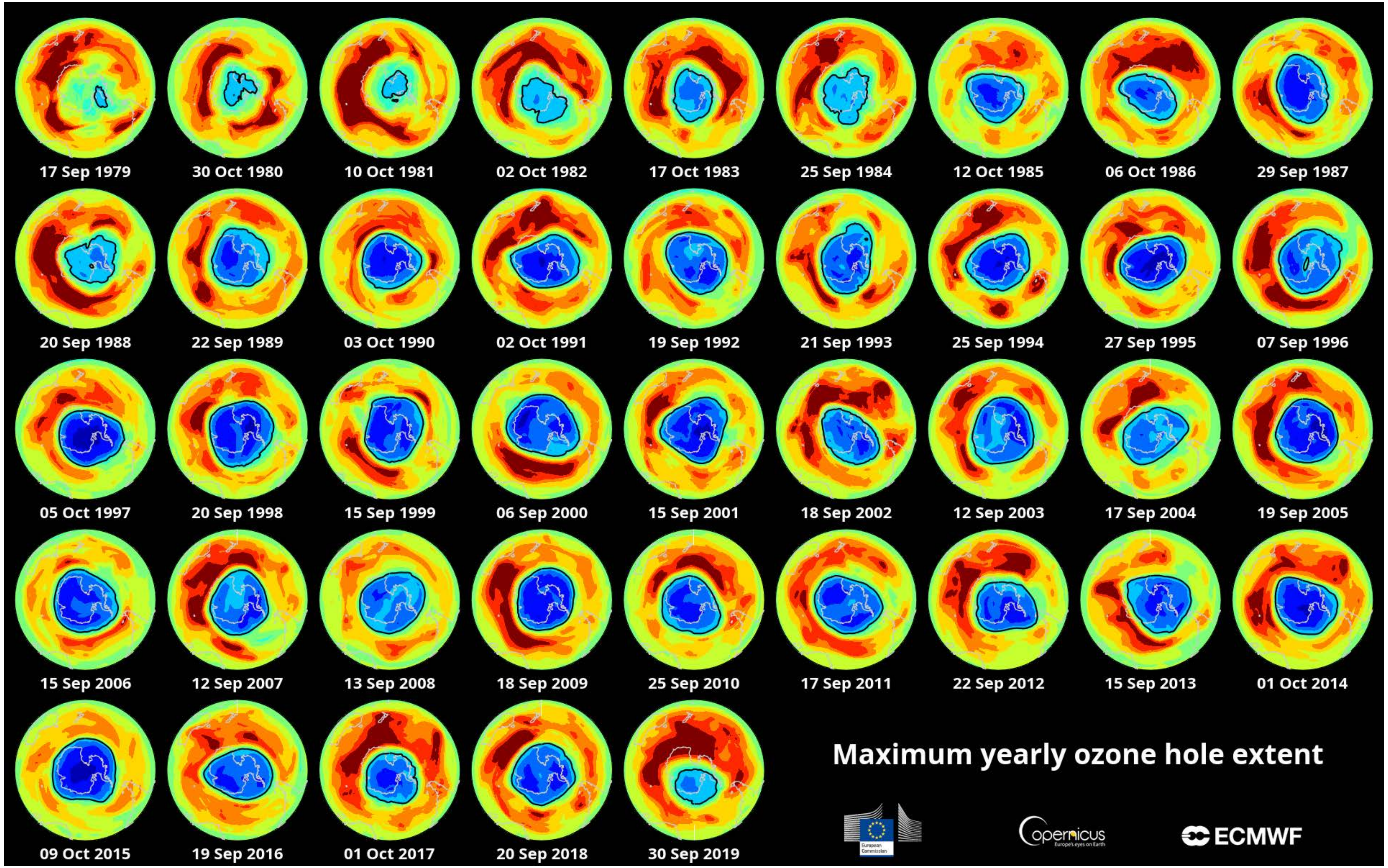


Could the space industry undermine Montreal Protocol?

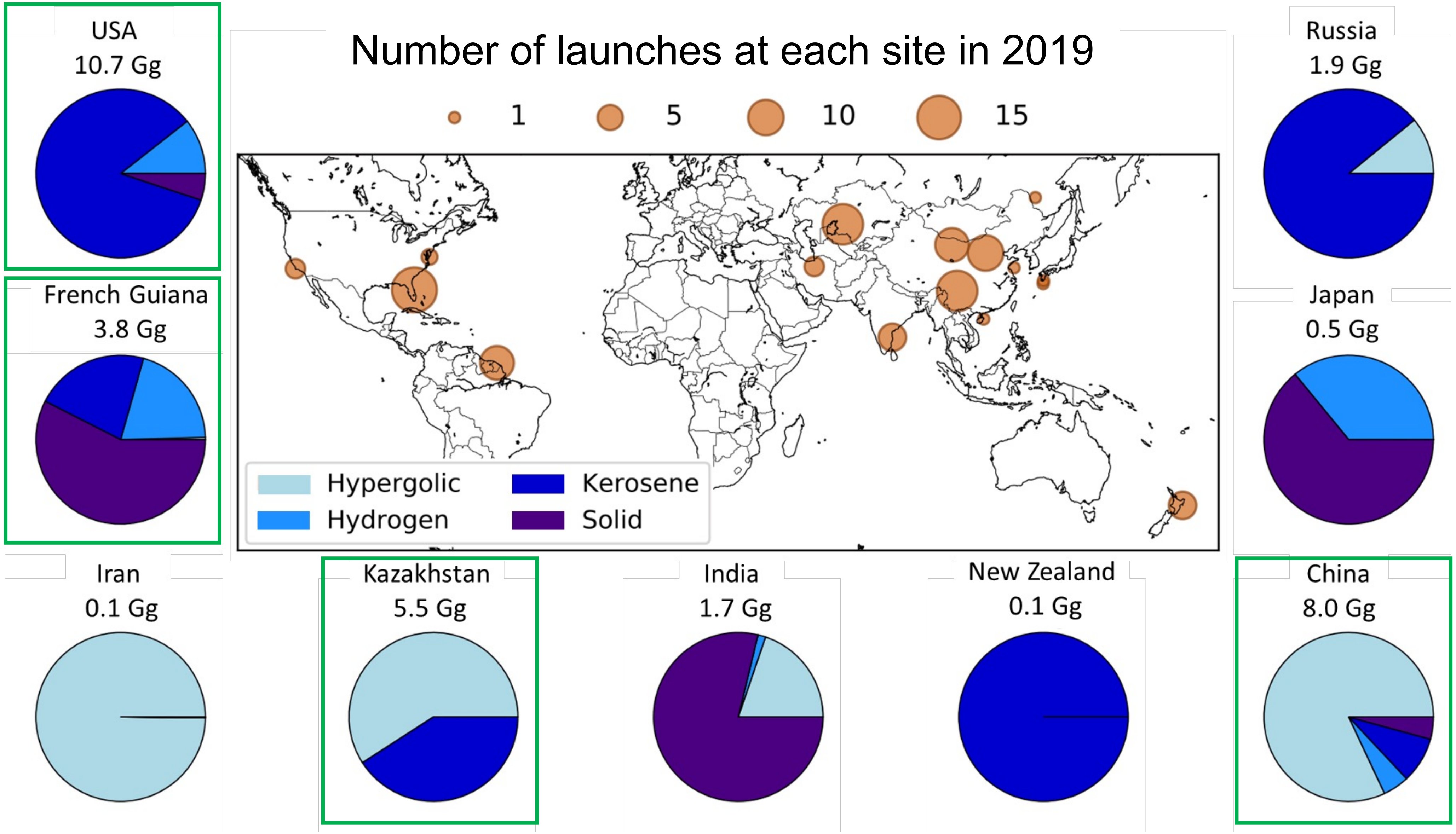
No regulation imposed on space industry emissions from rocket launches and returning parts

