Impact of rocket launch and re-entry heating pollution on ozone and climate

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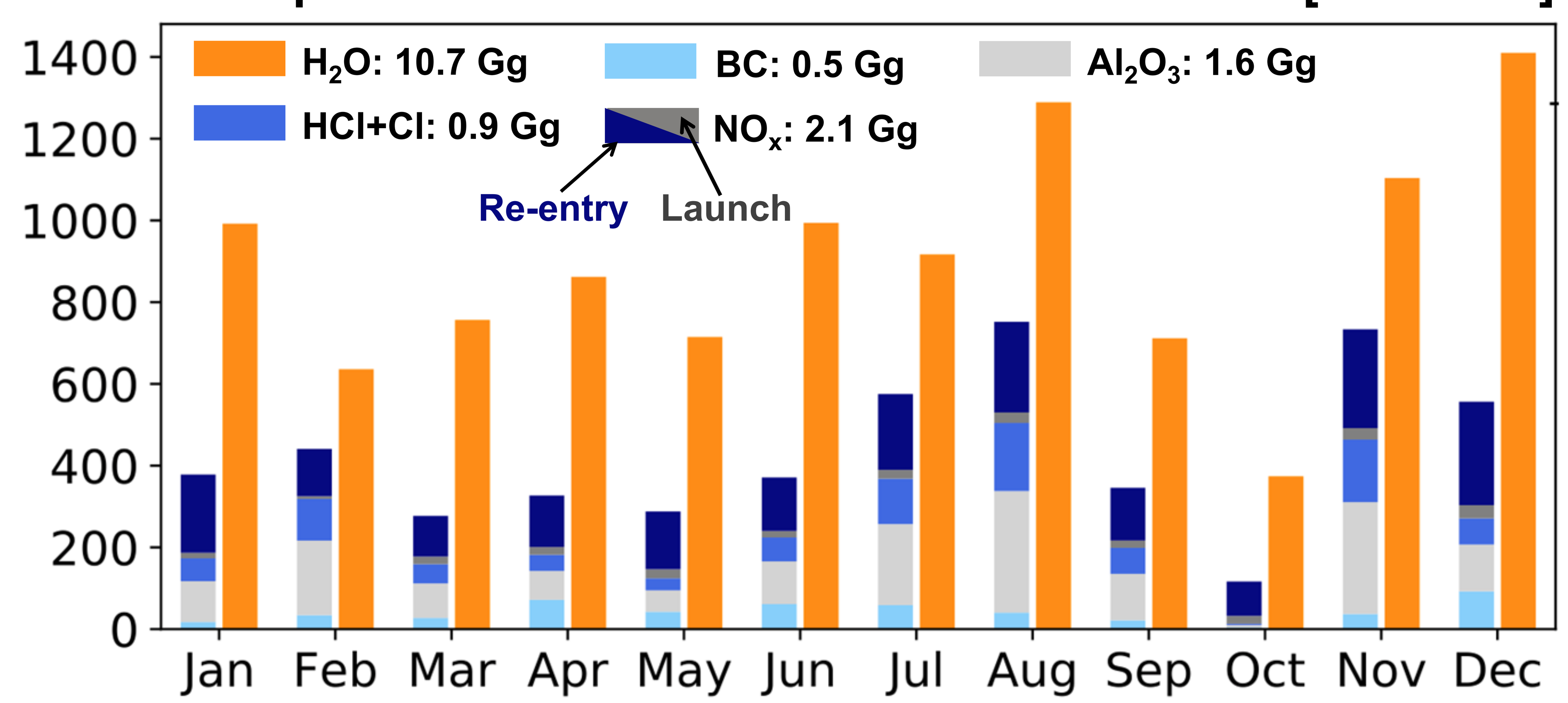
Major Finding: We used GEOS-Chem to determine that positive radiative forcing of black carbon released during launch of rockets that use carbon-based fuels (kerosene, hypergolic, solid) is 400-500 times greater per unit mass than Earth-bound sources. *In review in Earth's Future*

1. Emission Inventory Development

We compile an inventory of major air pollutants from 103 rocket launches and re-entry of recently discarded and historical space debris and reusable components in 2019. These include water vapor (H_2O), black carbon (BC), alumina (Al_2O_3), chlorine (99% HCl, 1% Cl), and nitrogen oxides (NO_x).

