The impact of rockets on climate and stratospheric ozone

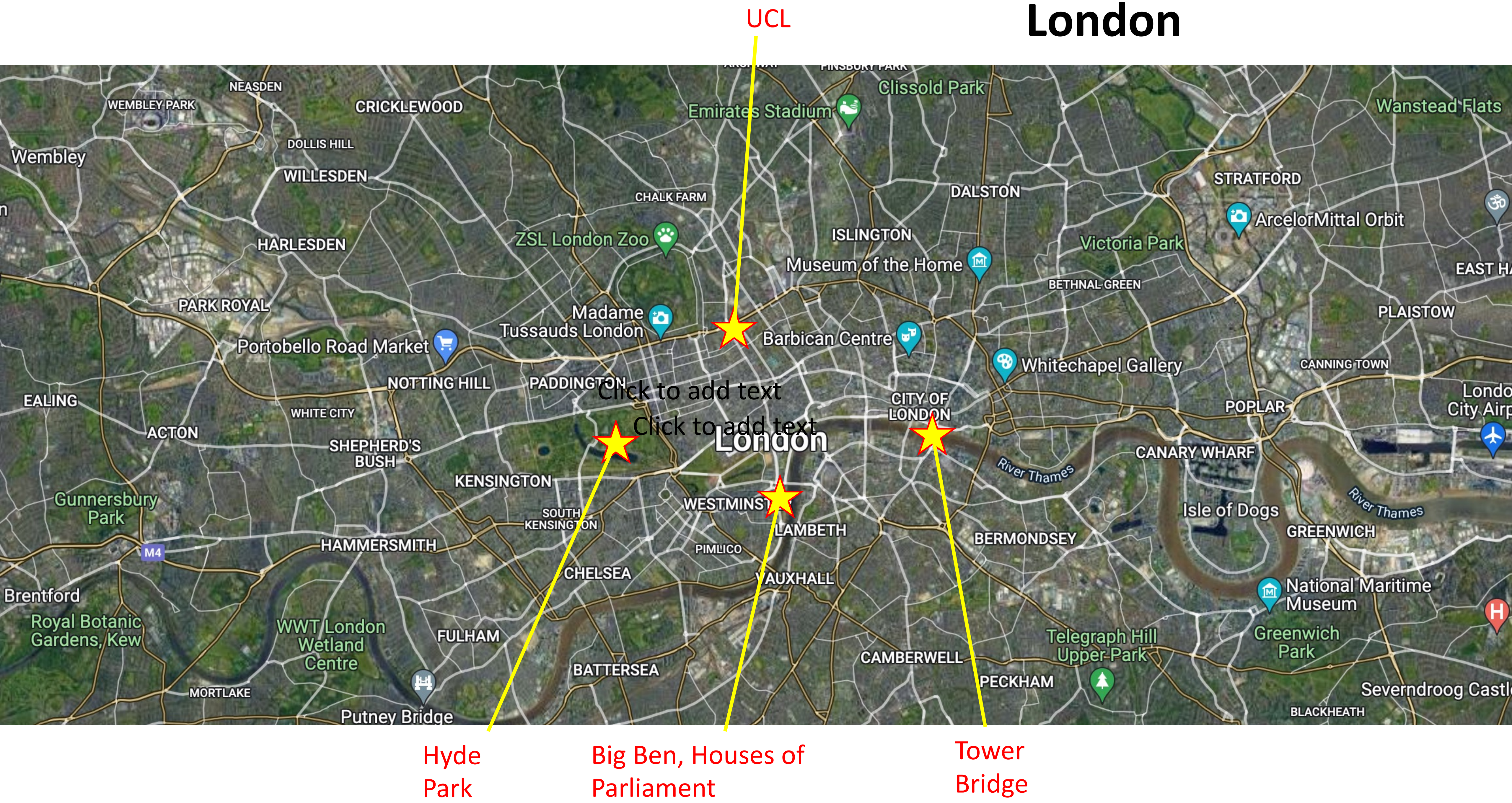
and

Upper tropospheric NO_x

an update from London

Rob Ryan, visiting University of Melbourne April 2022

London


UCL
NEASDEN
WEMBLEY PARK
CRICKLEWOOD
Emirates Stadium
Clissold Park
Wanstead Flats
Wembley
DOLLIS HILL
WILLESDEN
CHALK FARM
DALSTON
STRATFORD
ArcelorMittal Orbit
HARLESDEN
ZSL London Zoo
ISLINGTON
Museum of the Home
Victoria Park
BETHNAL GREEN
PARK ROYAL
Madame Tussauds London
Barbican Centre
PLAISTOW
Portobello Road Market
Whitechapel Gallery
CANNING TOWN
EALING
NOTTING HILL
PADDINGTON
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London
CITY OF LONDON
POPLAR
WHITE CITY
ACTON
SHEPHERD'S BUSH
CANARY WHARF
River Thames
KENSINGTON
WESTMINSTER
Isle of Dogs
River Thames
Gunnersbury Park
SOUTH KENSINGTON
LAMBETH
BERMONDSEY
GREENWICH
M4
HAMMERSMITH
PIMLICO
CHELSEA
VAUXHALL
Brentford
National Maritime Museum
Royal Botanic Gardens, Kew
WWT London Wetland Centre
FULHAM
Telegraph Hill Upper Park
Greenwich Park
CAMBERWELL
BATTERSEA
PECKHAM
MORTLAKE
Severndroog Castle
BLACKHEATH
Putney Bridge
Hyde Park
Big Ben, Houses of Parliament
Tower Bridge