International Day for the Preservation of the Ozone Layer

Friday 16 September

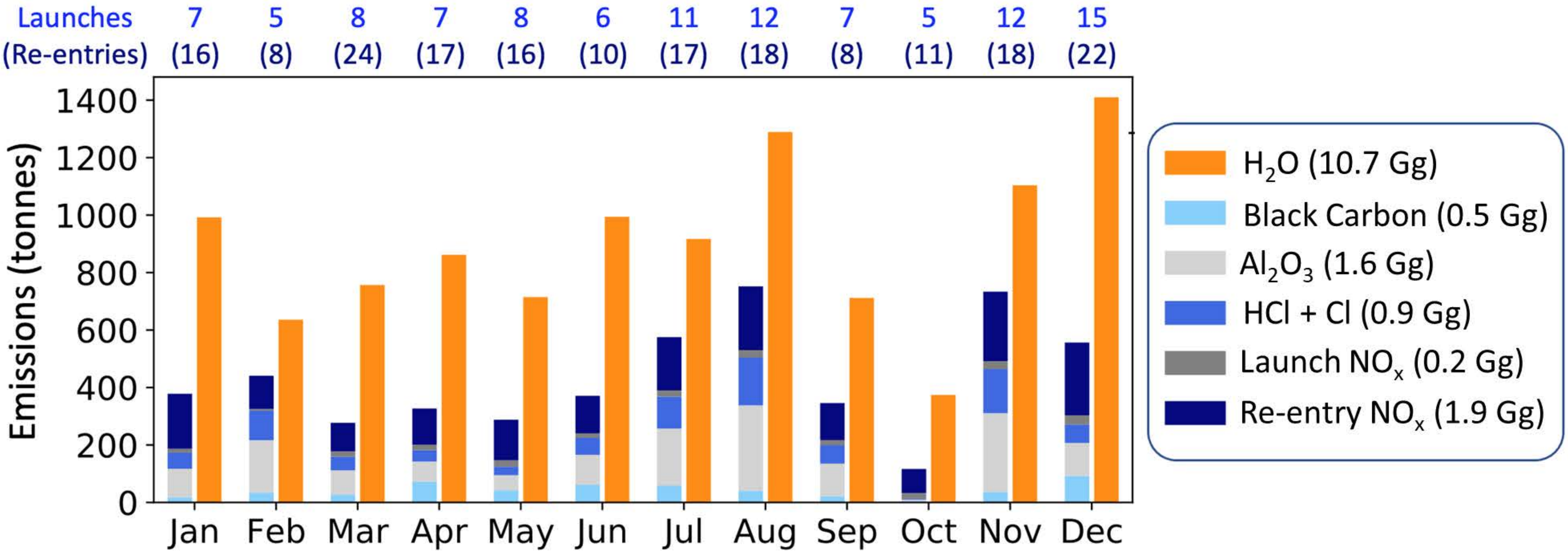


Geographic distribution of launch sites and fuels used



Space tourism: solid (rubber) [Virgin Galactic], hydrogen [Blue Origin], kerosene [SpaceX]

Total emissions from purposeful rocket launches



All emissions are relatively small, but most released directly released to the upper atmosphere

