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

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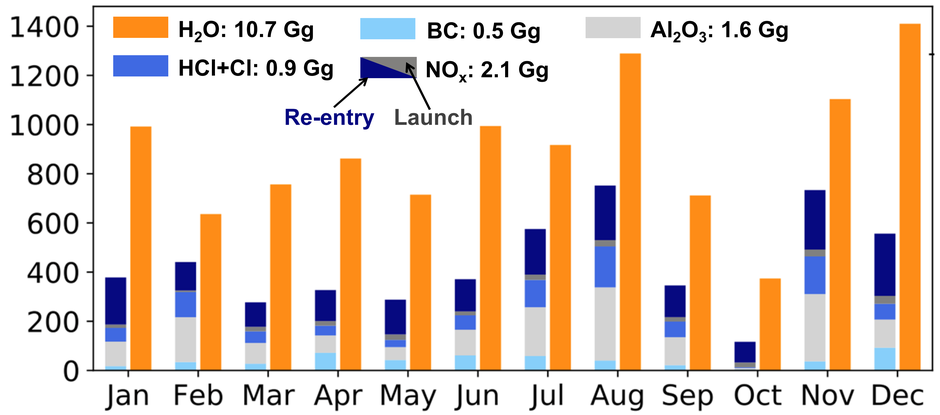
Major Finding: We used GEOS-Chem to determine that positive radiative forcing of black carbon released during launch of rockets that use carbon-based fuels (kerosene, hypergolic, solid) is 400-500 times greater per unit mass than Earth-bound sources. *In review in Earth's Future*

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).

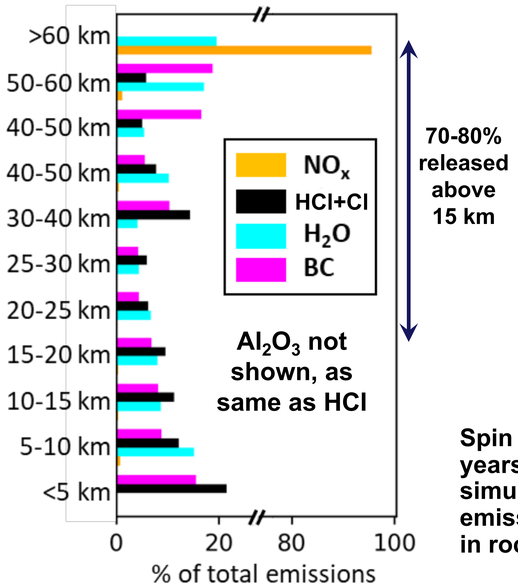
2. Implementation in GEOS-Chem

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.

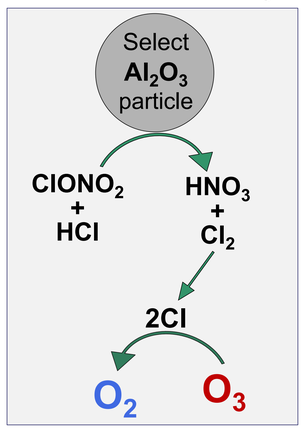
Emissions are vertically distributed using published profiles [1].

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

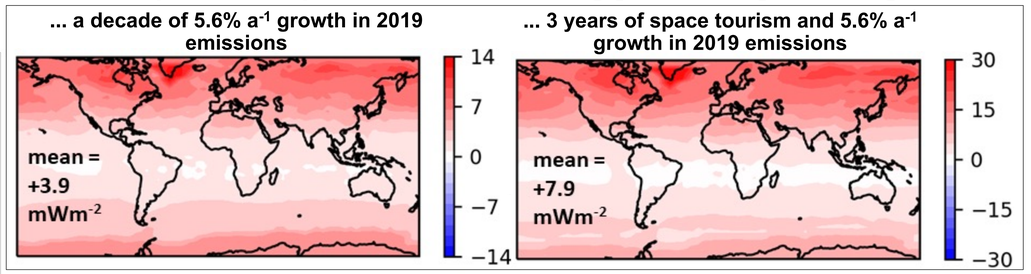


Spin up GEOS-Chem-RRTMG for 7 years before conducting a decade-long simulation with 5.6% a^{-1} increase in emissions based on average increase in rocket launches from 2003 to 2019.