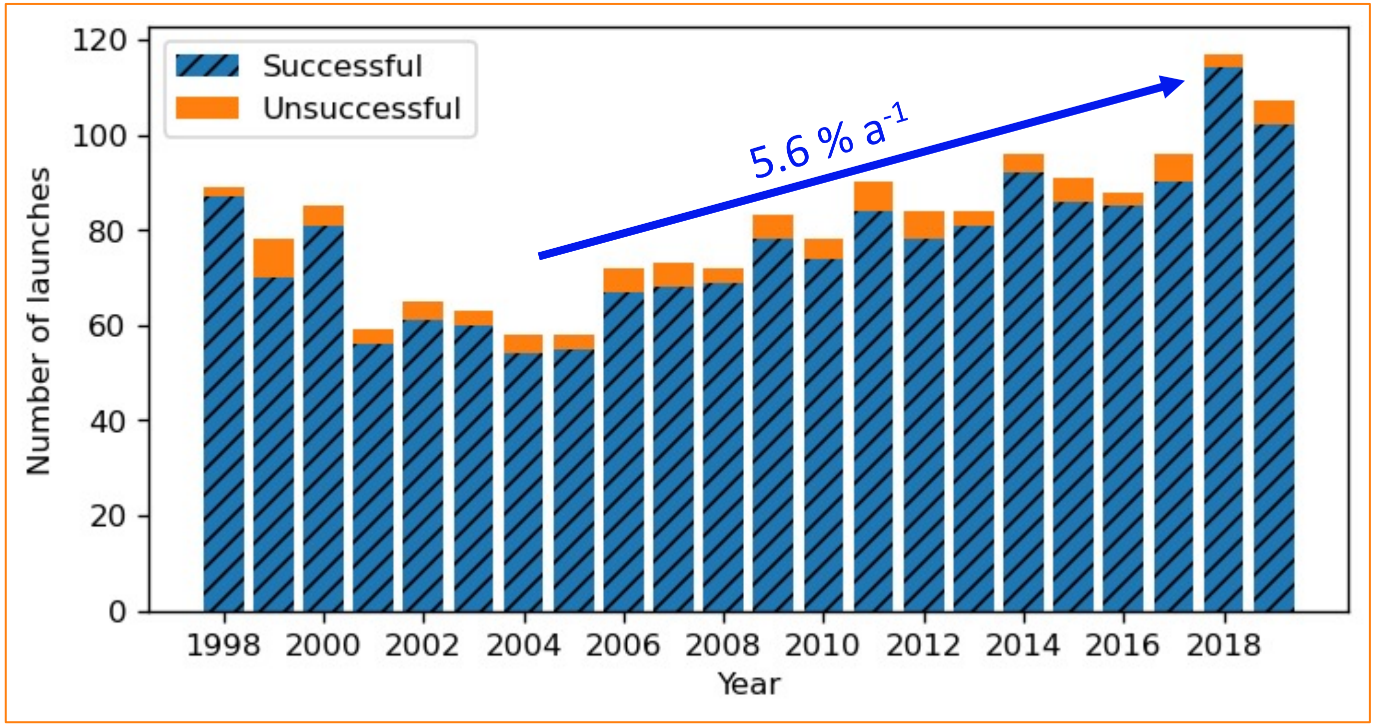

UCL

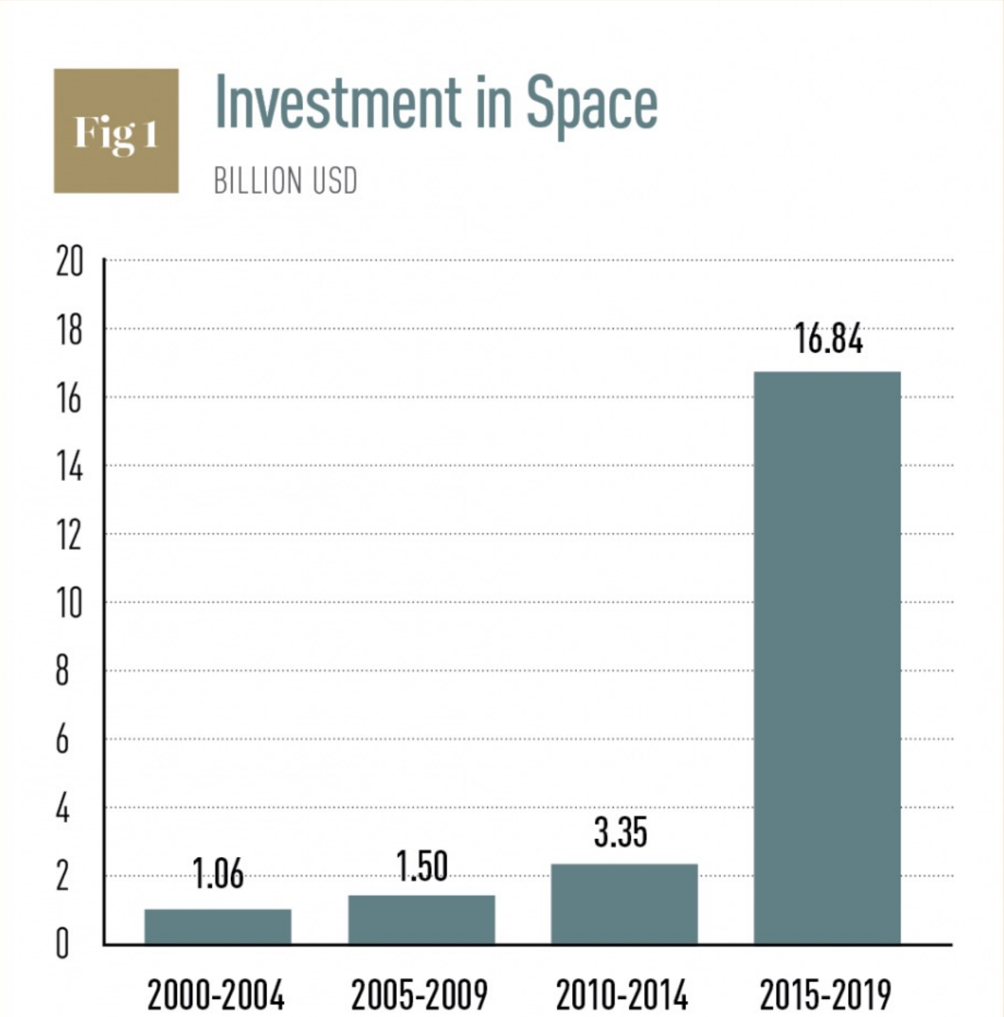
New rooftop MAX-DOAS at UCL

Upcoming project: 2D MAX-DOAS for TROPOMI validation and city-centre vertical profile analysis (NO_2, HCHO, HONO, aerosol extinction)

The modern space launch industry

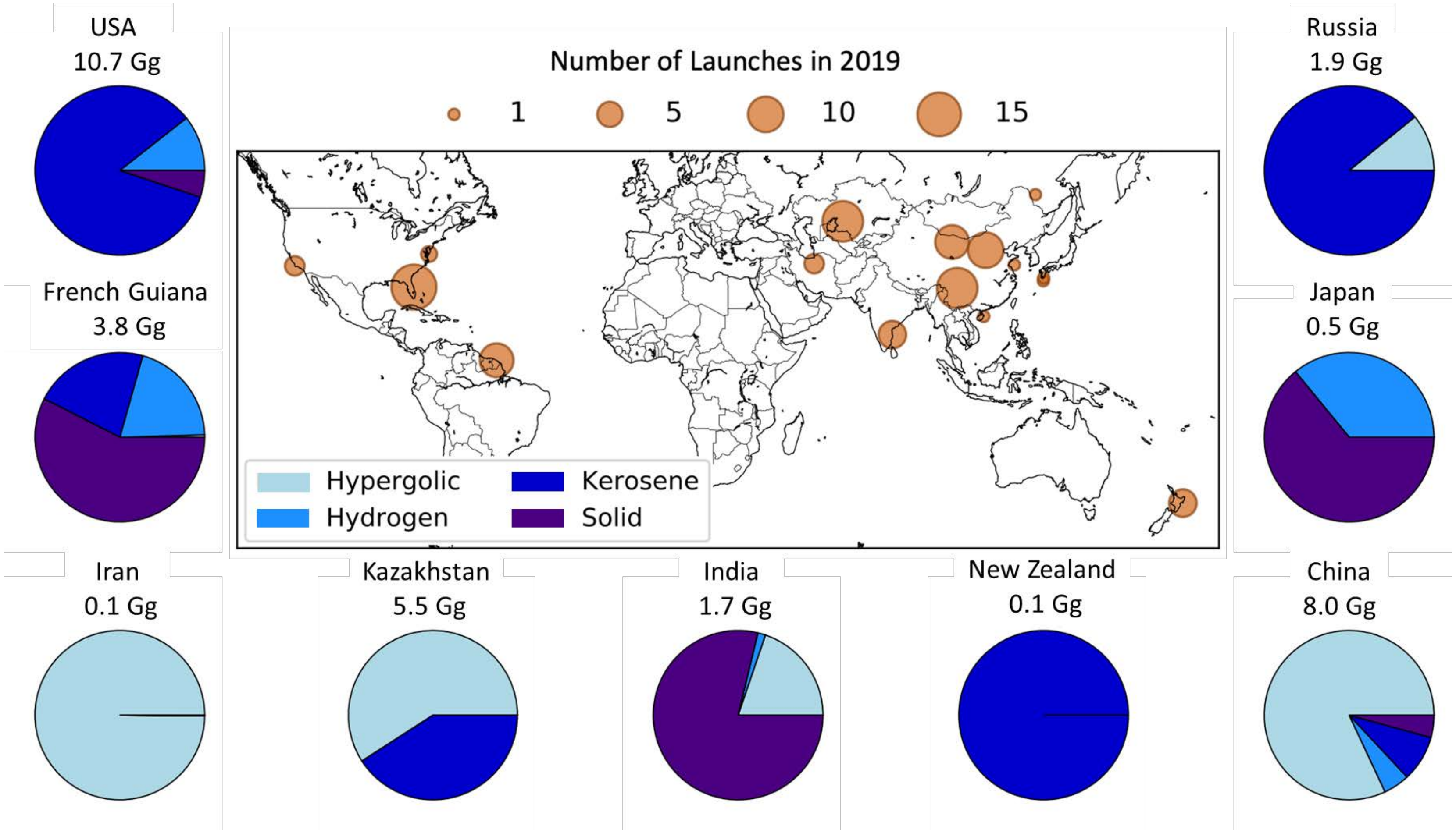
- Are launch rates about to accelerate, and what will the environmental consequences be?