Most NO_x from re-entry burn

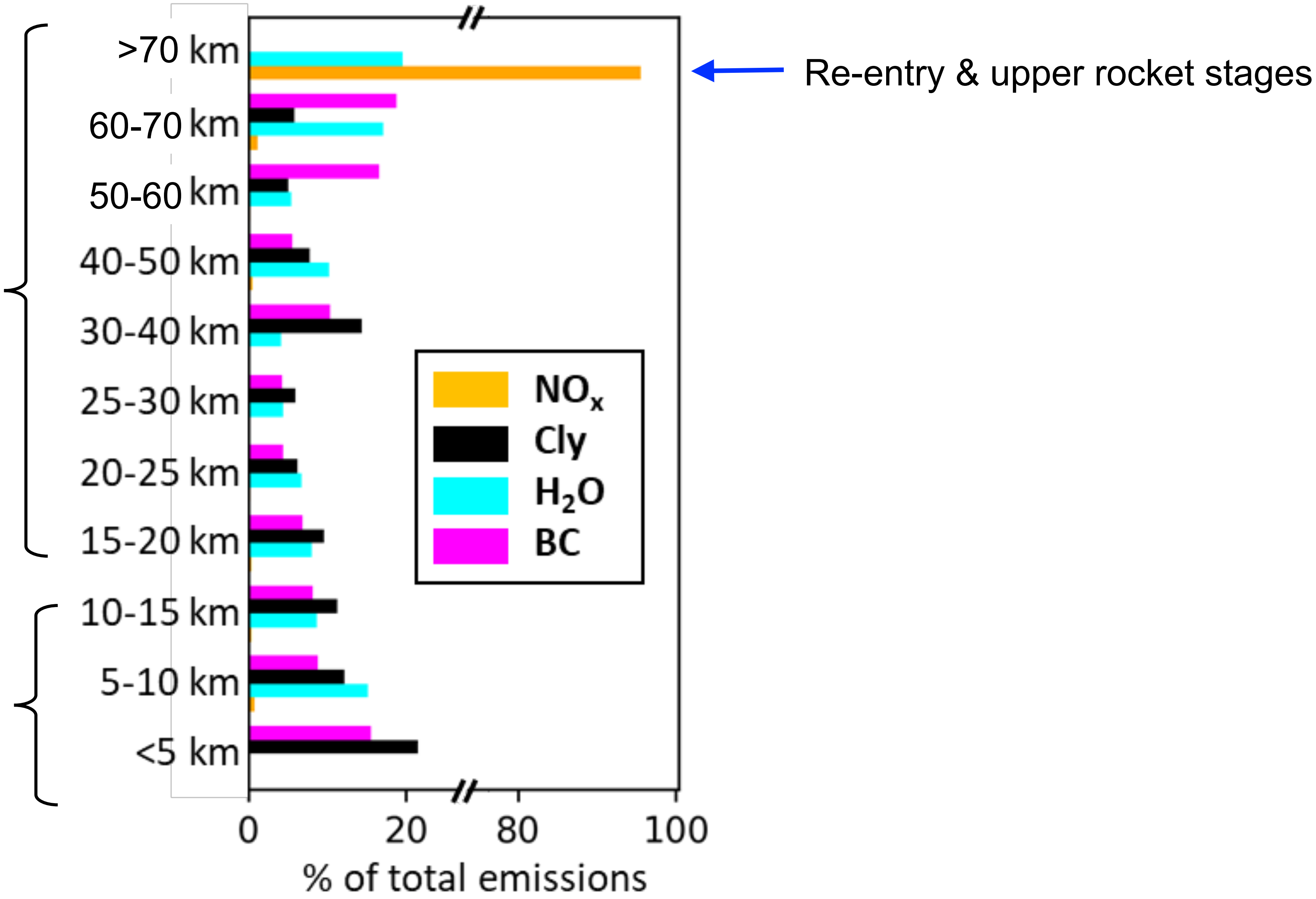
Conduct decade-long simulation with 5.6% a^{-1} increase in emissions.

Vertical distribution of air pollutant emissions

Altitude limit of GEOS-Chem
(**80 km**)

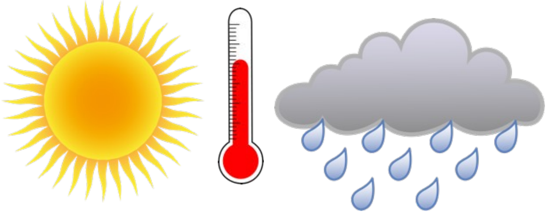
<u>Stratosphere and mesosphere:</u>
lifetimes 2-3 years
(*gravitational settling*)

<u>Troposphere:</u>
lifetimes weeks to months
(*wet and dry deposition, subsidence, chemical losses*)



Model impact on atmospheric composition and climate

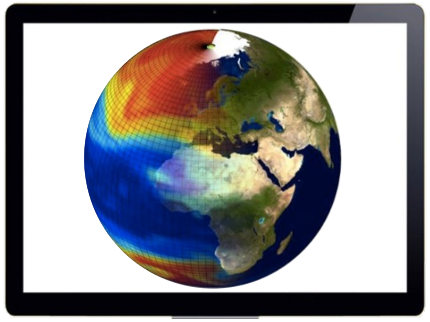
Input to GEOS-Chem coupled to a radiative transfer model



