The impact of rocket launches and space debris on ozone and climate

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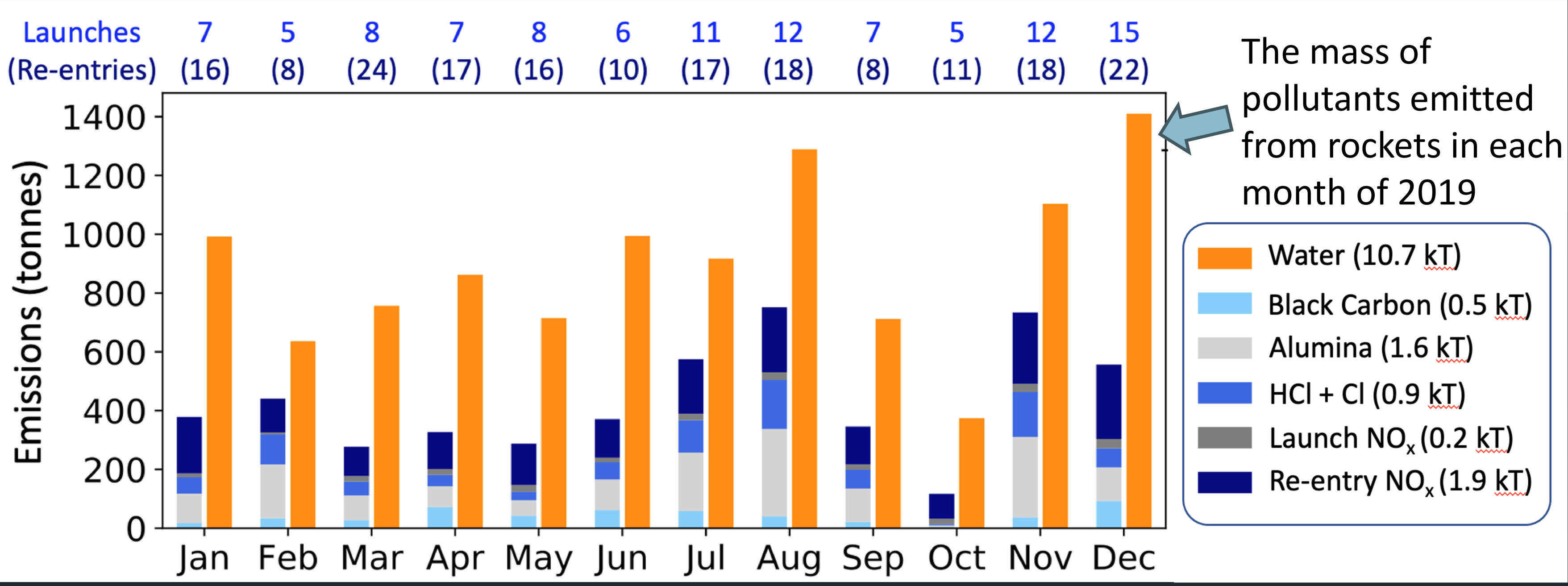
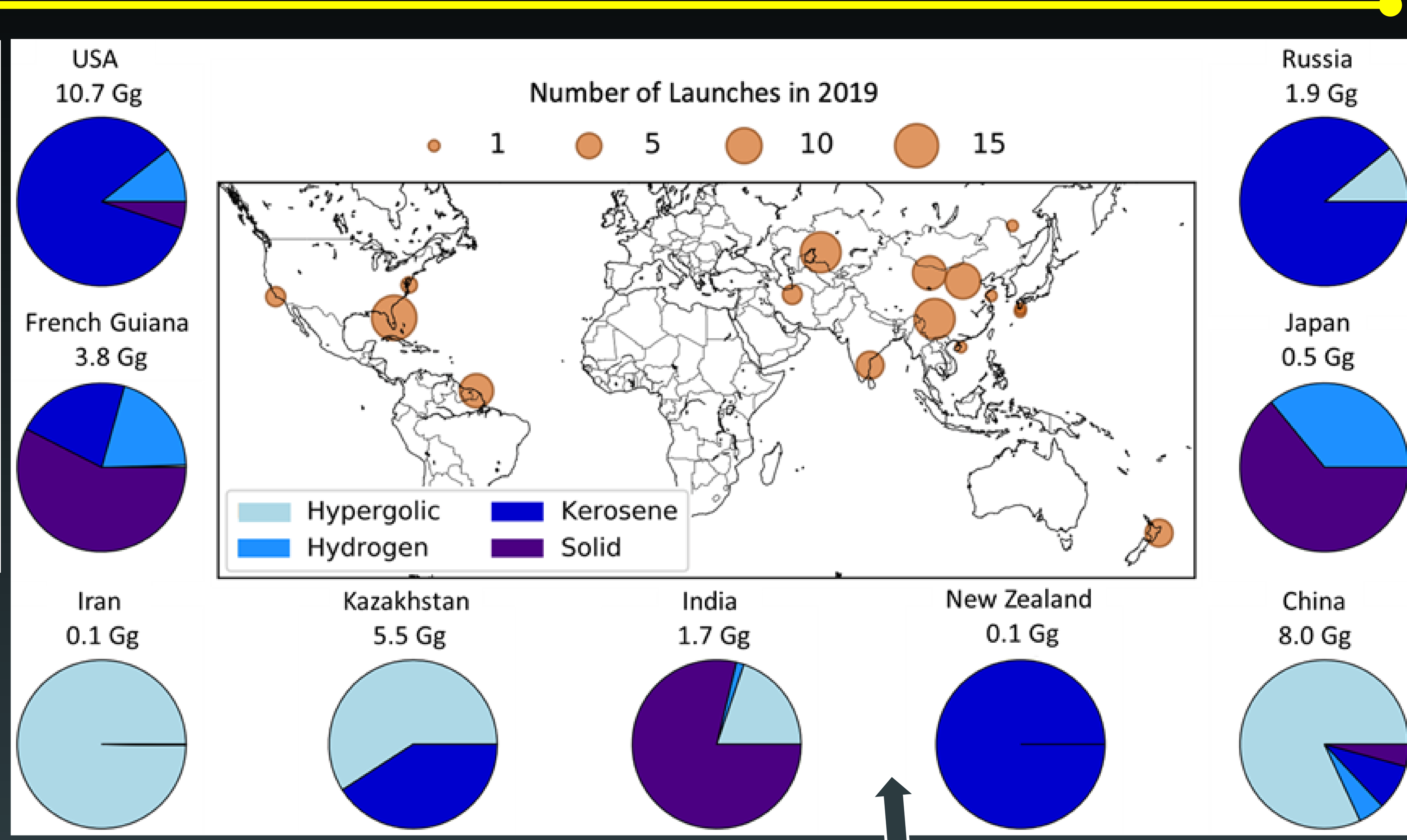