Air pollutant emissions in each month in 2019 [in tonnes]



We also estimate emissions from space tourism daily suborbital launches by Virgin Galactic and Blue Origin, and weekly orbital launches by SpaceX totaling 782 annual launches. These add 30 Gg H_2O, 1.0 Gg BC, and 2.1 Gg NO_x (67% launch; 33% re-entry).

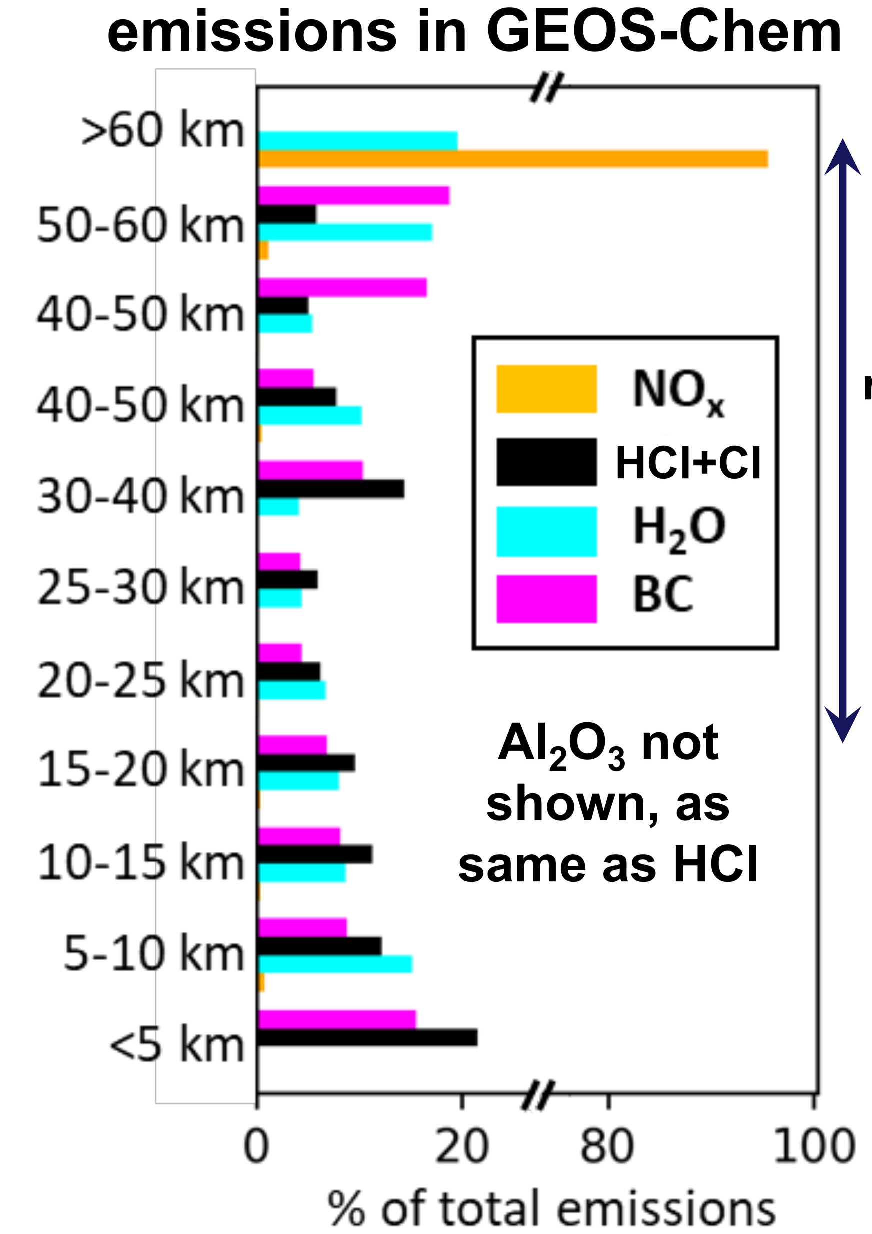
2. Implementation in GEOS-Chem

We use GEOS-Chem-RRTMG v12.9.3 to quantify BC radiative forcing and stratospheric ozone loss. Other details: UCX chemistry, 4° x 5°, 47 layers.