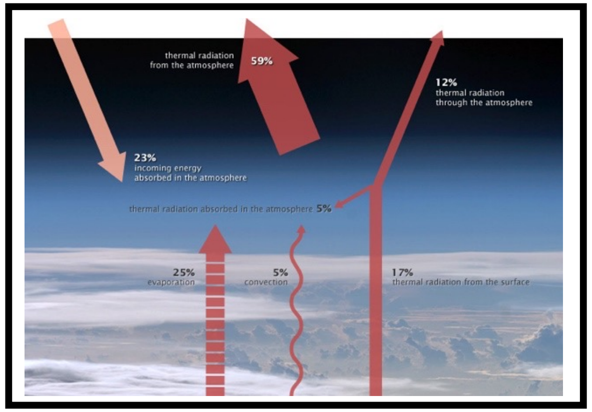
NASA Meteorology

Air Pollution Sources

GEOS-Chem



Chemistry Transport Model



Radiative Transfer Model

Effect on chemical composition

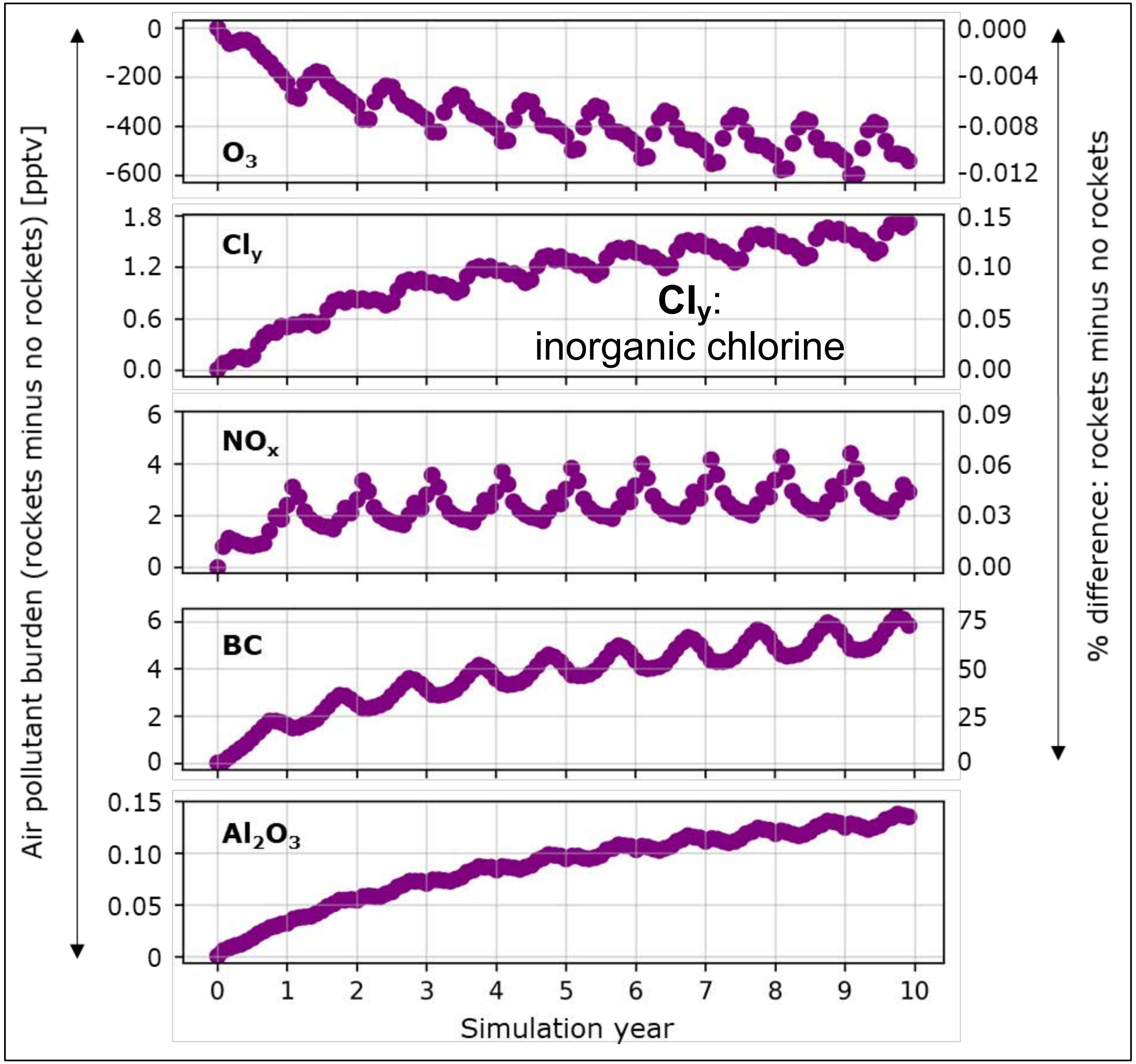
(Concentration)

Radiative forcing

(Heating)

To find out more about GEOS-Chem: http://acmg.seas.harvard.edu/geos/index.html

Evolution of impact on global atmospheric composition



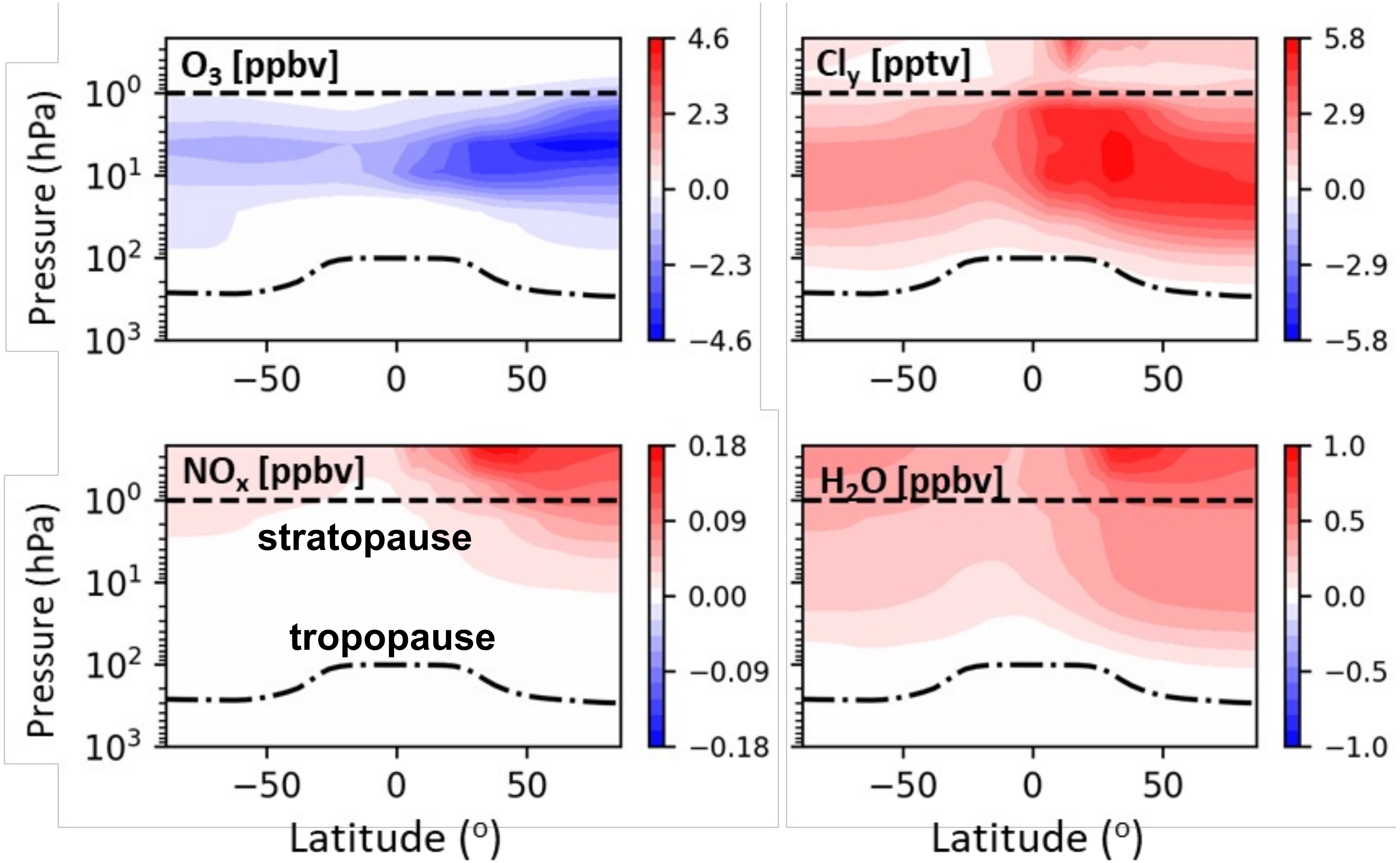
Difference between simulation with and without rocket emissions averaged from 200 to 1 hPa

All except NO_x take ~4 years to equilibrate. NO_x takes ~2 years

Greatest ozone loss occurs in the upper stratosphere (~5 hPa)