The mass of pollutants emitted from rockets in each month of 2019

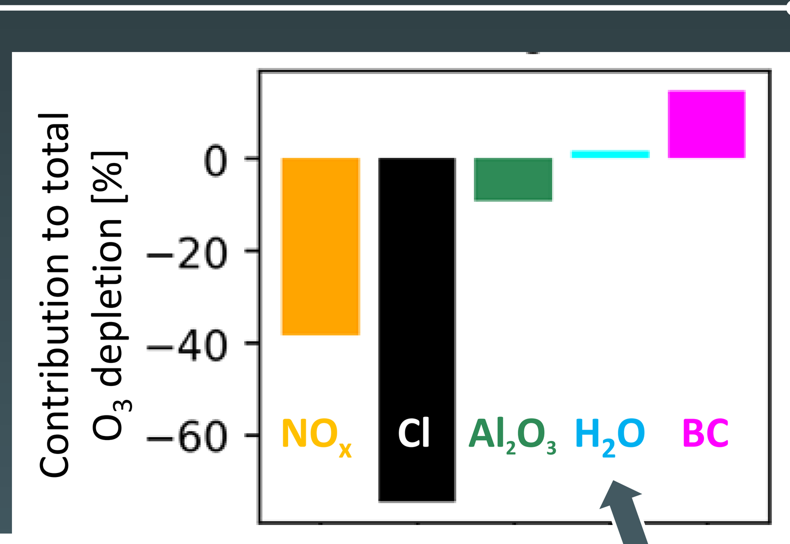


2019 rocket emissions inventory implemented in GEOS-Chem. Emissions specified by time, geolocation, fuel type, rocket stage, altitude. Key pollutants: NO_x, HCl + Cl, Al_2O_3, black carbon. We simulate a 'contemporary' scenario of a decade of 5.6% a^{-1} growth on 2019 levels, and a 'space tourism' scenario which adds daily launches by Virgin Galactic and Blue Origin and weekly launches by SpaceX to the inventory.

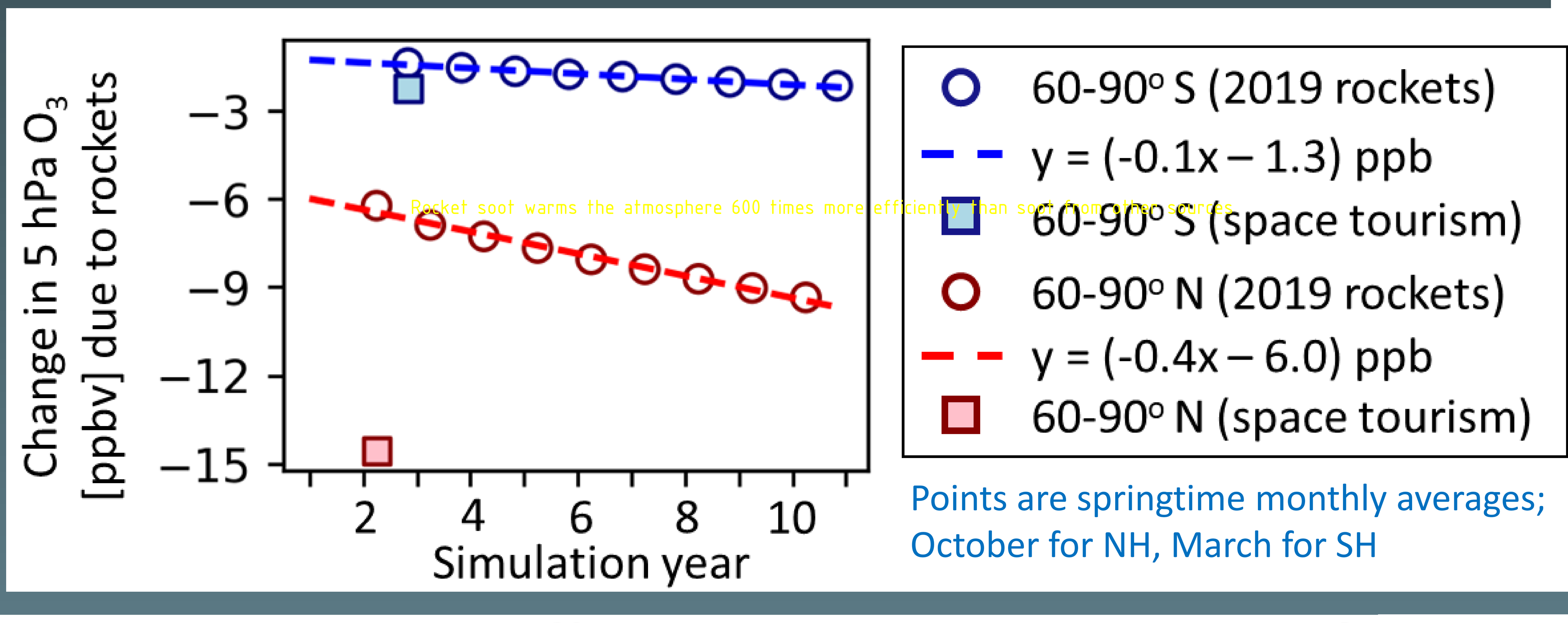
Launch locations and the proportion of fuel types used in each place