Source: Tauri Group via worldfinance.com

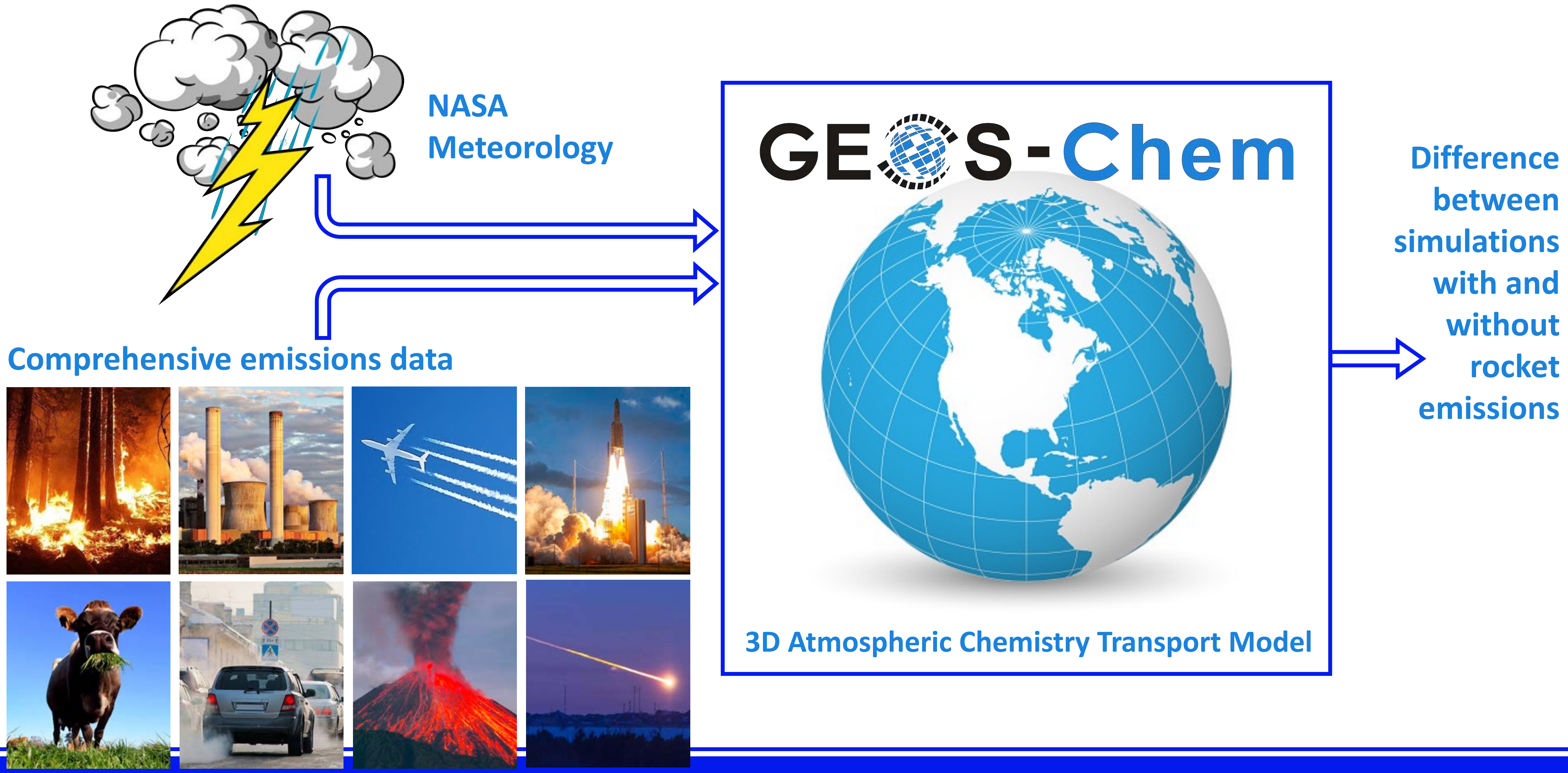
Compiling a rocket launch dataset



Fuel type	Emissions
Kerosene	NO_x, H_2O, soot
Hypergolic fuel	NO_x, H_2O, soot
Liquid hydrogen	NO_x, water
Solid fuel	NO_x, H_2O, Alumina, Chlorine
Re-entering components	NO_x