Most emissions are in the NH, so seasonality governed by conditions there

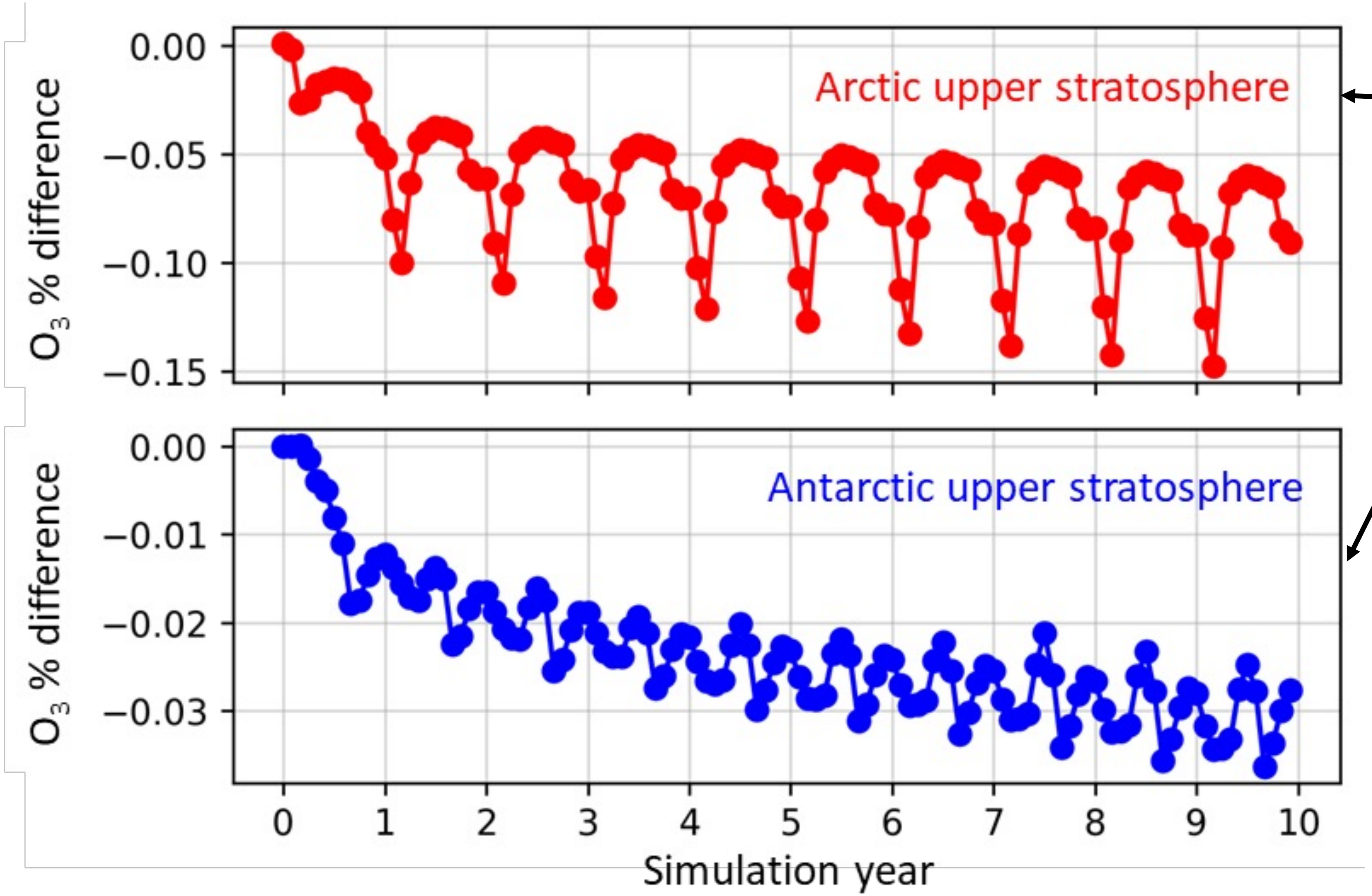
Change in composition after a decade of emissions

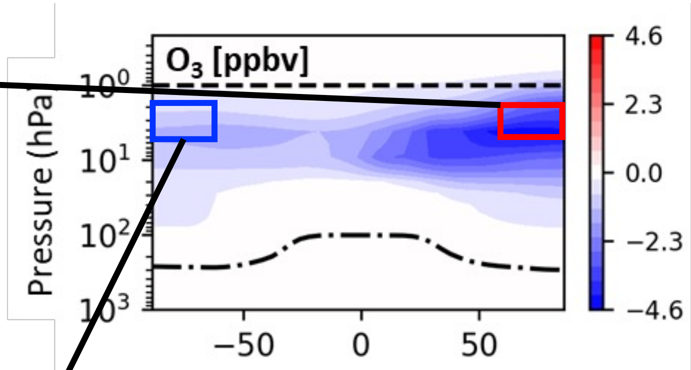


Cl_y:
inorganic chlorine

Decline in global stratospheric ozone of 0.01% is much less than ~2% decline due to banned ozone depleting substances

