

The Billionaire Space Tourism Race Could be One Giant Leap for Air Pollution

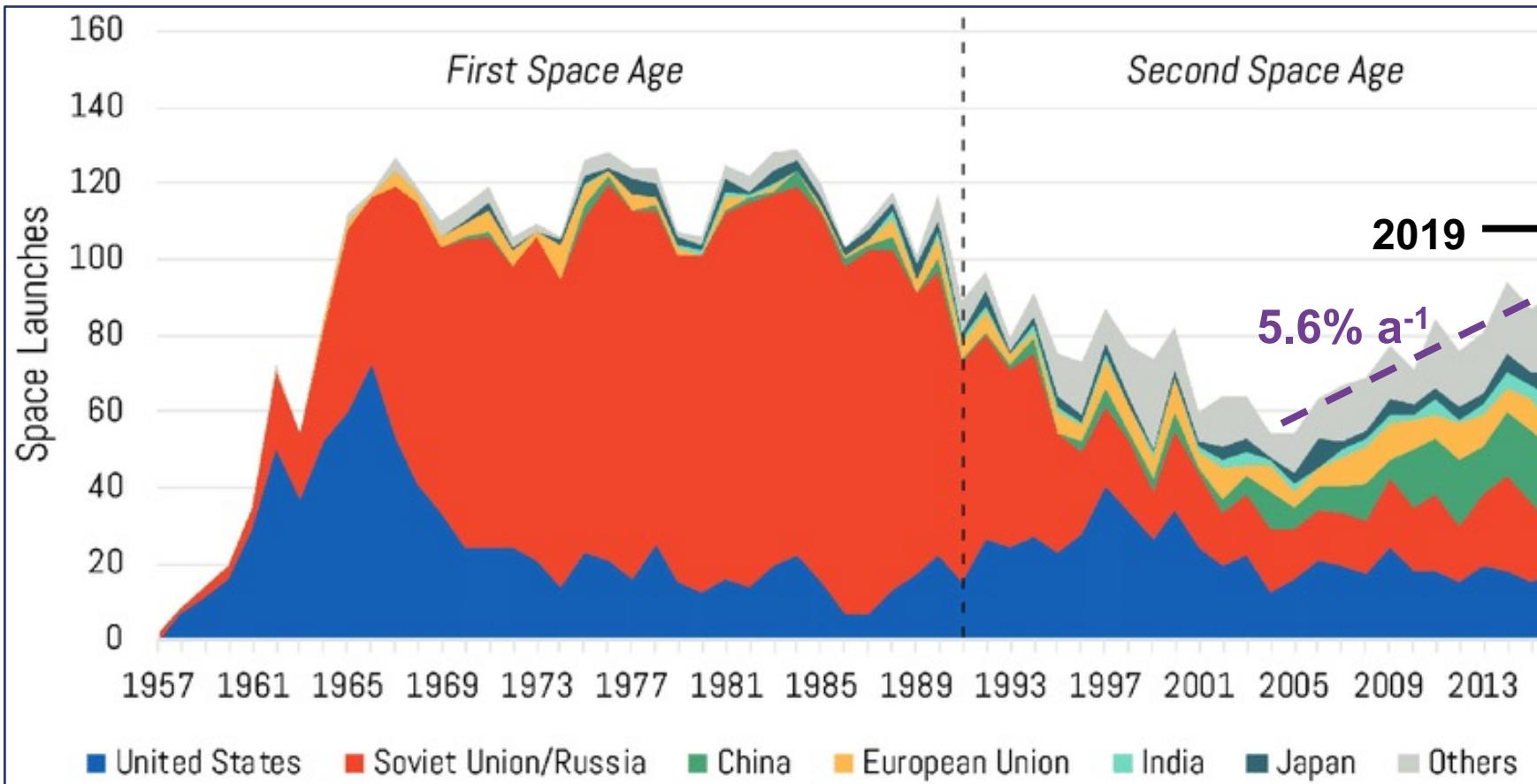


With: Rob Ryan (UCL), Chloe Balhatchet (U. Cambridge), Seb Eastham (MIT)

The Modern Space Sector

Space industry no longer dominated by Russia and the US. Increasingly diverse.

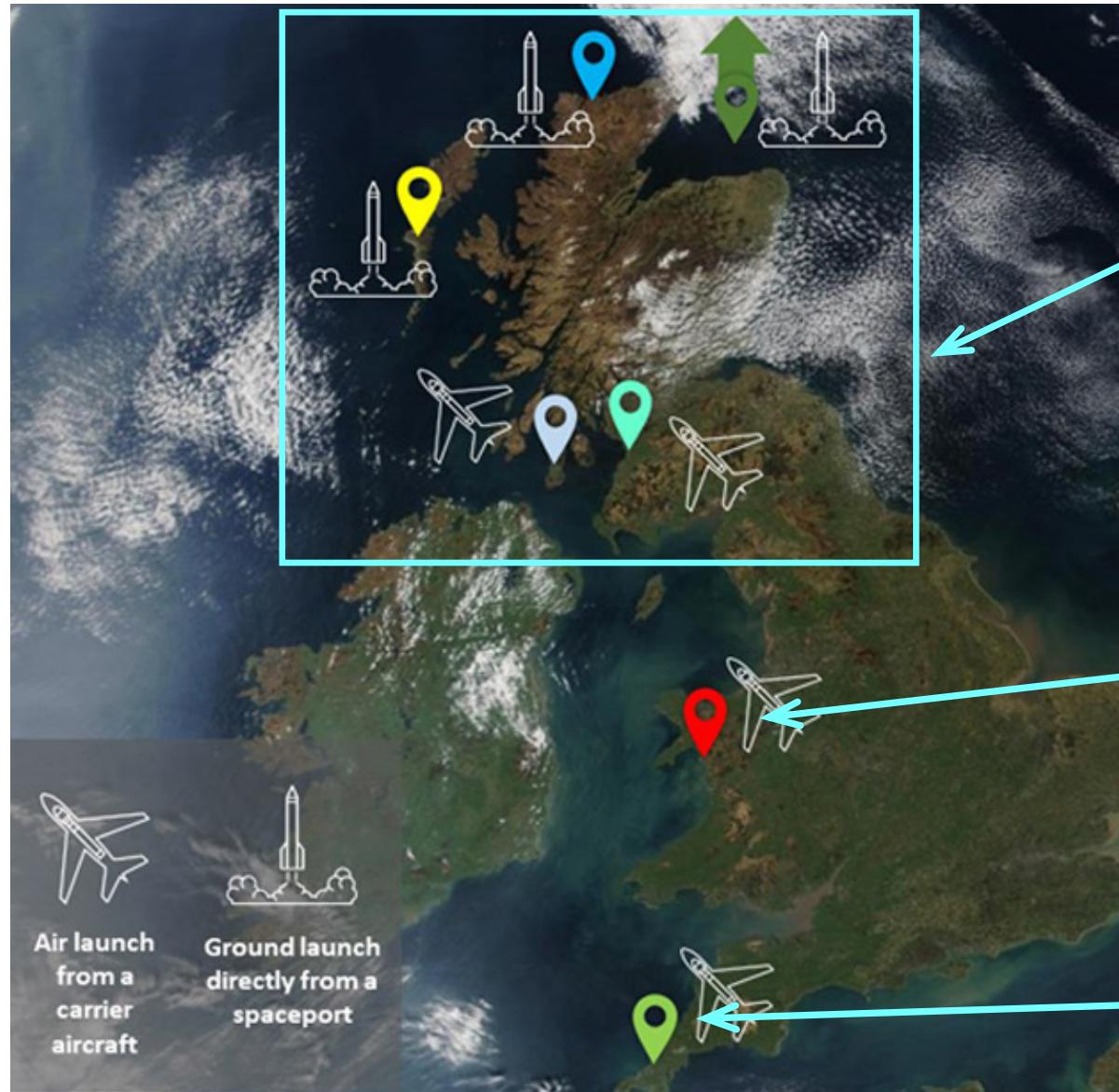
Space launches by country since dawn of space race