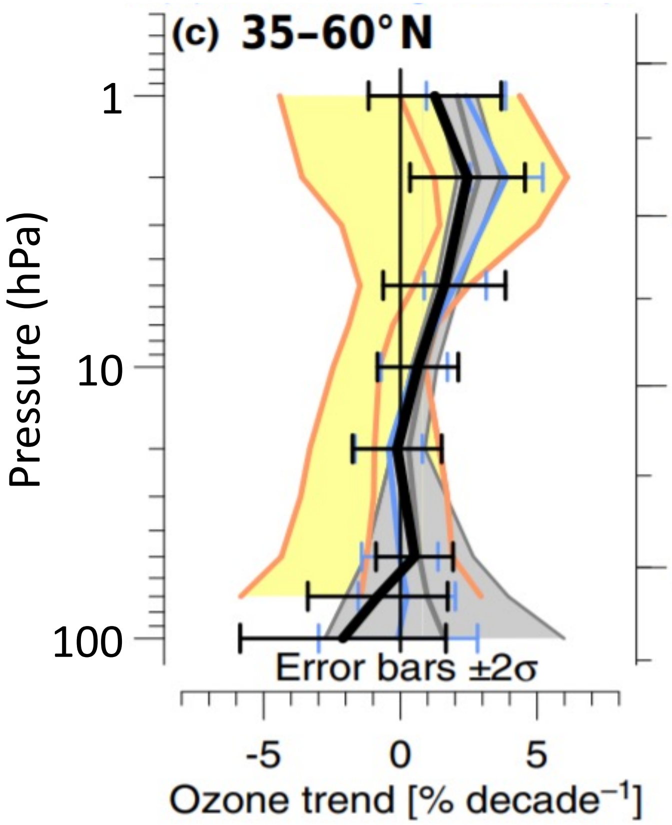
* Ozone depletion
* Atmospheric warming

Simulating ozone and radiative forcing changes

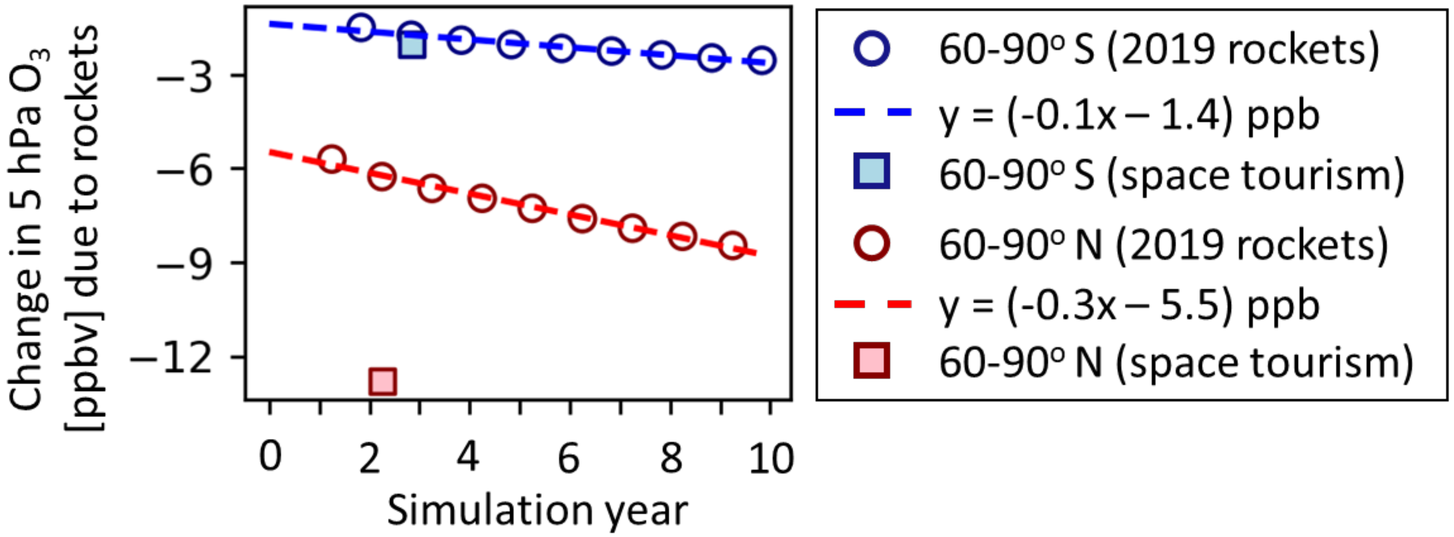


Stratospheric ozone depletion

Steinbrecht et al., 2017
7 satellite merged dataset,
Ozone trend 2000-2016



- The spring recovery trend in the Arctic upper stratosphere is 81 ppb dec^{-1}

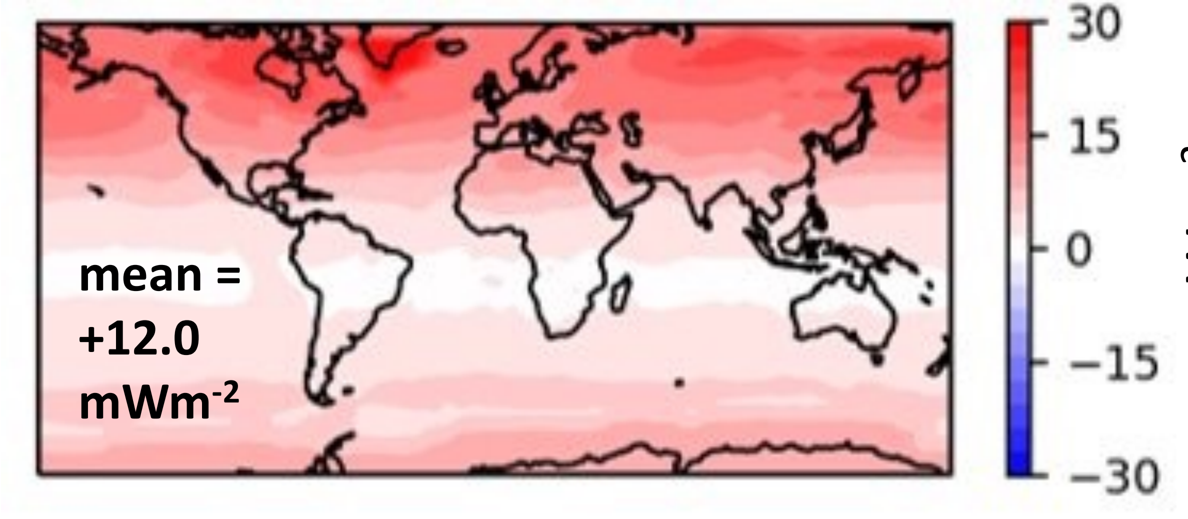


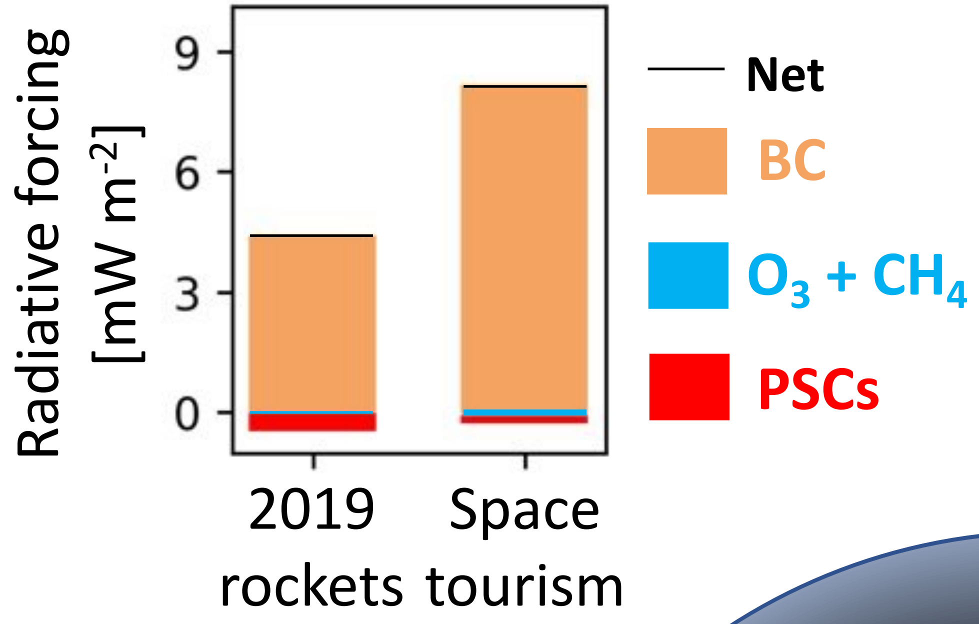