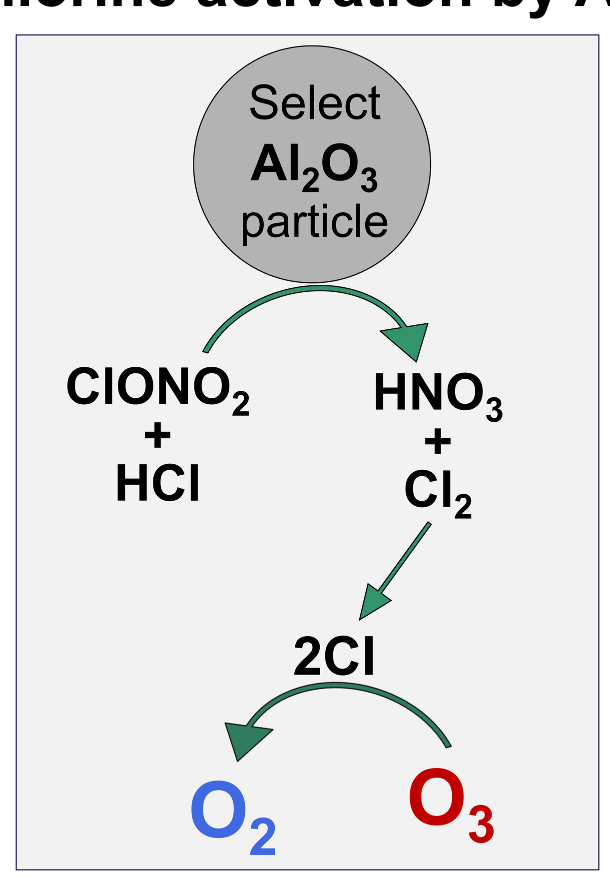
Emissions are vertically distributed using published profiles [1].

Heterogeneous chlorine activation on medium-sized Al_2O_3 particles added to UCX.

Vertical distribution of emissions in GEOS-Chem



Chlorine activation by Al_2O_3

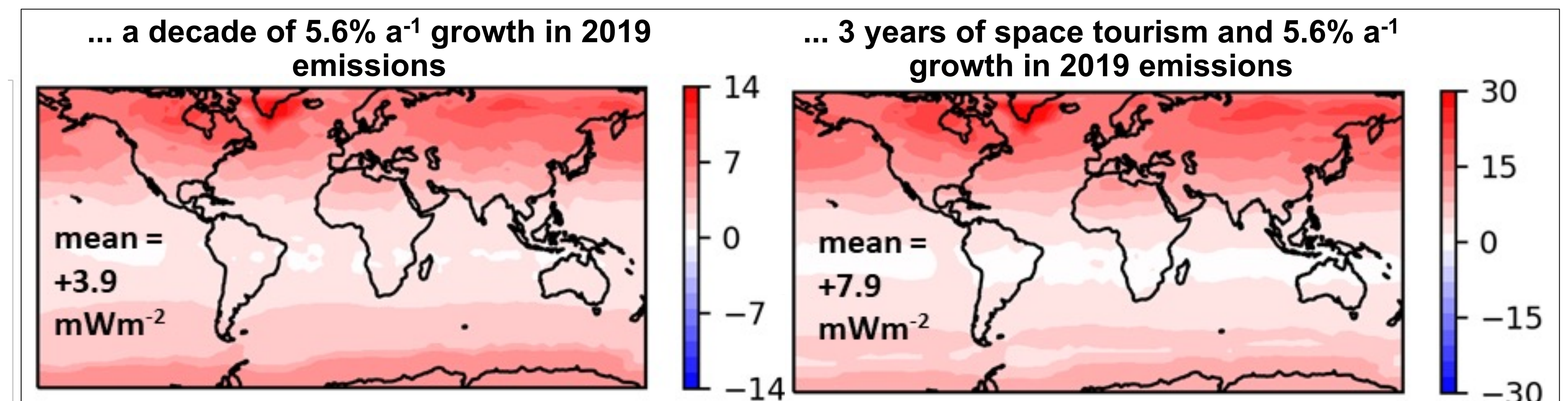


Spin up GEOS-Chem-RRTMG for 7 years before conducting a decade-long simulation with 5.6% a^{-1} increase in emissions based on average increase in rocket launches from 2003 to 2019.