Source: <http://dx.doi.org/10.13140/RG.2.2.15240.11525>

The Modern Space Sector

Even the UK has joined the race!



Operational from 2022

Source: UK Space Agency

The Modern Space Sector

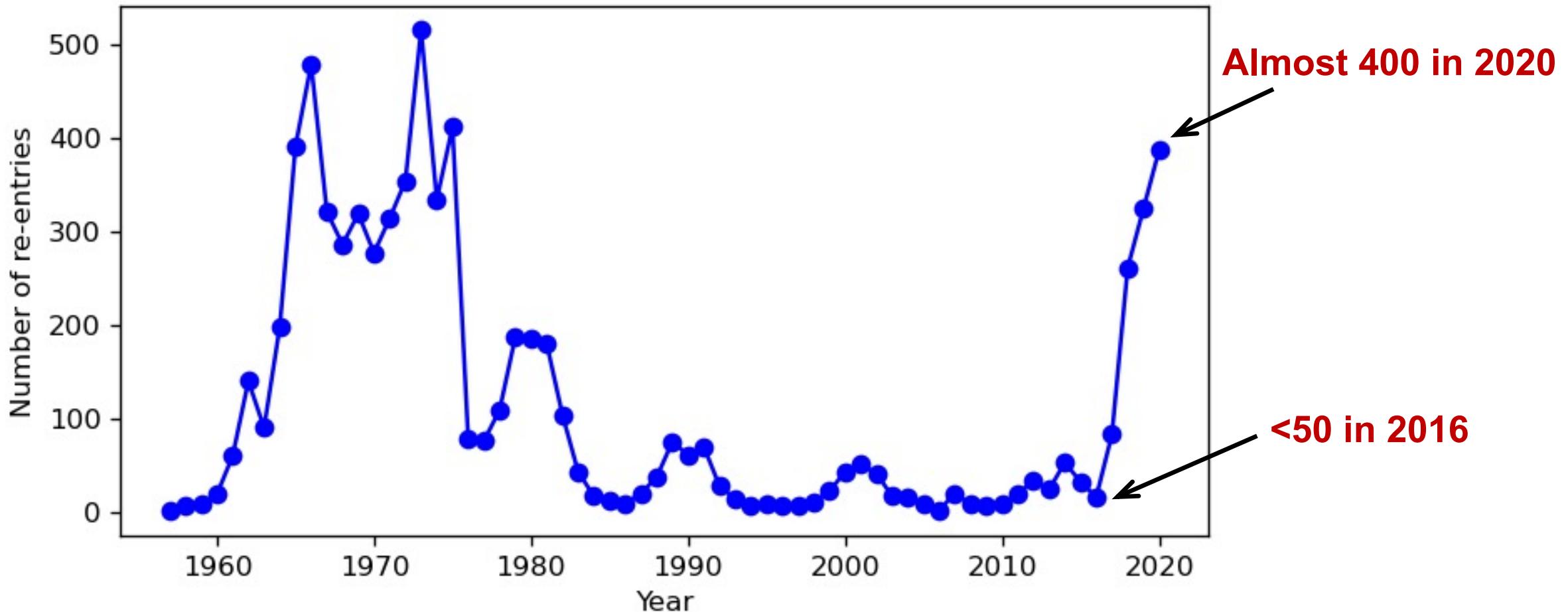
Space is littered with discarded rocket parts, spent satellites and other junk



Source: <https://www.nature.com/articles/d41586-021-02167-5>

The Modern Space Sector

Recent surge in returning space debris and reusable components



Plot generated with data from ESA (<https://discosweb.esoc.esa.int/>)