- We find springtime Arctic O_3 loss at 5 hPa is 9 ppb dec^{-1}
- This increases this to 16 ppb dec^{-1} with space tourism.

Potential to undermine 20 % of the post-Montreal Protocol gains

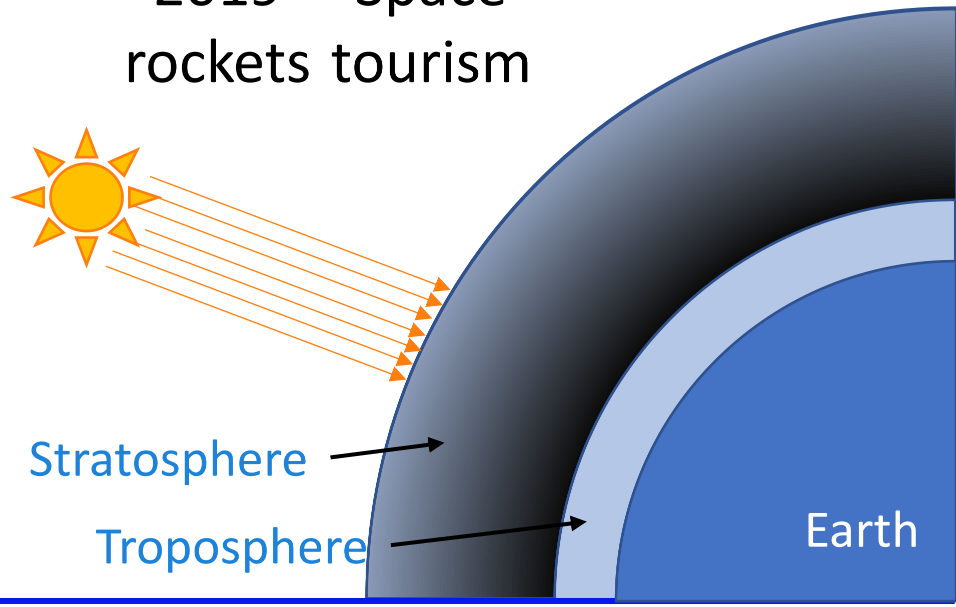
Global warming caused by soot emissions

Net radiative forcing (Space tourism)



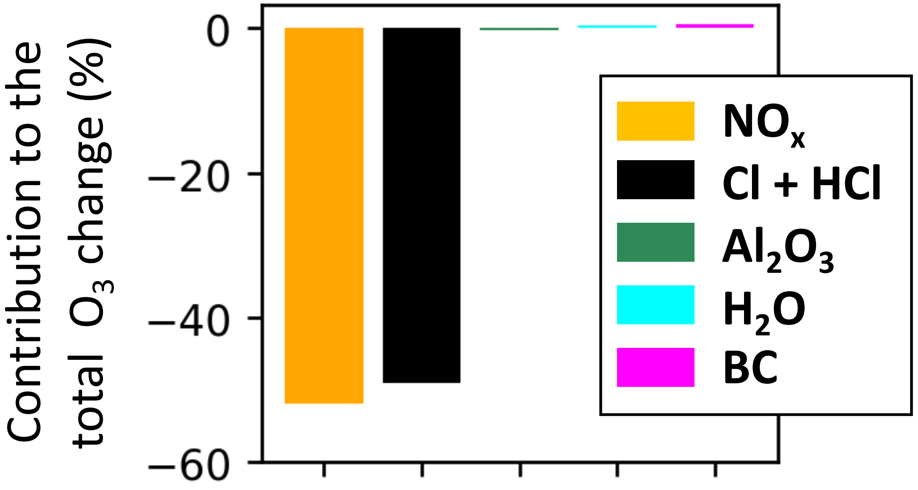


- Rocket soot makes up ~0.0002 % of global soot emissions but produces 6 % of the total soot warming