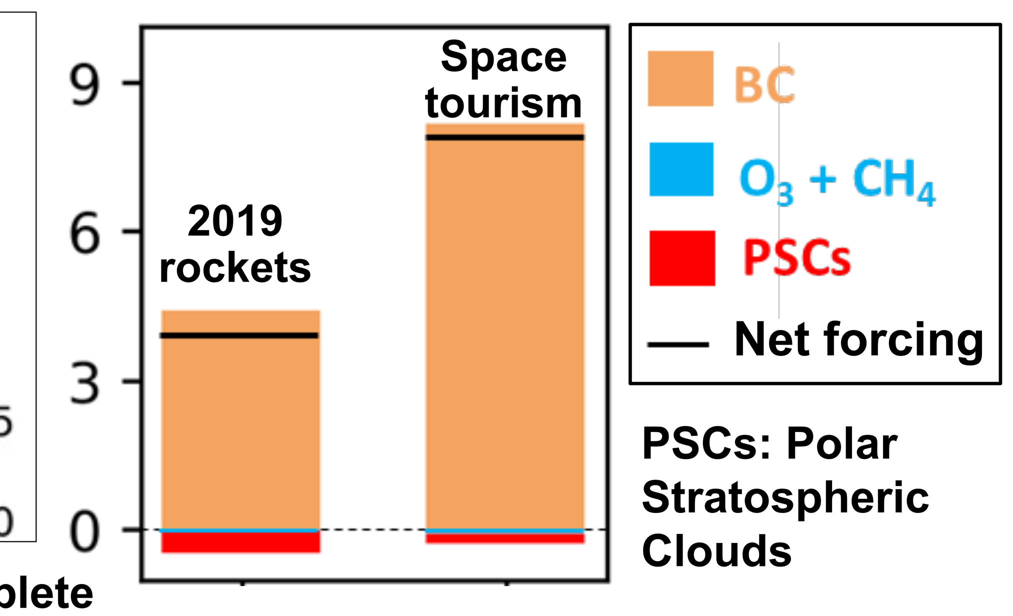
3. Black Carbon Radiative Forcing According to GEOS-Chem-RRTMG

Net global direct top-of-atmosphere radiative forcing of 3.9 mW m^{-2}, dominated by BC, after a decade of 2019 rocket emissions with 5.6% per year growth. Global radiative forcing doubles to 7.9 mW m^{-2} following just 3 years of space tourism emissions.

Direct top-of-atmosphere radiative forcing [in mW m^{-2}] following ...



Contribution of forcers [in mW m^{-2}]



