

Potential influence of a formidable space tourism industry on stratospheric ozone and climate



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Space Tourism is not New

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

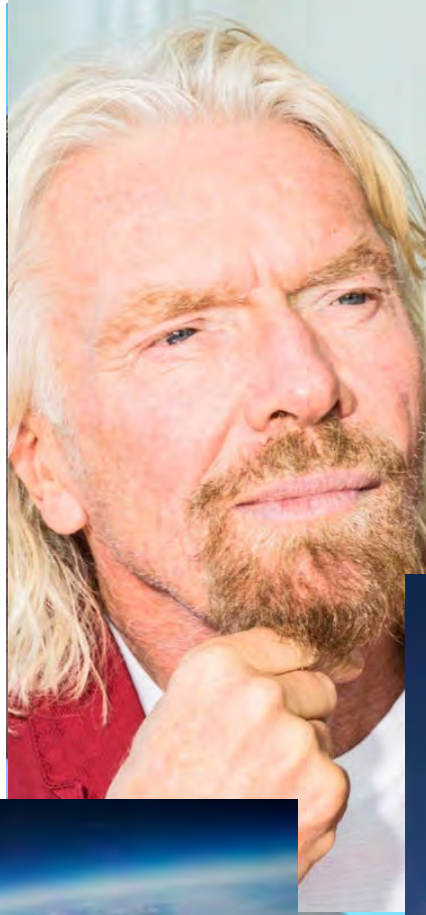


Ubuntu developer
Mark Shuttleworth
on the ISS in 2002

Revived again in 2021

Space Tourism Demonstrations in 2021

Modern space race era of billionaire space tourism



Virgin Galactic



Blue Origin



SpaceX



Virgin Galactic Demonstration

Virgin Galactic

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



WhiteKnight carrier aircraft

Hybrid:

solid fuel (HTPB) +
liquid oxidizer (N_2O)



VSS Unity spaceplane

Blue Origin Demonstration

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).



Cryogenic:

liquid fuel (H_2) +
liquid oxidizer (O_2)



New Shepard launch vehicle and pod

SpaceX Demonstration

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.



Liquid:
kerosene +
liquid oxidizer (O_2)

Falcon 9 2-stage rocket



Crew Dragon Resilience Capsule

Air Pollution from Space Tourism Rocket

Virgin Galactic



Carbon-based fuel

Nitrogen oxides (NO_x)

Water vapor (H_2O)

Black Carbon particles (**BC**)