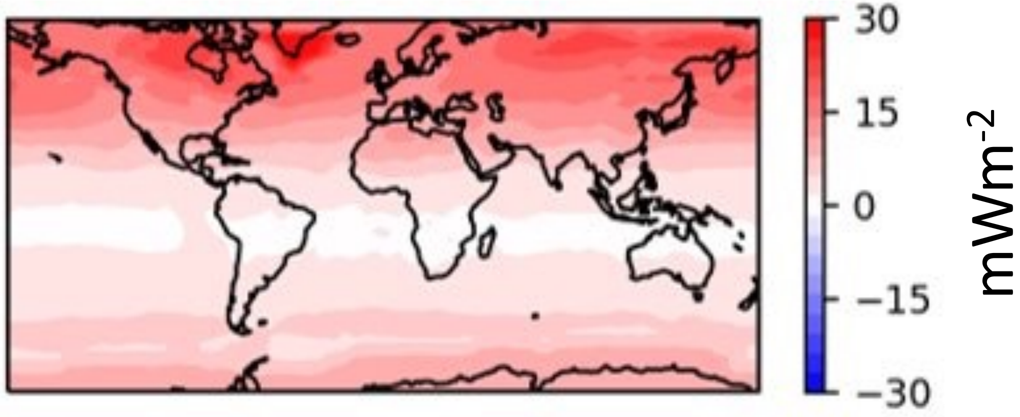
Are there any 'clean' rocket fuels?

Solid fuels:
Rocket chlorine emissions (Cl + HCl) cause the most ozone depletion



Hypergolic and kerosene-based fuels:
Hydrocarbon based fuel emissions are the cause of positive radiative forcing

Black carbon mean forcing:
8.0 mW m^{-2}



? Liquid hydrogen fuel
No BC or chlorine, but ubiquitous NO_x (including re-entry NO_x), which plays an important O_3 depletion role

Summary

We added an emissions inventory of pollutants from rocket launches to GEOS-Chem

- Contemporary emissions and emissions growth scenario
- Speculative space tourism emissions

Chlorine and nitrogen oxides are responsible for ozone depletion

- Small global average impact
- Strongest O_3 depletion in the upper stratosphere
- Potential to undermine ~20 % of gains made post-Montreal Protocol, in this part of the atmosphere

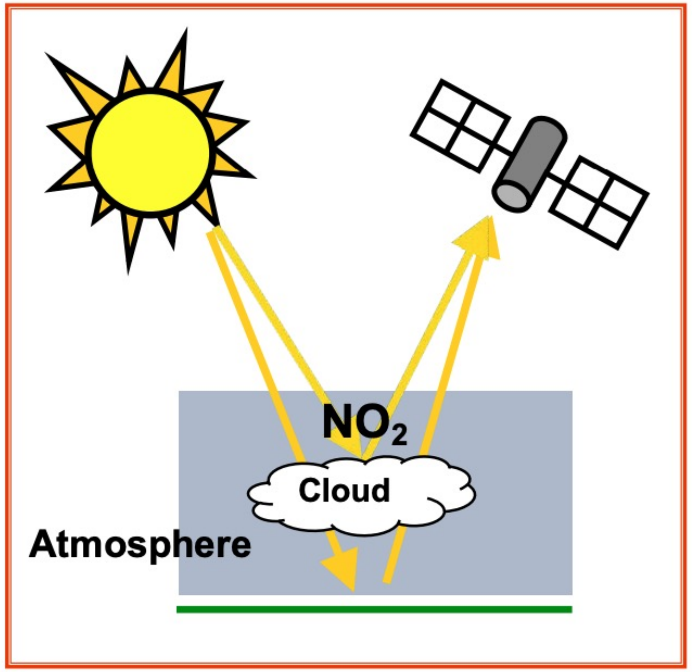
Black carbon (soot) is responsible for enhanced radiative forcing

- Due to the altitude of emission, rocket soot is extremely efficient (500 times other sources!) at warming the atmosphere.