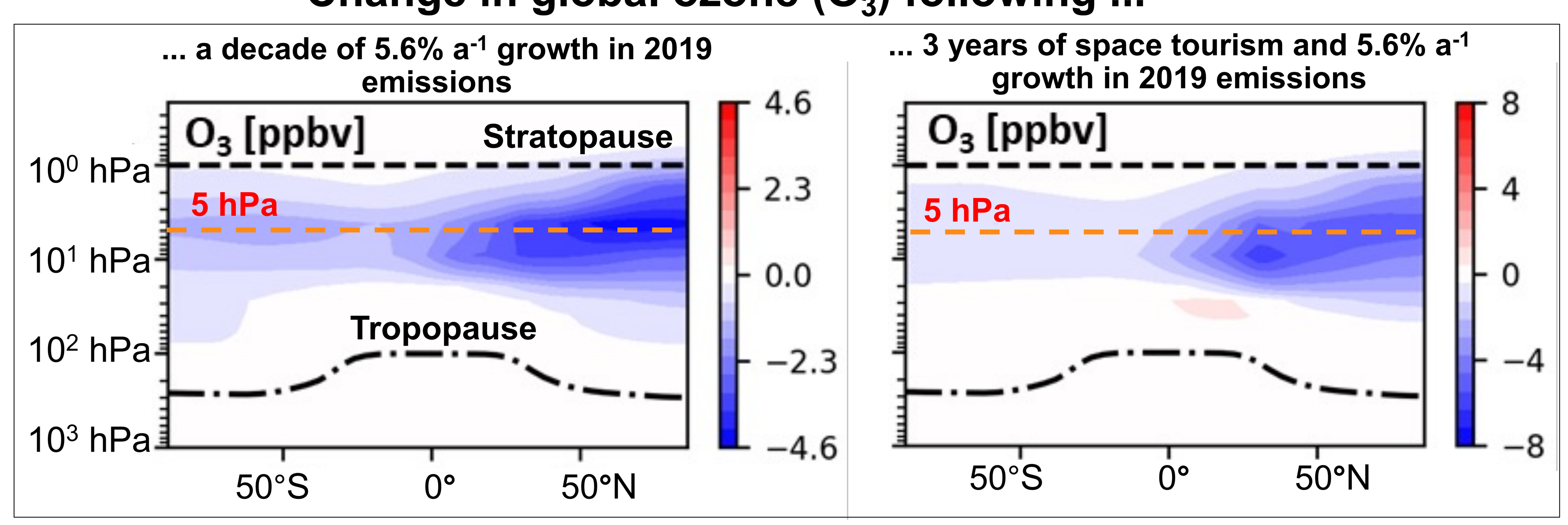
Rocket launch emissions directly add BC, promote PSCs formation (from H_2O emissions), deplete CH_4 (oxidized by Cl), and increase transparency of the stratospheric O_3 layer. Contributions from O_3 and CH_4 negligible and PSCs small.

2019 emissions are 3% of radiative forcing and only 0.01% of all BC emissions. With space tourism, this doubles (6% radiative forcing; 0.02% emissions). BC is long lived (~2 years) and efficient at absorbing incoming sunlight at high altitudes, so BC from rockets has a 400-500 times greater radiative effect (7,800-9,900 mW m^{-2} a^{-1}) than Earth-bound sources (21 mW m^{-2} a^{-1} [2]) per Tg BC emitted.

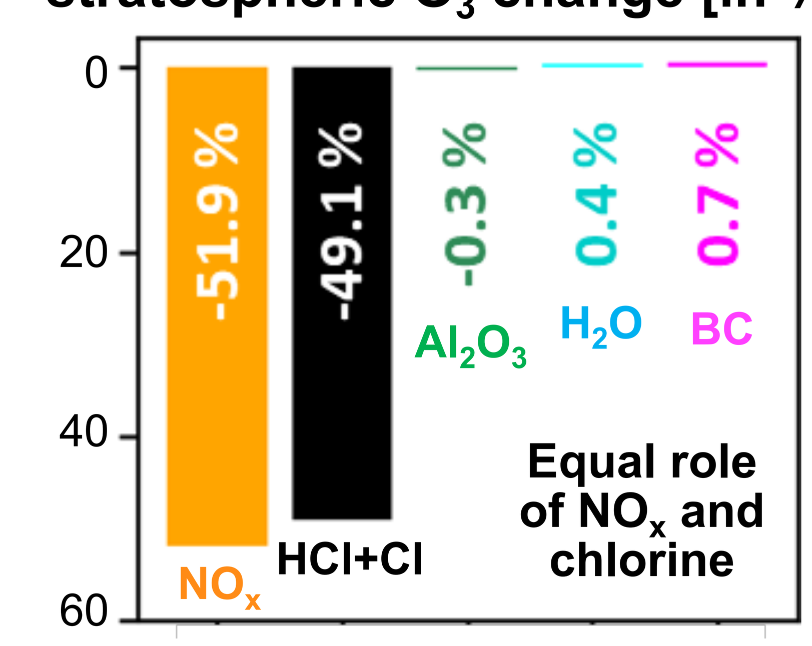
4. Stratospheric Ozone Depletion According to GEOS-Chem

Stratospheric ozone depletion from rocket pollution is most severe in the spring polar upper stratosphere (~5 hPa). Depletion dominated by launch emissions of chlorine from solid fuels and launch and re-entry emissions of NO_x from high-temperature conversion of N_2.