The Modern Space Sector

Reusable components includes vehicles transporting people and rocket stages

The NASA Space Shuttle



SpaceX Reusable Booster



The Modern Space Sector

Pollution produced during launch and during re-entry ablation

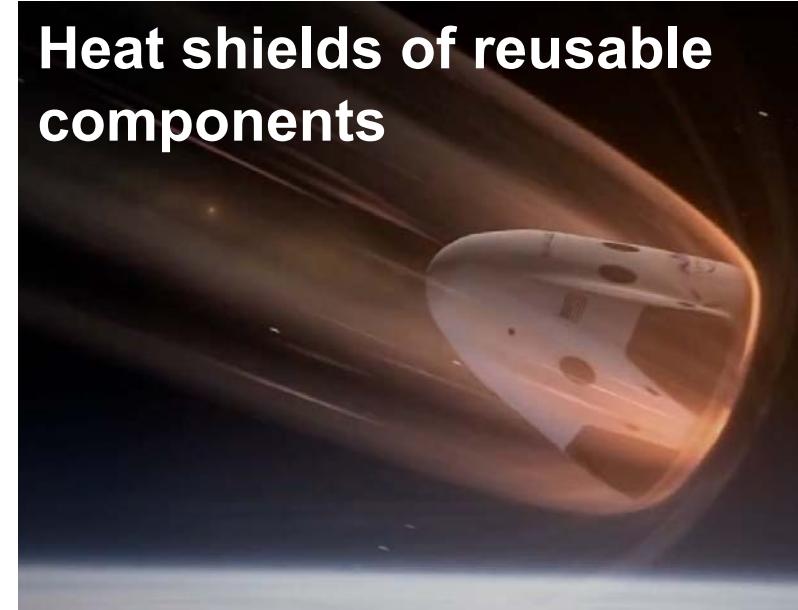
Combustion of rocket propellant



Propellant = fuel + oxidizer

High temperature re-entry ablation

Heat shields of reusable components



Burn-up of junk

Space Tourism

Costly (>\$20 million) trips to the International Space Station in 2001-2009



Ubuntu developer
Mark Shuttleworth
on the ISS in 2002

Revived again in 2021

Space Tourism

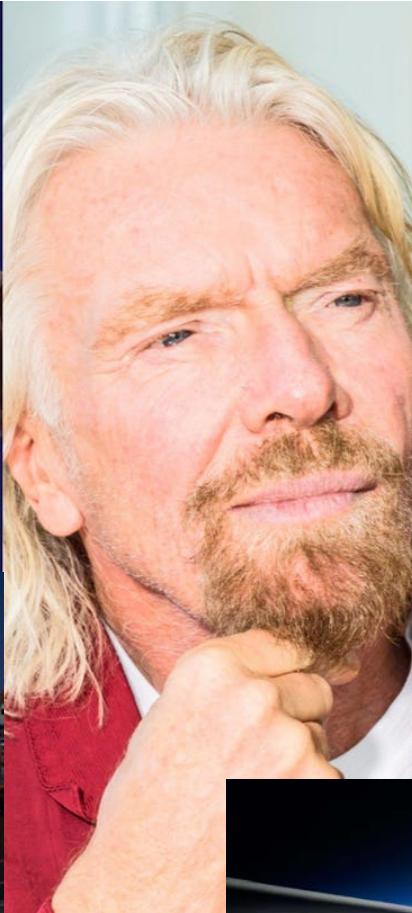
New era of billionaire space tourism



SpaceX



Blue Origin



Virgin Galactic



Space Tourism

Virgin Galactic Space Tourism Offering

First to conduct demonstration on 12 July 2021. Reached altitude of 86 km.



WhiteKnight carrier aircraft



VSS Unity spaceplane

Launch video on YouTube: <https://www.youtube.com/watch?v=KRsh2GsOk6E>

Space Tourism

Blue Origin Space Tourism Offering (NS-16)

Reusable rocket and space pod

Reached 105 km (past Karman line) on anniversary of moon landing (21 July). 2 more launches since.

Tourists: Wally Funk, William Shatner, ABC host



New Shephard launch vehicle and pod



Launch video on YouTube: <https://www.youtube.com/watch?v=tMHhXzpwwU>

Space Tourism

SpaceX Space Tourism Offering (Inspirati④n)

Reusable first stage and space capsule. Discarded second stage.

Multiday trip orbiting the Earth. Demonstration mission on 16 September 2021.



Falcon 9 2-stage rocket



Crew Dragon Resilience Capsule

Launch video on YouTube: <https://www.youtube.com/watch?v=ly9t1G5dKvc>

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

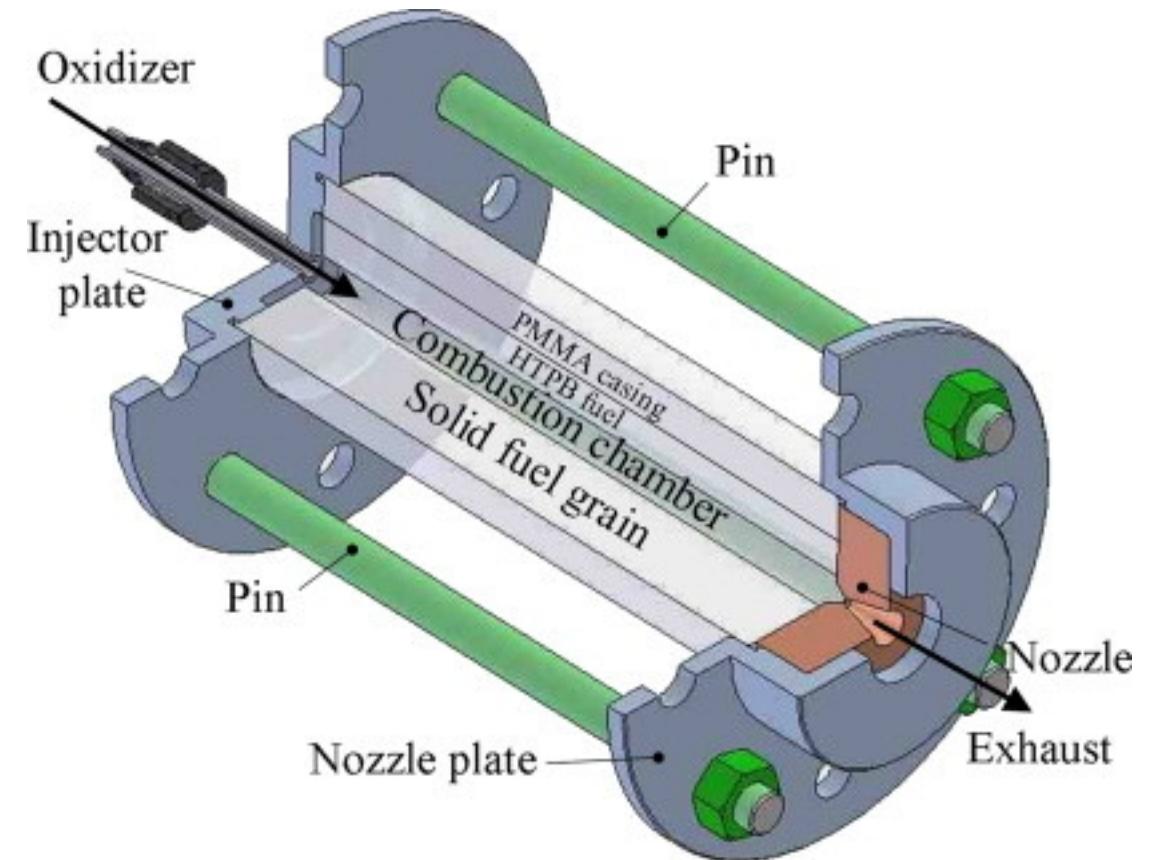
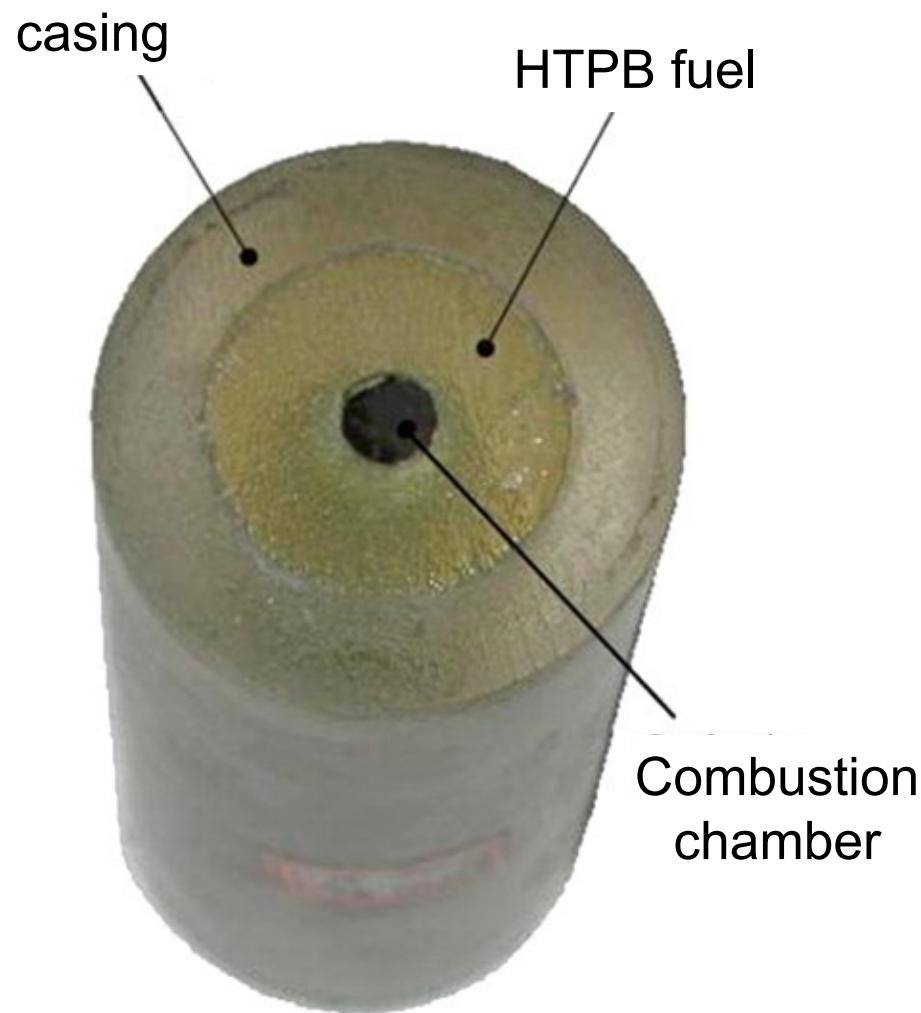