Response of polar upper stratospheric composition





60-90 degree latitude

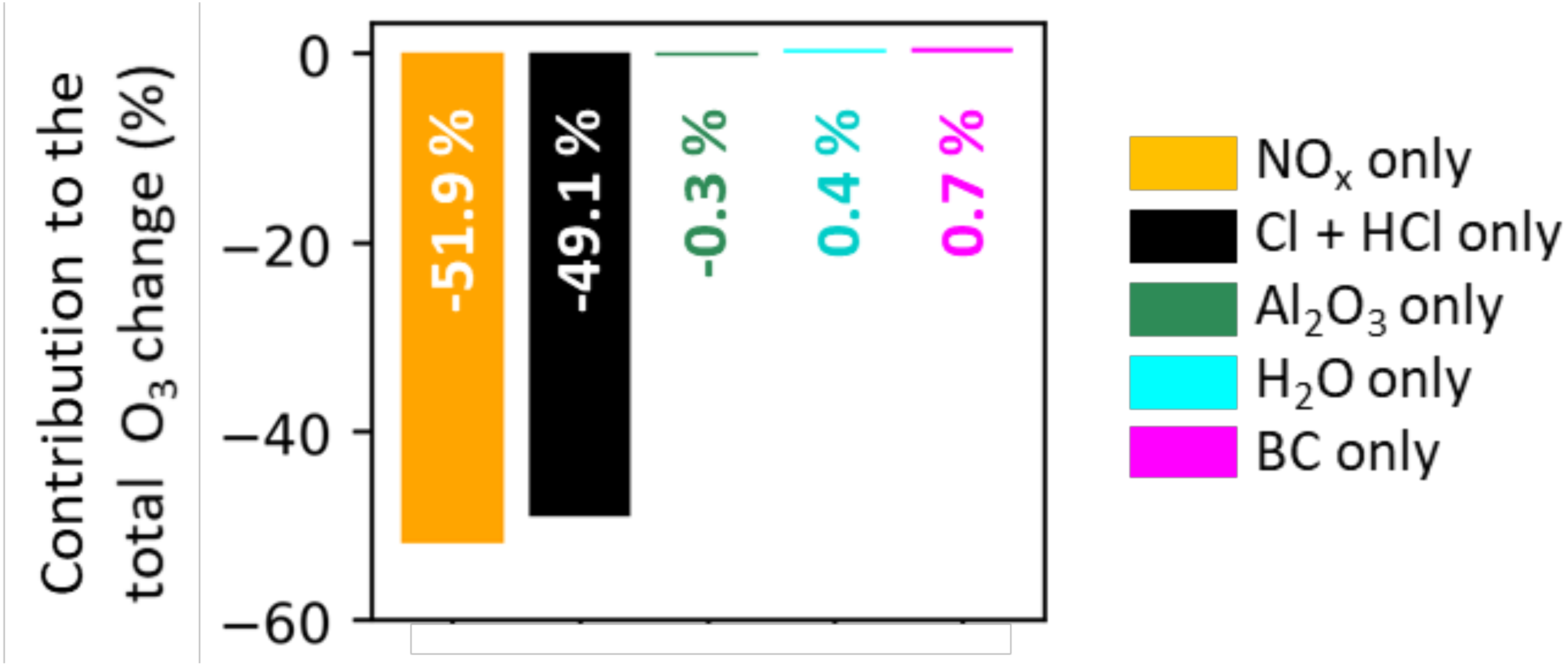
3-6 hPa

Oscillation tracks seasonality of sunlight and chlorine

Maximum decline in spring peaks at **0.15% in the NH** and **0.04% in the SH**

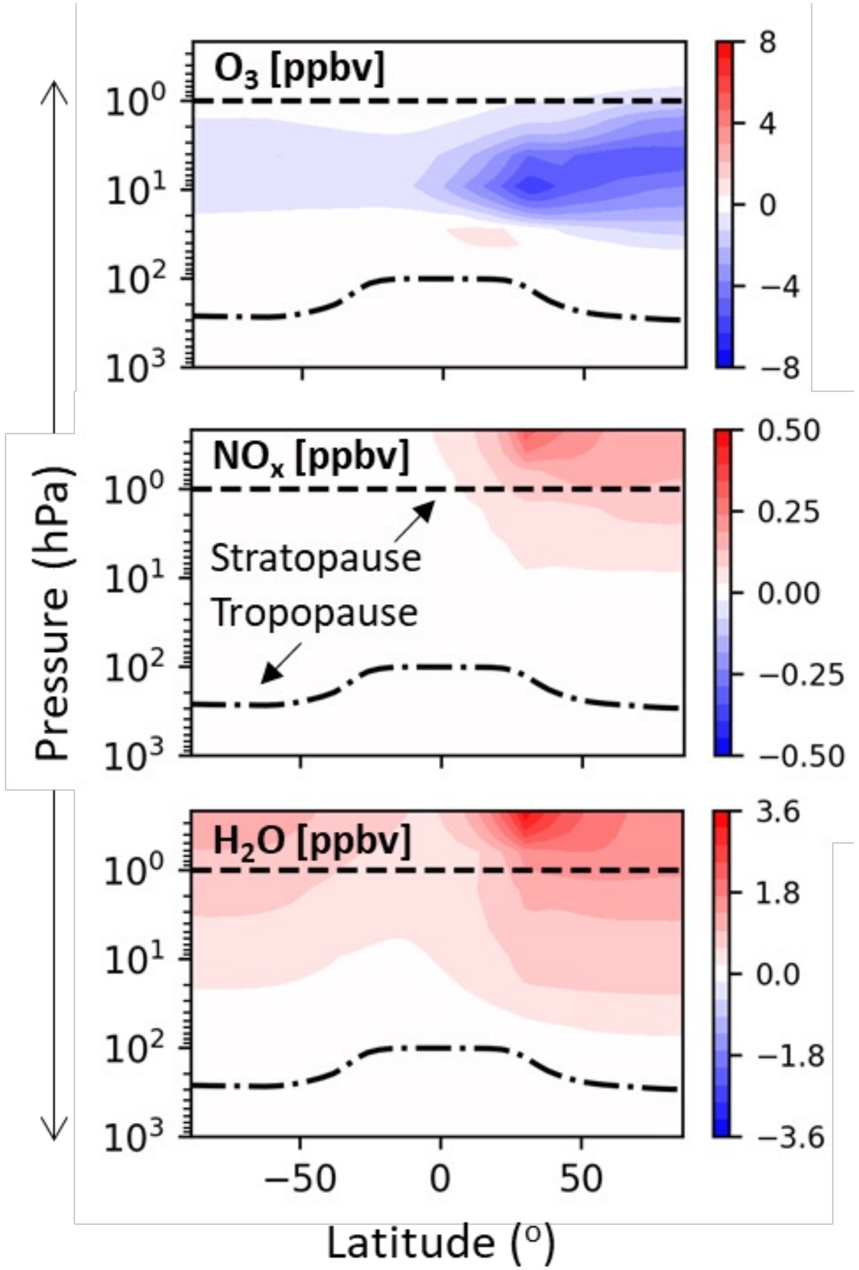
Relative role of each pollutant type

Determined with GEOS-Chem sensitivity simulations (single-pollutant runs)



Contribution to stratospheric ozone depletion dominated by near-equivalent contribution from NO_x (33% re-entry, 66% launch) and chlorine (solid rocket fuel only)