Blue Origin



No carbon in fuel

NO_x

H_2O

NO_x and H_2O are ubiquitous

SpaceX



Carbon-based fuel

NO_x

H_2O

BC

Air Pollution from Re-entry

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



Blue Origin

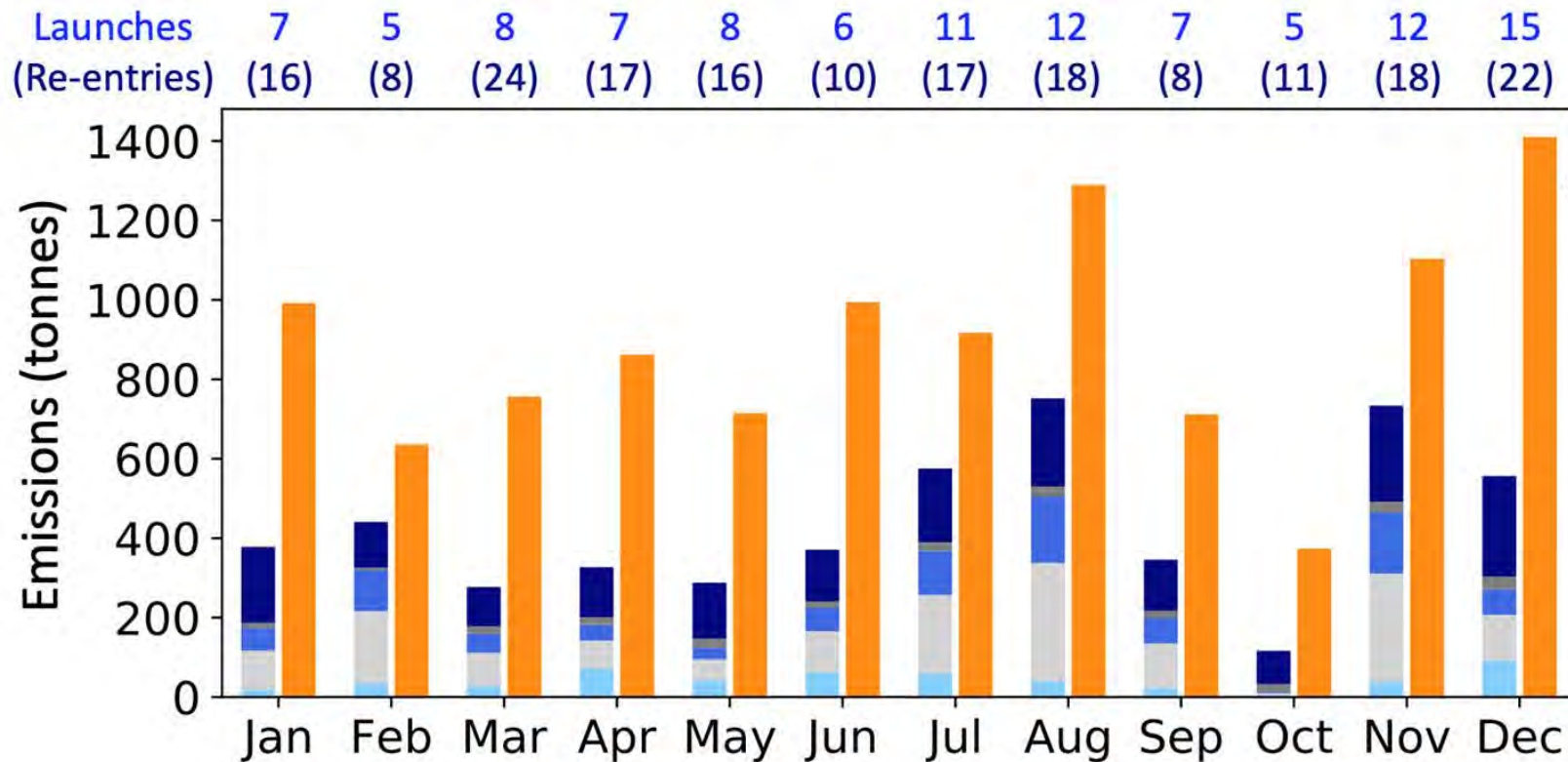


SpaceX









Air Pollution Emissions Totals

Monthly air pollutant emissions for 2019 launches



2019 + space tourism totals

Pollutant (2019 + space tourism)	
	H ₂ O: (10.7 + 30.4) Gg
	BC: (0.5 + 1.0) Gg
	Al ₂ O ₃ : (1.6 + 0) Gg
	HCl+Cl: (0.9 + 0) Gg
	↑ NO _x : (0.2 + 1.6) Gg
	↓ NO _x : (1.9 + 0.7) Gg

Detailed description of 2019 launch and re-entry emissions in Ryan et al. (2022):
<https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021EF002612>

Space tourism emissions 3-times more than 2019 emissions for H₂O, double for BC, similar for total NO_x