Liquid:

kerosene +
liquid oxidizer (O_2)

Carbon-based fuel

hydroxyl-terminated poly-butadiene (HTPB) Fuel



Source: <https://www.sciencedirect.com/science/article/pii/S0094576512004936>

Air Pollution from Rocket Launches

Type of propellant determines mix of air pollutants produced

Virgin Galactic



Nitrogen oxides (**NO_x**)

Water (**H₂O**)

Black Carbon (**soot** particles)

Blue Origin



Nitrogen oxides (**NO_x**)

Water (**H₂O**)

SpaceX



Nitrogen oxides (**NO_x**)

Water (**H₂O**)

Black Carbon (**soot** particles)

Nitrogen oxides (**NO_x**) and water vapour (**H₂O**) are ubiquitous

Air Pollution from Re-entry Ablation

NO_x emitted on re-entering Earth's atmosphere proportional to mass burned



Blue Origin



SpaceX



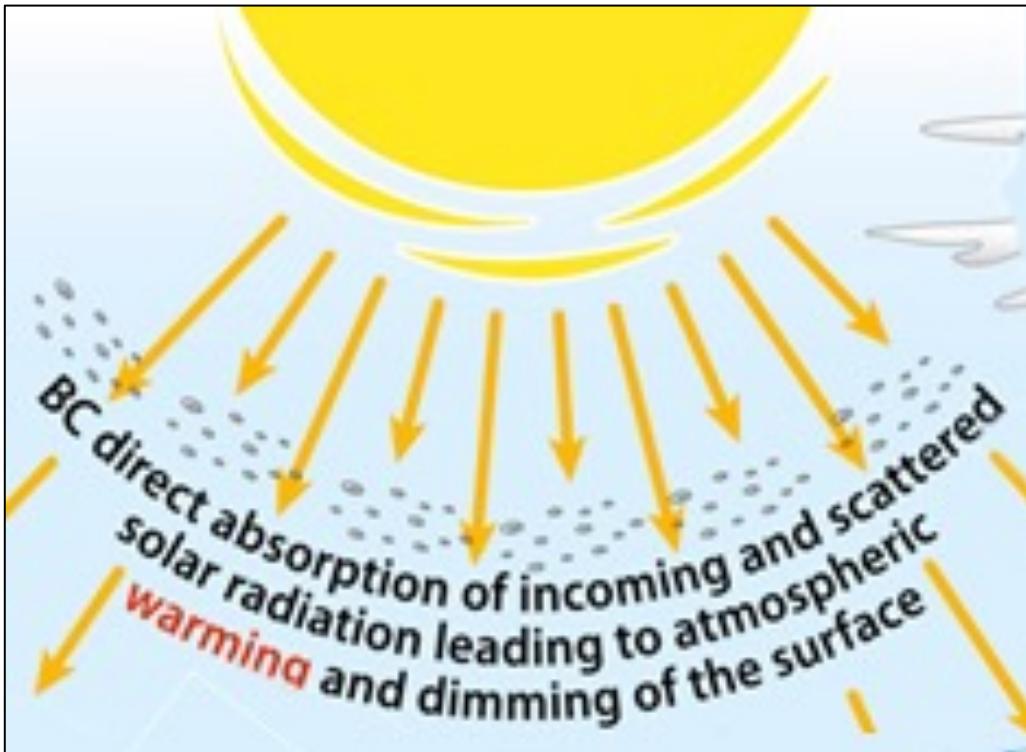
Space Tourism

Blue Origin tweet comparing their space tourism offering to Virgin Galactic's

 		
Flies above the Kármán line (internationally recognized boundary of space, 100 km)	Yes	No
Vehicle type	Rocket	High altitude airplane
Windows	Largest windows in space 42" x 28" (107 cm x 71 cm)	Airplane-sized windows
Escape system	Yes	No
Ozone layer impact*	Minimal Exhaust is water with minimal impact on environment	High Hybrid rocket engine with HTPB & nitrous oxide, 100x more harmful
Flight history	15 Safe flights	3 Flights above 80 km