Composition changes with formidable space tourism industry



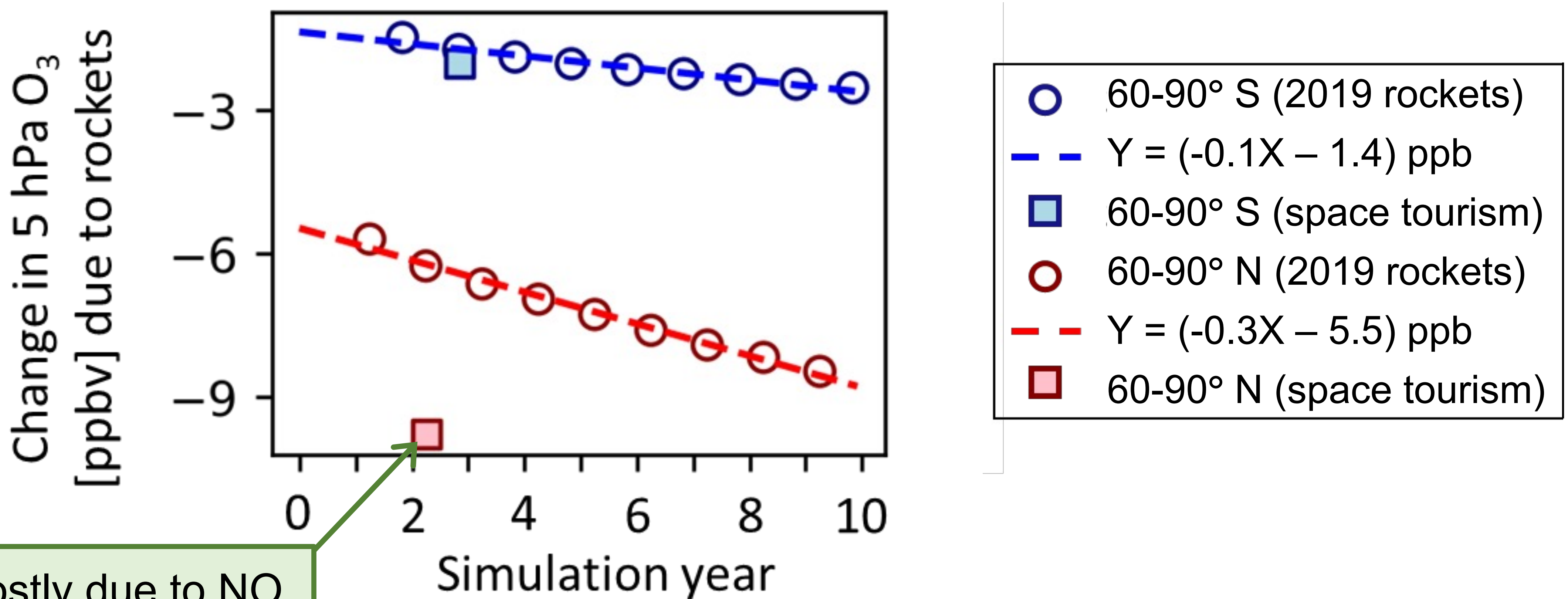
<u>After 3 years of:</u>

Daily suborbital Blue Origin and Virgin Galactic launches
Weekly multiday orbital launches by SpaceX

No change in seasonality, but 3-4 ppbv more upper stratospheric ozone loss in the NH due to increase in NO_x emissions

Effect of formidable space tourism on stratospheric ozone

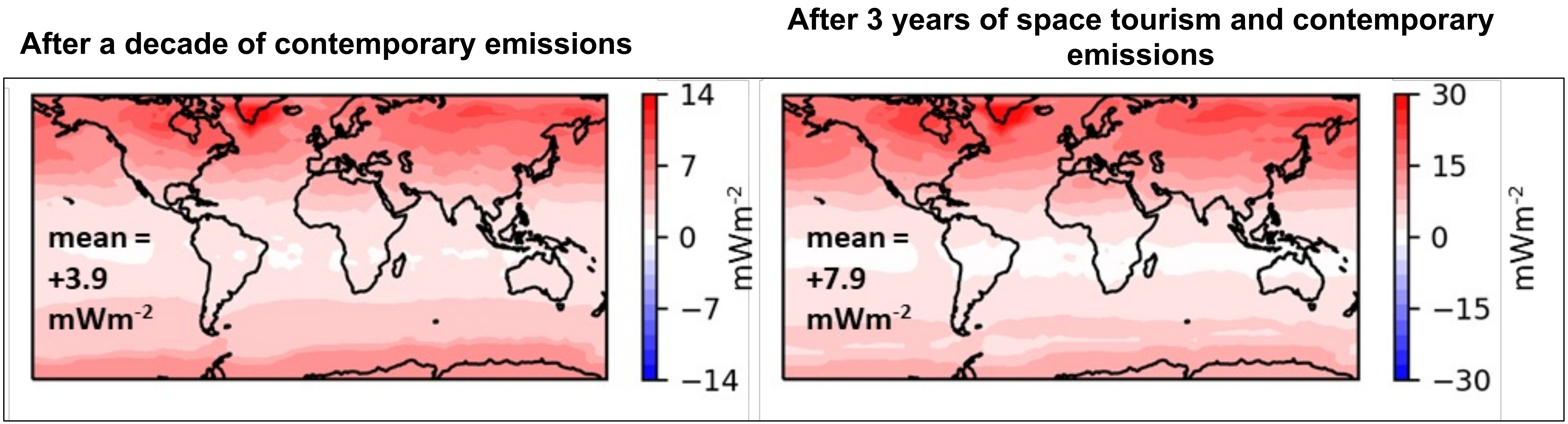
Change in upper stratospheric ozone in the upper latitudes (60-90° N/S)



Mostly due to NO_x from re-entry

Space tourism simulation suggests ozone depletion of **0.24% decade^{-1}** in the NH high latitudes
This is 16% of the NH upper stratospheric ozone recovery attributable to Montreal Protocol