Vertically Distribute Emissions for Input to 3D Model

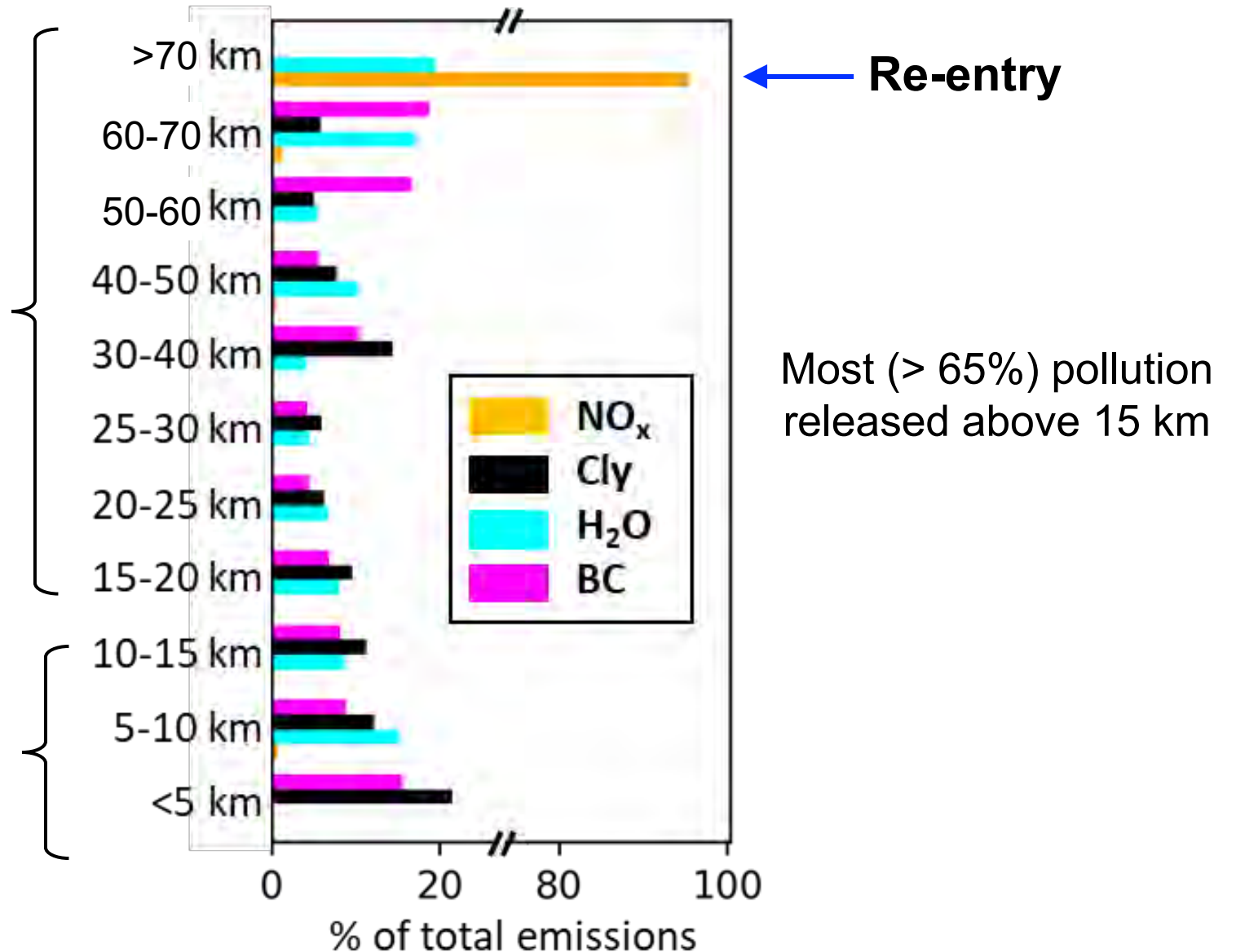
80 km: model ceiling

Stratosphere & mesosphere:

lifetime >2 years
(*gravitational settling*)

Troposphere:

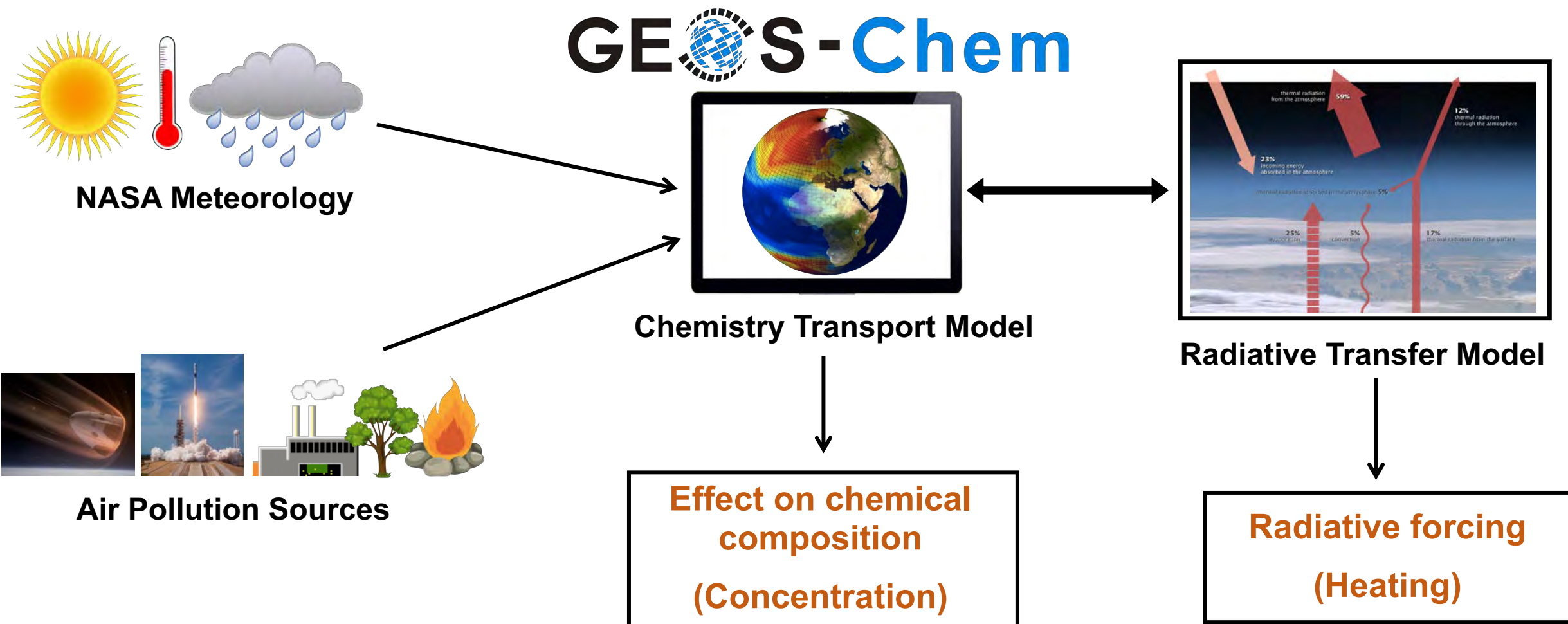
lifetime weeks to months
(*wet and dry deposition,
subsidence, chemical losses*)



Vertical profiles mapped using propellant mass consumption profiles of Ross and Sheaffer (2014)