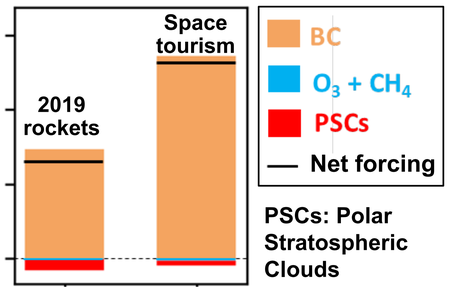
3. Black Carbon Radiative Forcing According to GEOS-Chem-RRTMG

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}]



PSCs: Polar Stratospheric Clouds

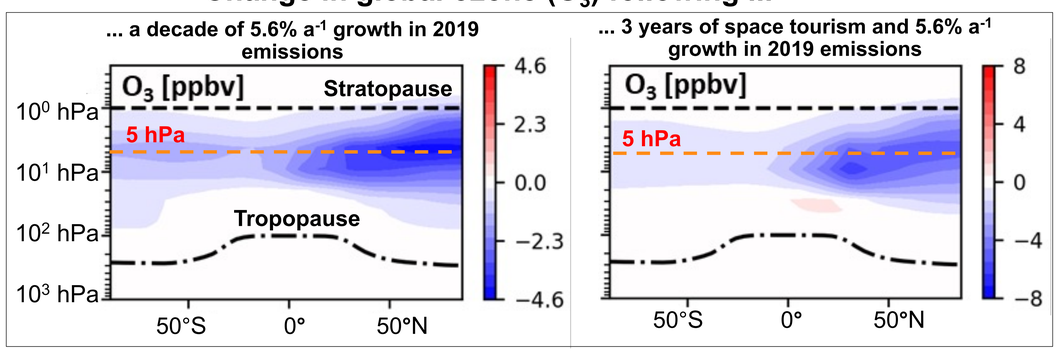
Rocket launch emissions directly add BC, promote PSCs formation (from H_2O emissions), deplete CH_4 (oxidized by Cl), and increase transparency of the stratospheric O_3 layer. Contributions from O_3 and CH_4 negligible and PSCs small.

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.

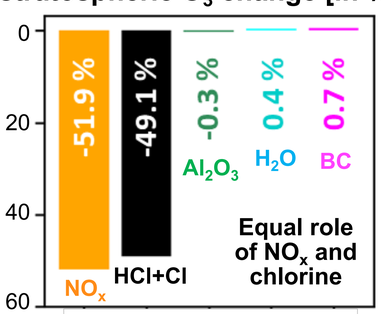
4. Stratospheric Ozone Depletion According to GEOS-Chem

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.

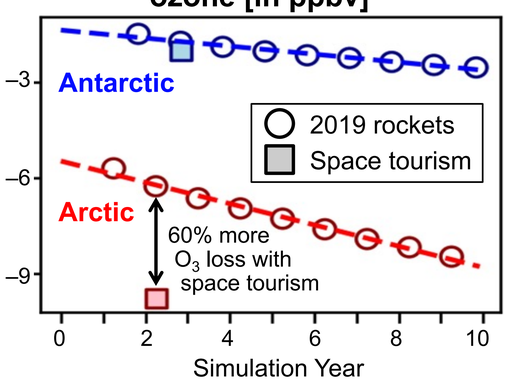
Change in global ozone (O_3) following ...



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

This work is funded by the European Commission. EAM is grateful to NOAA for an IGC10 travel award.

References

[1] Ross & Sheaffer, Earth's Future, 2014 doi:10.1002/2013EF000160.
[2] Dong et al., GRL, 2019, doi:10.1029/2018GL081242.
[3] Eyring et al., ACP, 2010, doi:10.5194/acp-10-9451-2010.