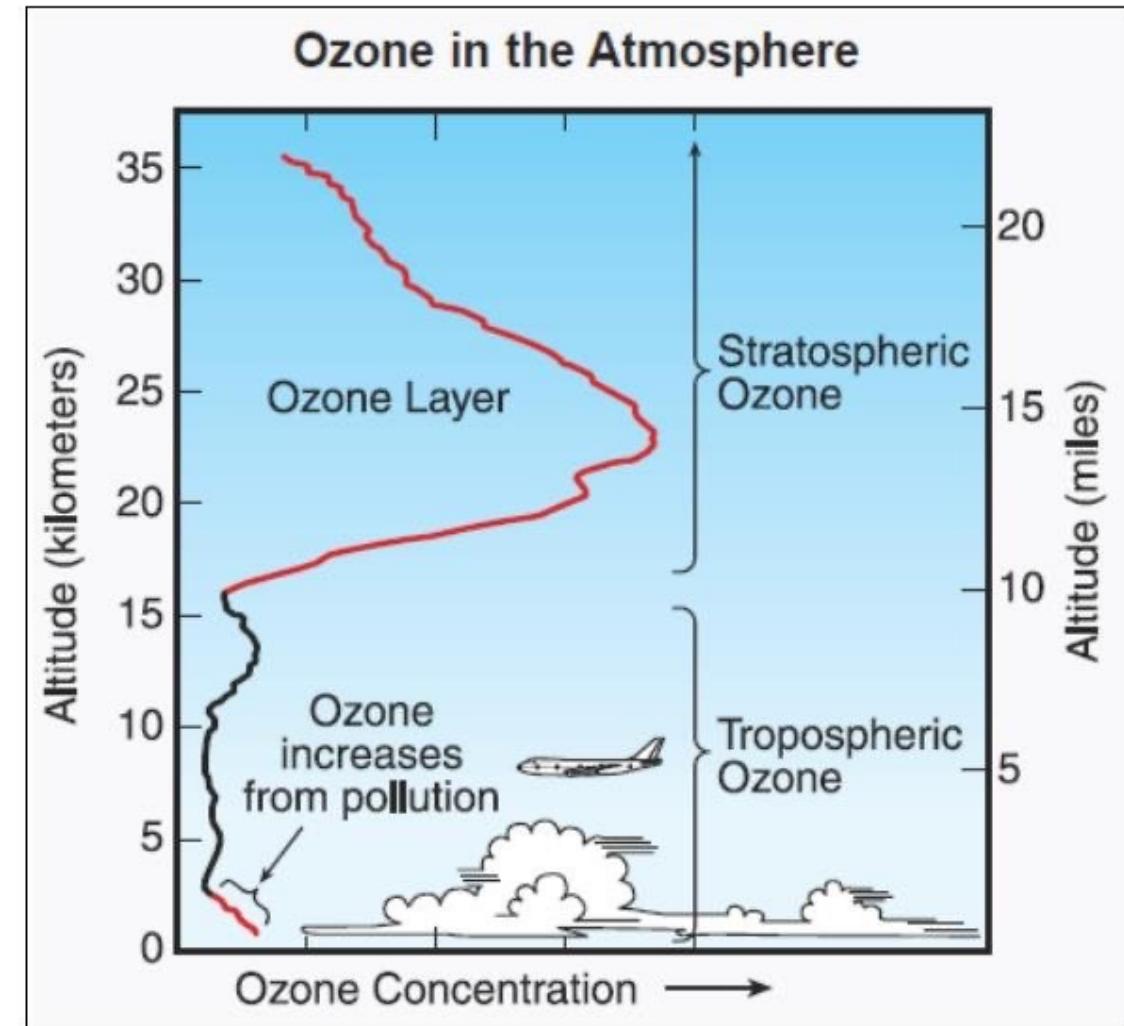
Air Pollution from Rockets

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



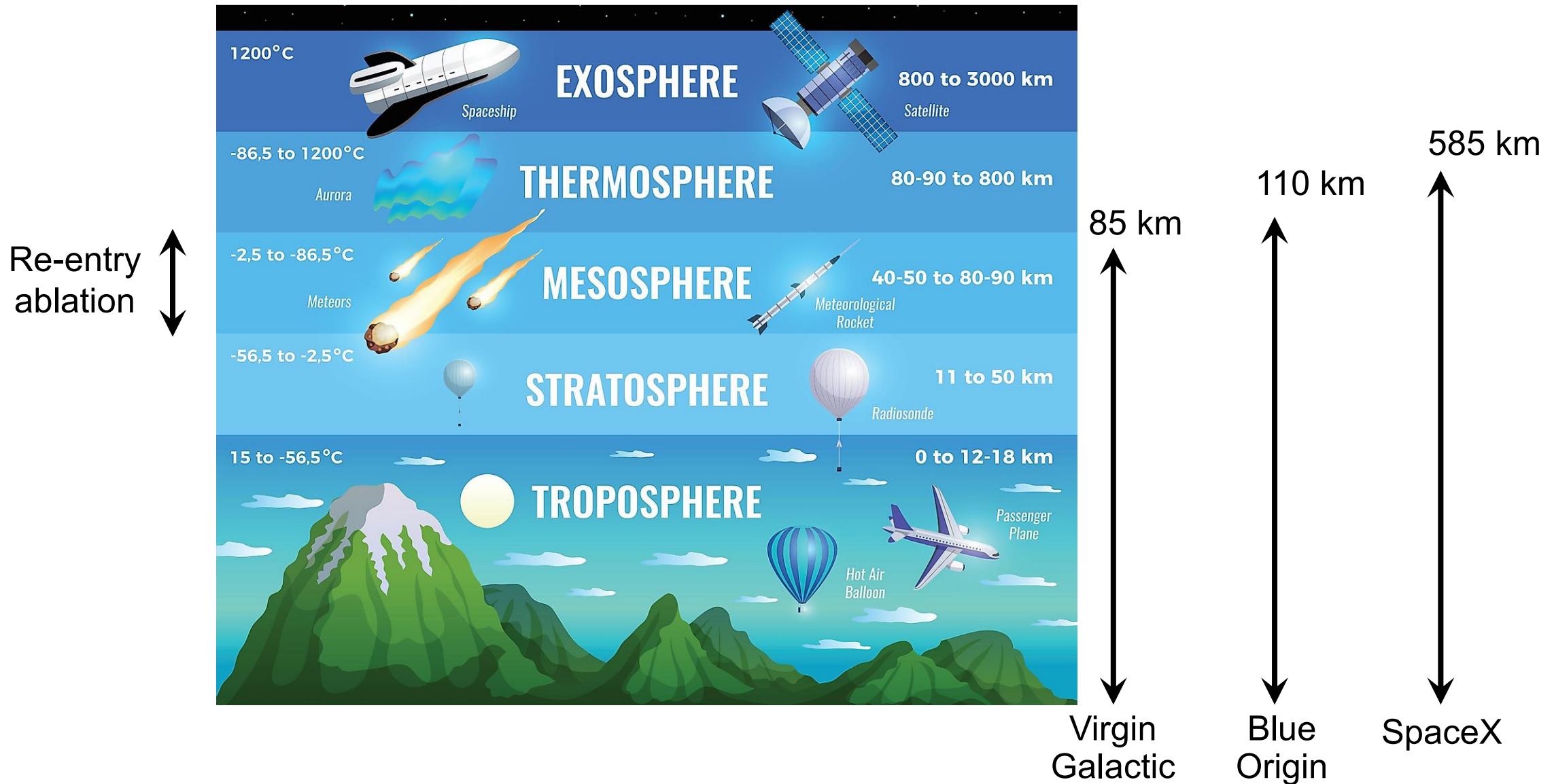
3rd largest climate warming (radiative forcing) after CO₂ and CH₄