Emissions Implemented in the GEOS-Chem Model

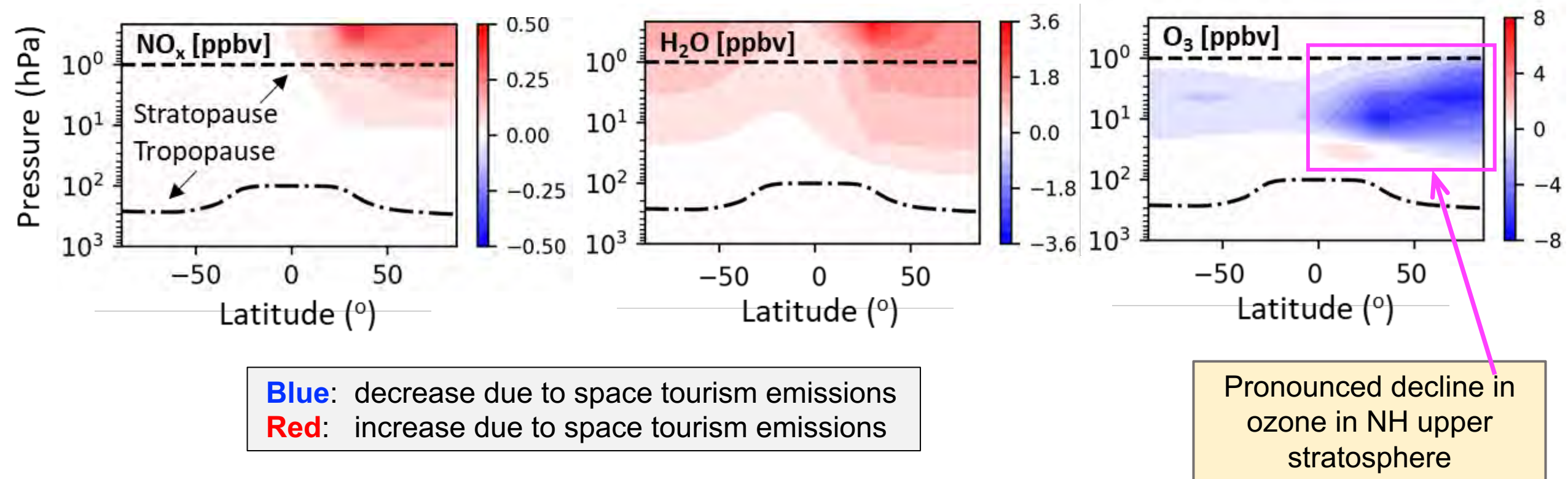
Conduct 3-year long simulation for atmospheric influence to establish