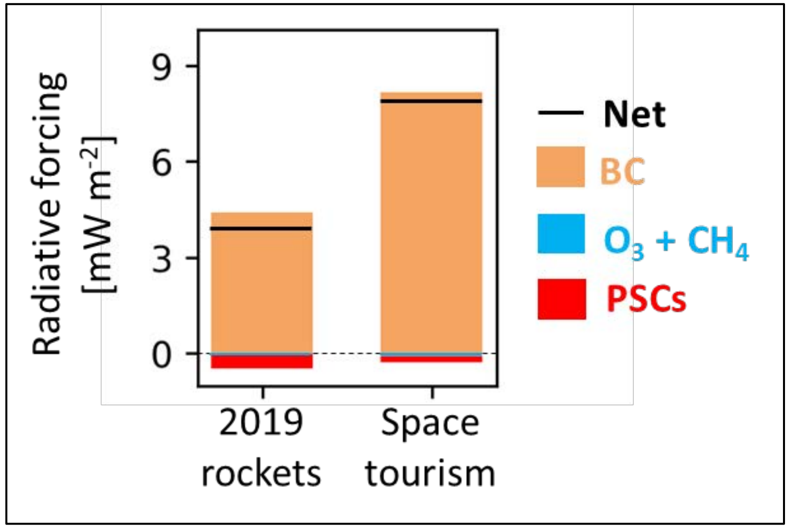
Largest concern is radiative forcing from black carbon



Mostly due to black carbon (BC)

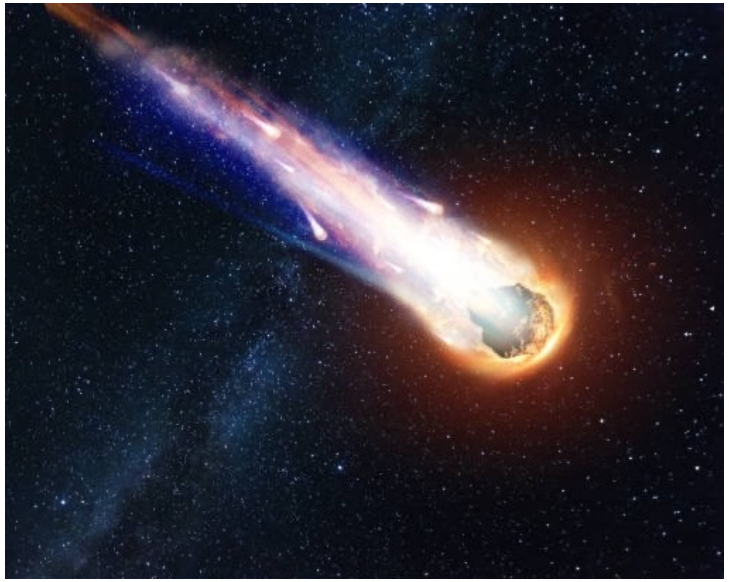
Contemporary rockets are ~0.01 % of global BC emissions, but 3.2% of BC radiative forcing.

Suggests BC from rockets have **~500 times greater radiative effect** than BC from Earth-bound sources



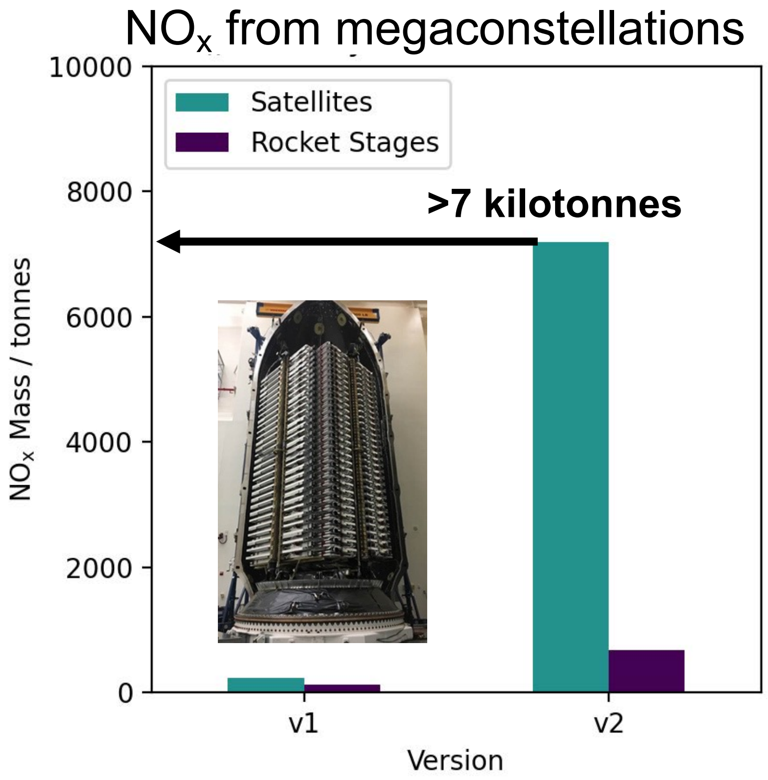
Artificial vs natural (meteor) NO_x emissions?

Could NO_x emissions from space junk and reusable components outcompete natural emissions from meteors?



Meteors: 2-40 kilotonnes/yr

Artificial: 0.7 kilotonnes in 2019



Future megaconstellations have potential to emit similar amounts of NO_x to meteors

V1: 60 satellites/launch
V2: 400 satellite/launch

Satellite ablation also produces Al_2O_3 (not yet quantified)

Conclusions

- Impact of purposeful rockets on stratospheric ozone small, assuming no dramatic increase in launches.
- Large sensitivity of climate to rocket BC emissions, due to altitude emitted
- Space tourism scenario has potential to undermine Montreal Protocol progress in repairing the ozone layer and contribute substantial warming from BC emissions
- **Lots of caveats**: radiative forcing excludes Al_2O_3, many other chemicals produced from rocket fuel and re-entry burn, re-entry burn NO_x emissions uncertain, space tourism hasn't grown since 2021 demonstration missions
- Regardless, no international regulation imposed on "tail-pipe" rocket launch emissions, so nothing to stop the use of the most hazardous fuel types.
- Sustainable growth of space industry also challenging, as no emissions-free way to dispose of junk and all rockets produce hazardous pollutants

Additional resources and references

Ryan et al. Earth's Future paper: https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021EF002612

Rocket emissions dataset: https://doi.org/10.5522/04/17032349

The Conversation piece 1: https://theconversation.com/space-tourism-rockets-emit-100-times-more-co-per-passenger-than-flights-imagine-a-whole-industry-164601

The Conversation piece 2: https://theconversation.com/axiom-launch-why-commercial-space-travel-could-be-another-giant-leap-for-air-pollution-180990

Media coverage: https://maraisresearchgroup.co.uk/media_coverage.html

More about other policy-relevant research in my group here:

https://maraisresearchgroup.co.uk/

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