H₂O and NO_x deplete stratospheric ozone by promoting conversion of O₃ to O₂



Air Pollution from Rockets

Additional concerns: released to multiple atmospheric layers (not regulated)



Environmental Impact

We develop an inventory of emissions for a speculative space tourism industry

Virgin Galactic



Daily Launches

Blue Origin



Daily Launches

SpaceX



Weekly Launches

Run the model for 3 simulation years needed for influence on atmosphere to establish
Also has emissions from rocket launches and re-entry ablation of rockets, reusable stages and
space junk for 2019

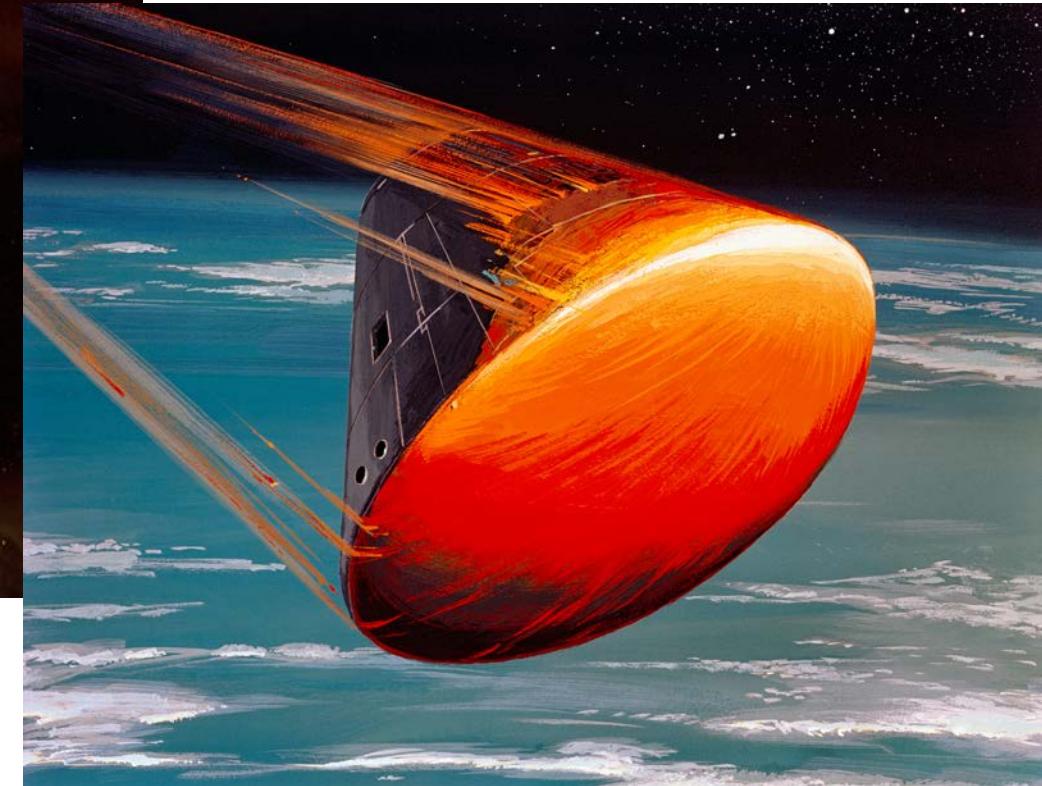
Air Pollution from Rockets

Comparison of natural (meteorites) and artificial (space industry) ablation NO_x emissions



Annual NO_x from artificial objects:
5.5 kilotonnes

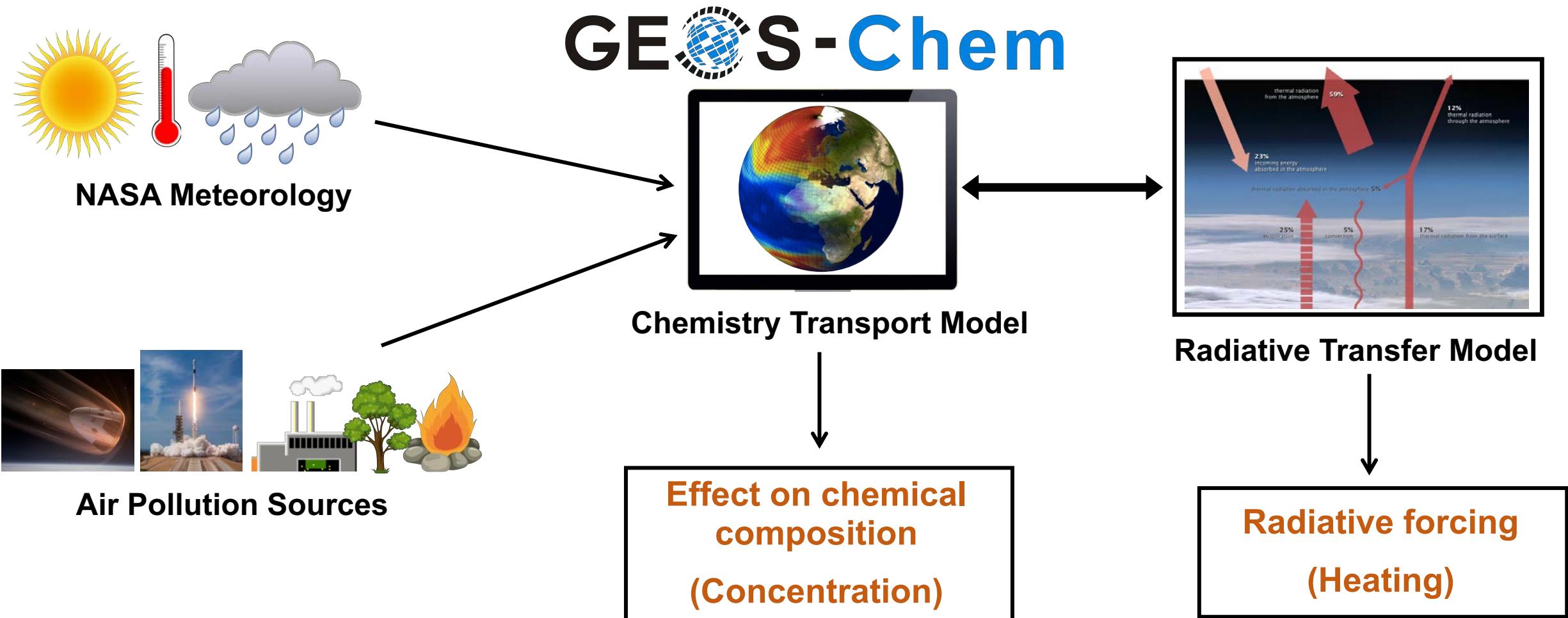
Annual NO_x from meteorites:
2-40 kilotonnes