To find out more about GEOS-Chem: <https://geoschem.github.io/>

Changes in Atmospheric Composition

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

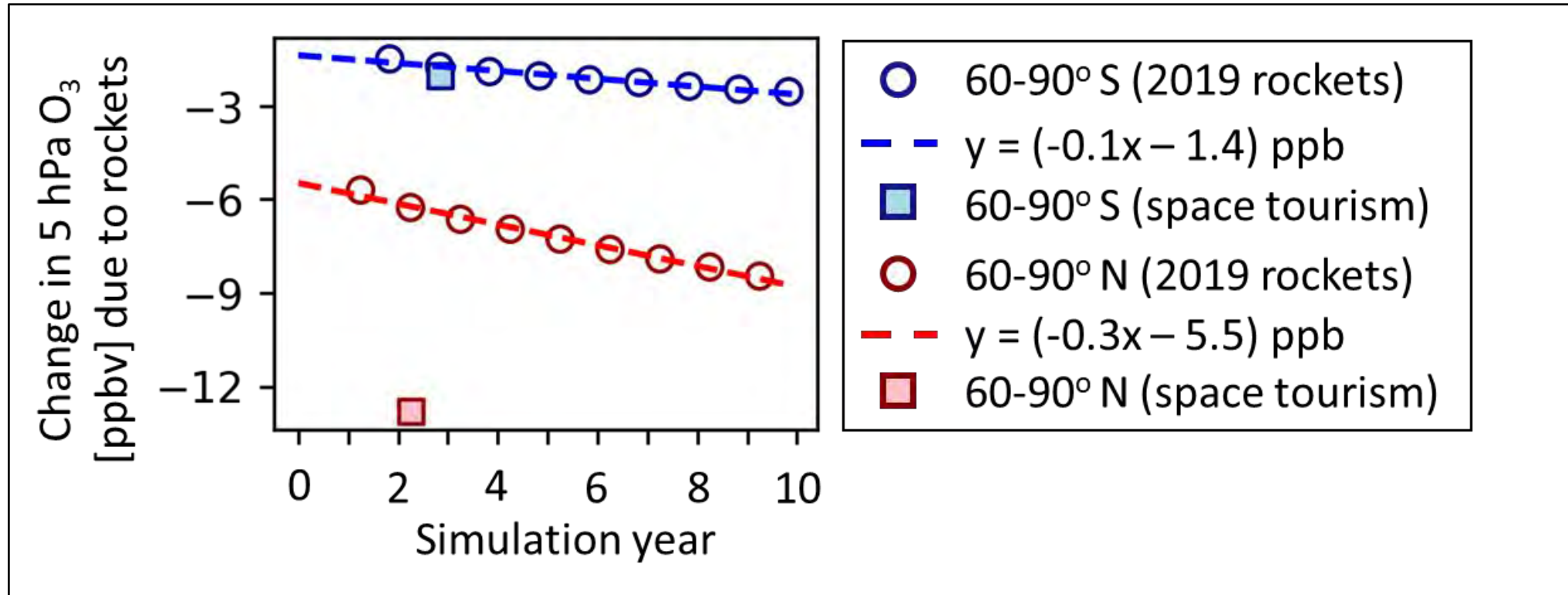


Overall, stratospheric ozone declines by **<0.1%** from space tourism rockets. Much less than **1-2%** from Earth-bound ozone-depleting substances

The effect throughout the stratosphere is small.

Springtime Polar Stratospheric Ozone Depletion

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

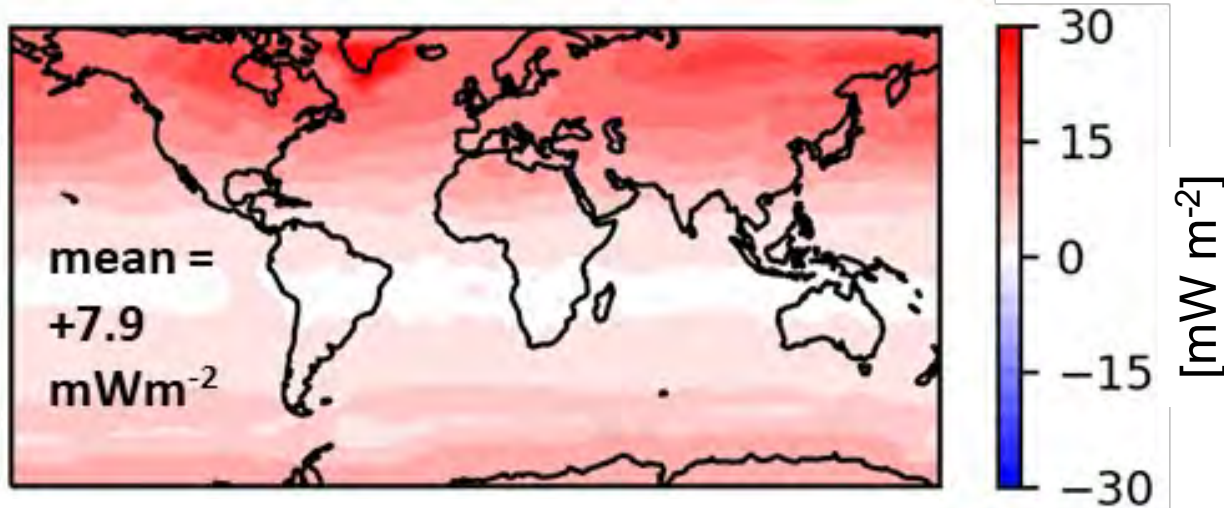


Potential for modest growth and routine space tourism launches to **reverse 20% of the recovery in stratospheric ozone** in NH attributed to **Montreal Protocol** ban on ODS