Potential to undermine ~20% of the gains made by the Montreal Protocol

The clearest O_3 recovery trends following implementation of the Montreal Protocol are in the upper stratosphere (Steinbrecht et al., *ACP*, 2017). The spring recovery trend in the Arctic upper stratosphere is 81 ppb dec^{-1} (Eyring et al., *ACP*, 2010; 60-90°N, 5 hPa altitude) In our contemporary rockets scenario, springtime Arctic O_3 loss at 5 hPa is 10 ppb dec^{-1}, 13% of the post-Montreal Protocol recovery. This increases this to 18 ppb dec^{-1} (23% of the recovery trend) with inclusion of space tourism emissions.

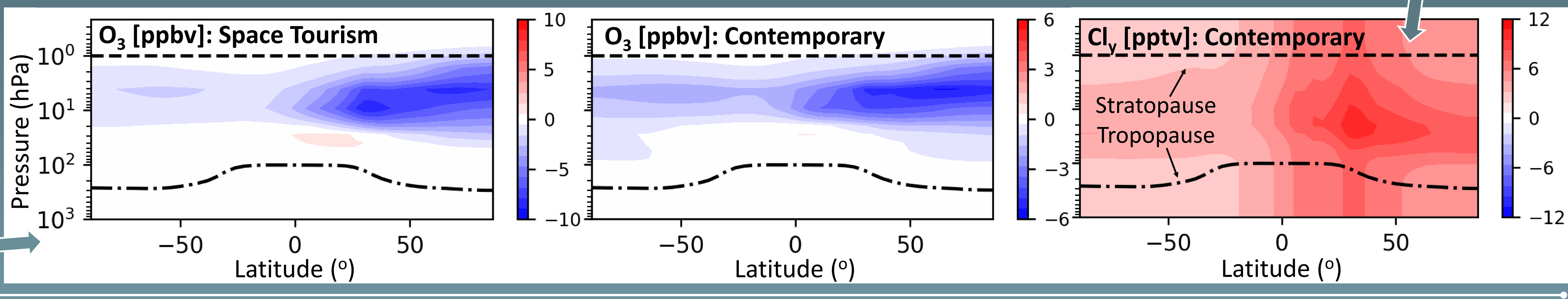


Cl and NO_x are the two most detrimental rocket pollutants for O_3 loss. NO_x is released by all rocket launches and re-entry. Re-entry ablation accounts for 90% of NO_x emissions. Cl is only released by solid-fuel rockets, resulting in an overall increase in total inorganic chlorine (Cl_y).



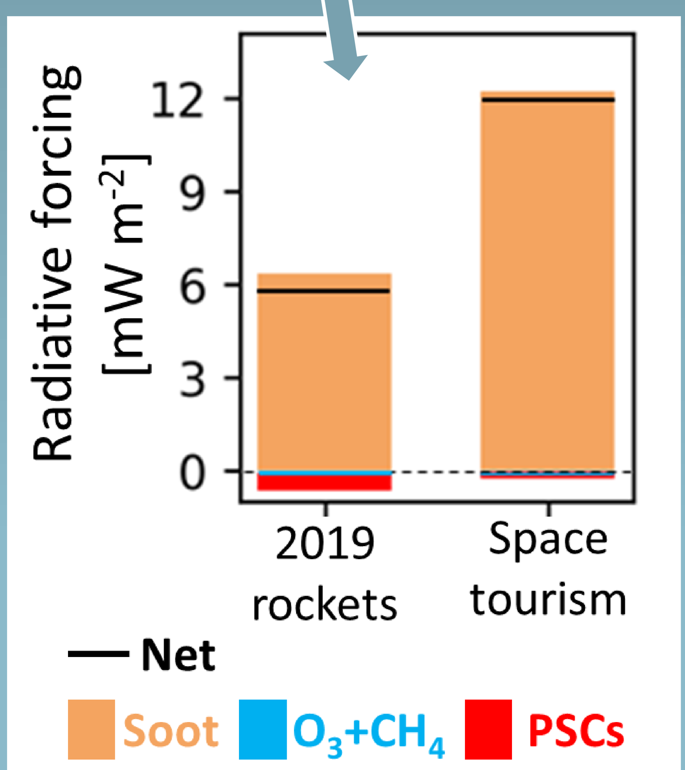
Points are springtime monthly averages; October for NH, March for SH