Similar natural and artificial ablation NO_x emissions

Environmental Impact

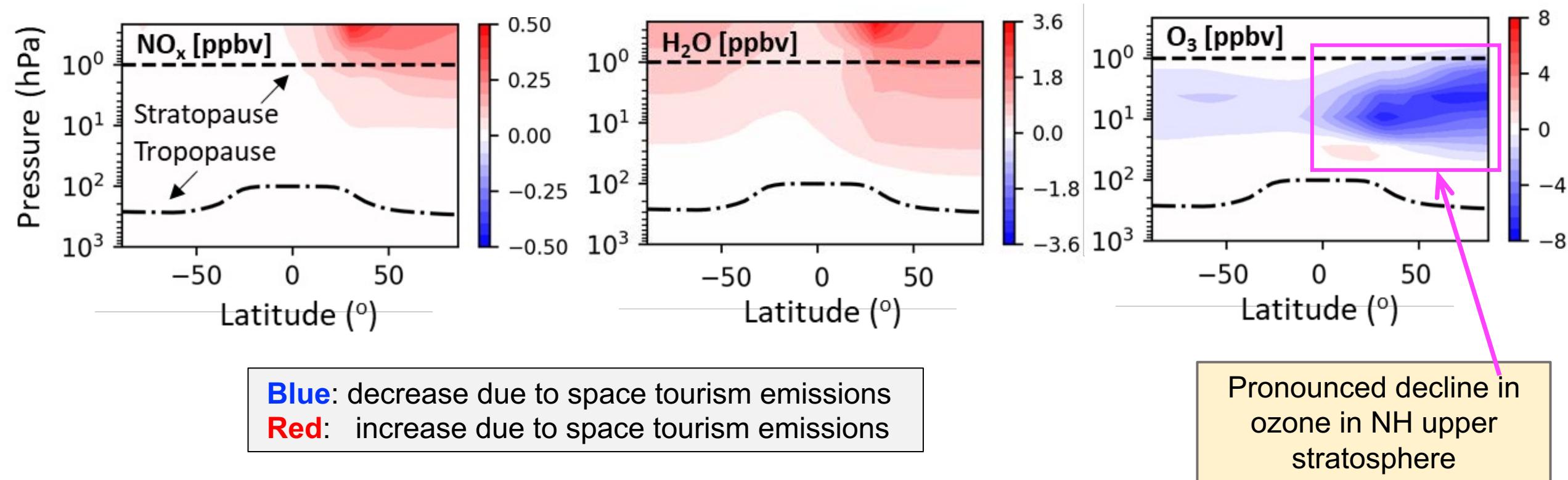
Determine impact with a 3D atmospheric chemistry transport model



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

Environmental Impact

Changes in nitrogen oxides (NO_x), water vapour (H_2O), and ozone (O_3) after 3 years of space tourism

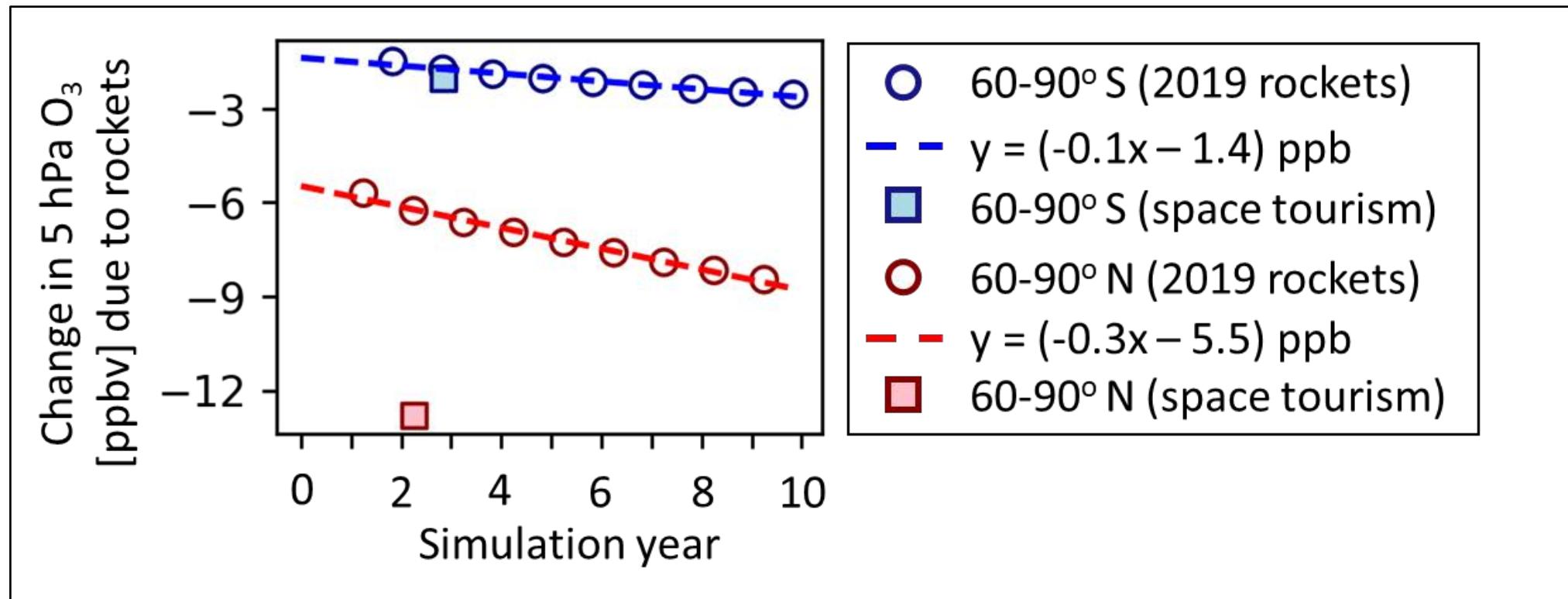


Stratospheric ozone declines by <0.1% from space tourism rockets. Much less than 1-2% from Earth-bound ozone-depleting substances

The effect throughout the stratosphere is small.