Top-of-Atmosphere Warming

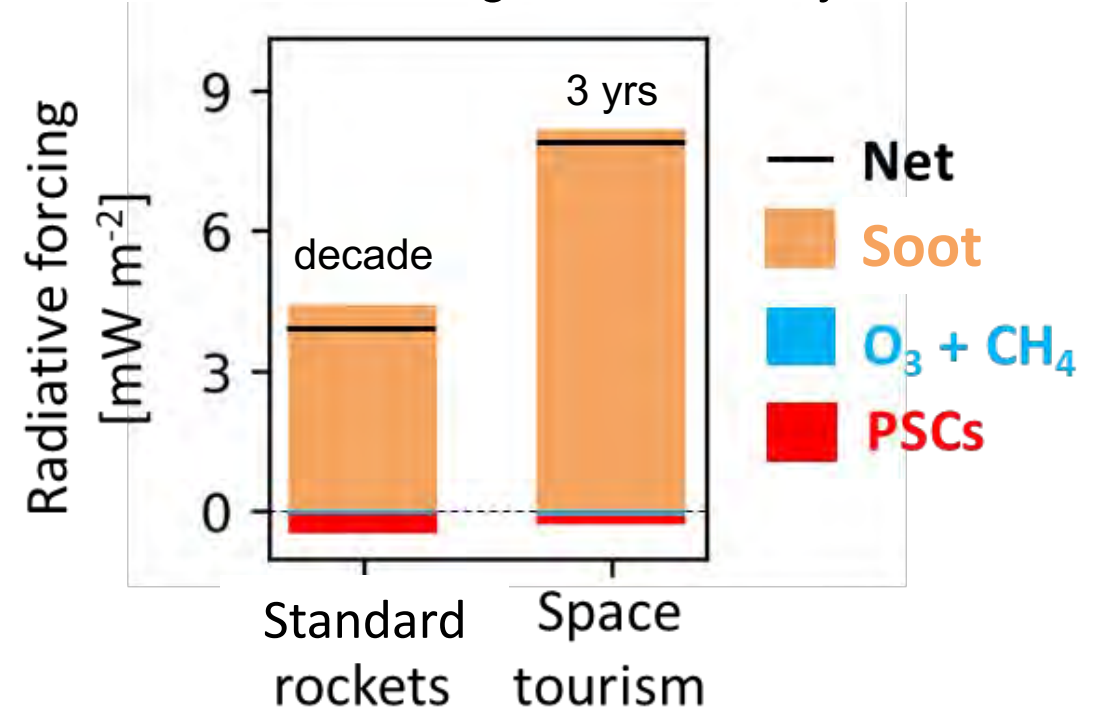
Radiative forcing (warming) due to black carbon (BC) emissions from rockets

Net radiative forcing due to space tourism
and 2019 emissions



(red = warming)

Radiative forcing dominated by BC



Net warming from standard and space tourism rockets is **6%** of global warming of all Earth-bound BC sources, but negligible (**0.02%**) contribution to emissions

Rocket BC emissions 500-times more efficient at warming top of atmosphere than surface sources

Implications of a Formidable Space Tourism Industry

- No international **regulation** exists to mitigate harm of space tourism to environment
- Greenwashing rampant (unsubstantiated / false / incorrect sustainability pledges)
- Bogus science experiments used to motivate space tourism flights
- Routine space tourism launches could **undermine** progress achieved with the **Montreal Protocol**
- Large **warming efficiency** of BC from rocket launch emissions (500-times more than Earth-bound sources), so modest growth could have large implications.
- Major challenge is validating model results
- Space tourism industry hasn't really materialized:
 - Blue Origin has had 5 more crewed launches
 - SpaceX has sent tourists to the ISS
 - Virgin Galactic had 7 more flights in 2023. And is still selling tickets.
 - Many other activities proposed: edge of space balloon rides, space hotels, commercial space station