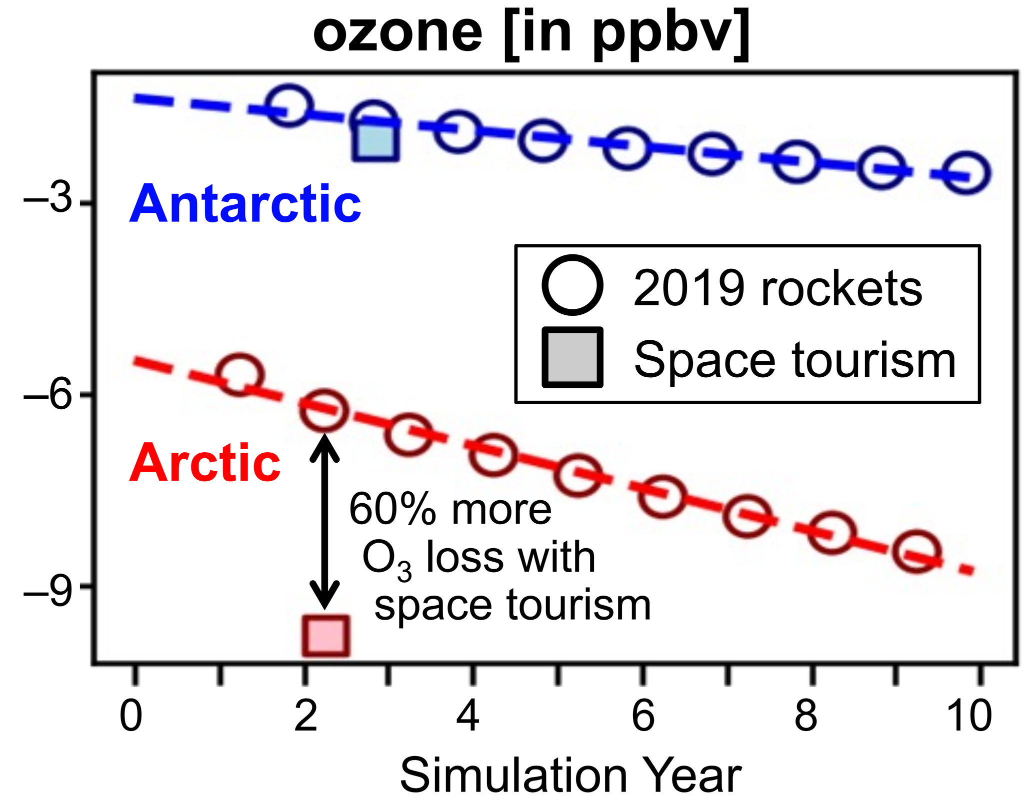
Change in global ozone (O_3) following ...



Contribution of pollutants to stratospheric O_3 change [in %]



Change in upper stratospheric ozone [in ppbv]



Estimated recovery of ozone in the spring upper stratosphere of 81 ppbv per decade attributed to Montreal Protocol ban on ozone depleting substances [3].

Contemporary (2019) rocket launches offset 10% of this recovery.

Routine space tourism could offset 16%.

Ongoing Work

Lots! Better vertical distribution of emissions, calculate 2020 and 2021 emissions, add Al_2O_3 formed during re-entry ablation, sensitivity to model vertical and horizontal resolution, consider Al_2O_3 radiative effect, parameterize BC influence on stratospheric O_3, detect artificial bolides from lightning detectors and pollution from Earth observations.

Acknowledgements

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References

[1] Ross & Sheaffer, Earth's Future, 2014 doi:10.1002/2013EF000160.
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[3] Eyring et al., ACP, 2010, doi:10.5194/acp-10-9451-2010.