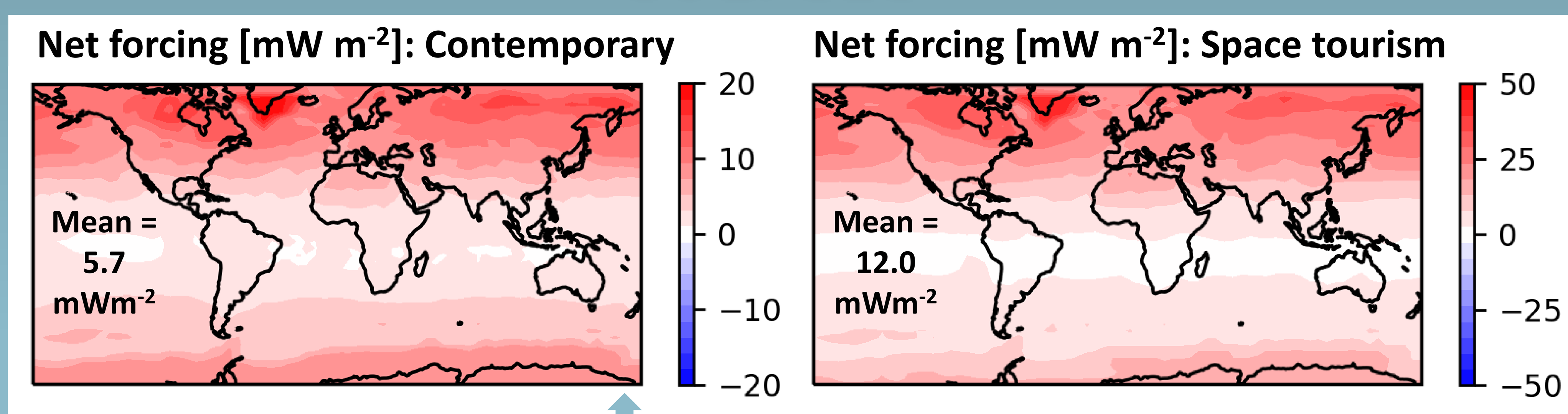
Annual and zonal mean O_3 mixing ratio changes for the contemp. and space tourism scenarios



Rocket soot warms the atmosphere 600 times more efficiently than soot from other sources

Warming is due to soot (black carbon). O_3 and CH_4 depletion and enhanced polar stratospheric clouds (PSCs) and cause a slight cooling.





Global distribution of radiative forcing changes. Soot emitted to the stratosphere accumulates at mid-high latitudes. Warming is greatest in the NH which receives most of the emissions

The high warming efficiency of rocket soot is because rockets release soot directly into the stratosphere.

Radiative forcing (RF) normalized by emitted soot mass is 20.7 mW m^{-2} a^{-1} Tg^{-1} for all other sources (Dong et al., *GRL*, 2019). In both simulation scenarios, rocket soot RF exceeds 12,000 mW m^{-2} a^{-1} Tg^{-1} . Rocket soot produces 9% of the global soot RF despite making up <0.001% of the emissions.

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