Environmental Impact

Modelled depletion of NH springtime upper stratospheric ozone of **16 ppb per decade** due to space tourism air pollutant emissions



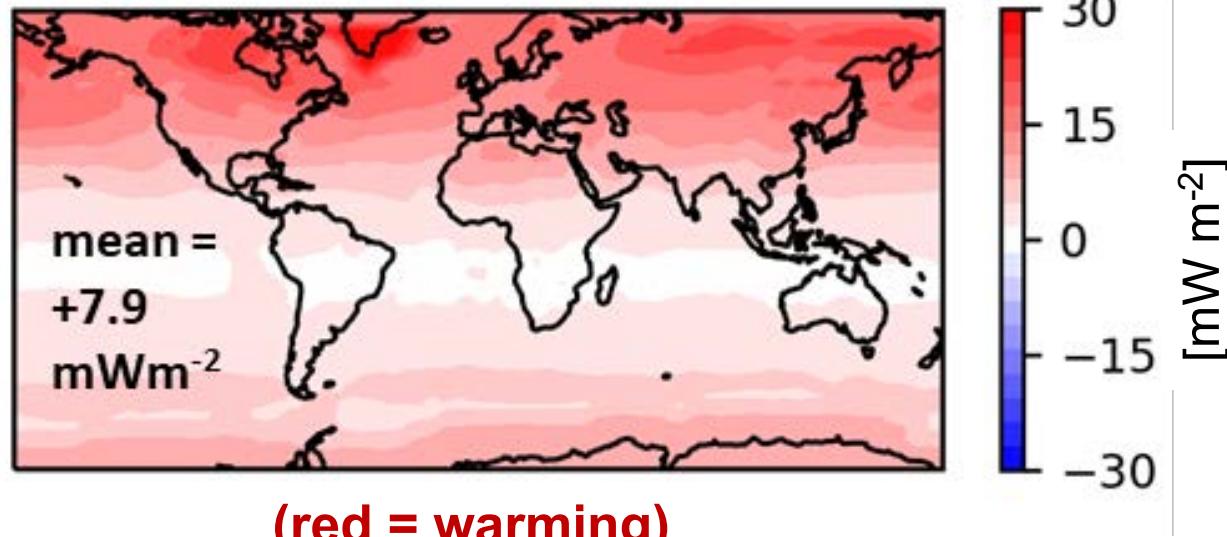
Potential to **reverse 20% of the recovery in stratospheric ozone** in this region that is attributed to the **Montreal Protocol** ban on ozone depleting substances

It could take 10 years to undermine 35 years of progress!

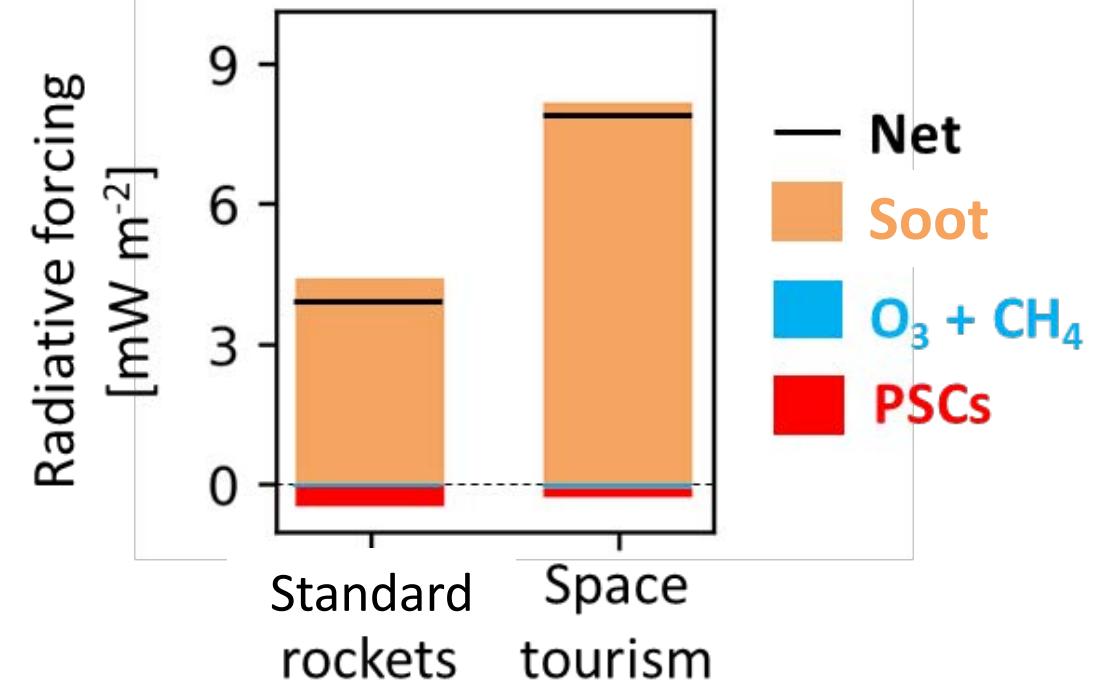
Environmental Impact

Radiative forcing (warming) due to black carbon (soot) emissions from rockets

Spatial distribution of radiative forcing due to space tourism emissions



Radiative forcing dominated by soot



6% of global warming due to all Earth-bound soot sources, but negligible (<0.001%) contribution to emissions

Rocket soot emissions 500-times more efficient at warming than surface sources

Implications of a formidable space tourism industry

- **Artificial** ablation emissions may **outcompete natural** emissions from meteorites
- Space tourism air pollutant emissions from launches and ablation have potential to **undermine** progress achieved with the **Montreal Protocol**
- Large **warming efficiency** of soot particles from rocket launch emissions (500-times more than Earth-bound sources). Small growth could have large implications.
- Lots of **room for improvement** to our work:
 - better knowledge of future launch frequencies
 - missing other chemicals formed during launch and ablation
 - only account for direct forcing
- Regardless, no **international regulation** exists.
- It's crucial that we act now to formulate regulation that minimizes harmful impact of a space tourism industry of the rich on the environment for the many.

More about other policy-relevant research in my group here:
<https://maraisresearchgroup.co.uk/>

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