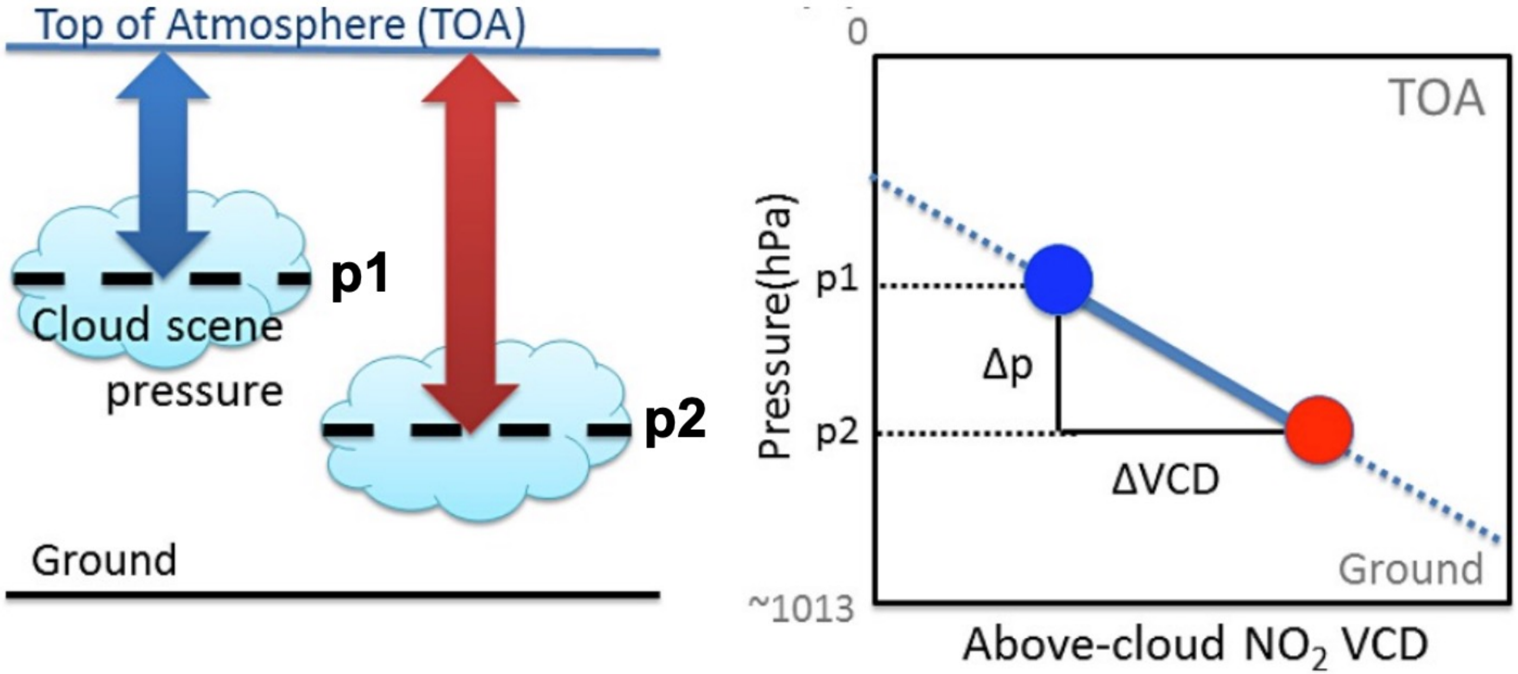
Project 2: Understanding upper tropospheric NO_x using GEOS-Chem and TROPOMI

Cloud slicing for retrieving upper tropospheric mixing ratios

APPROACH



Use cloud height variability to derive partial columns



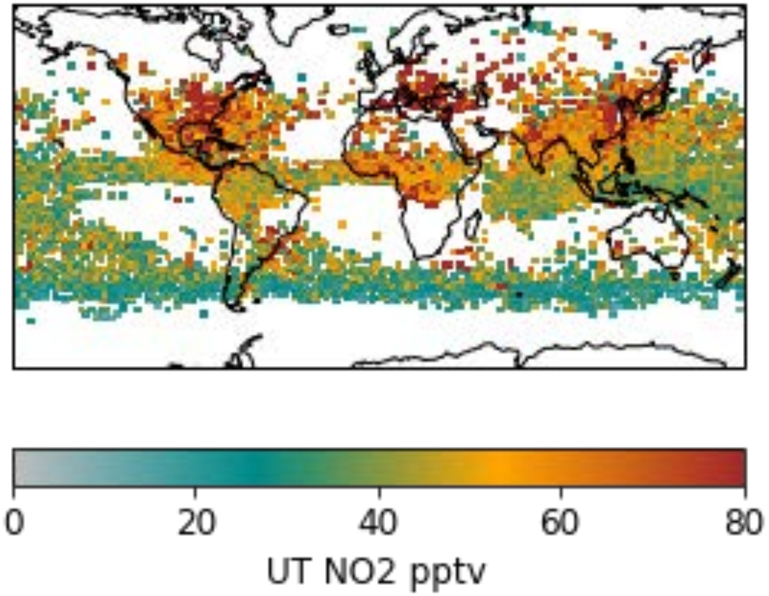
[adapted from Choi et al., 2014]

NO_2 volume mixing ratio (VMR) between clouds at p1 and p2

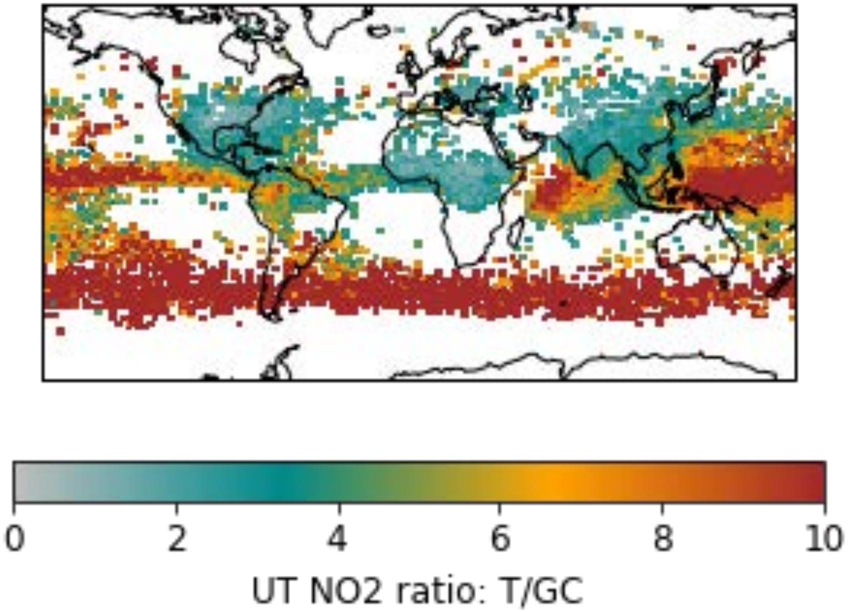
$$\mathrm{NO_2\ VMR} = \frac{\Delta\mathrm{VCD}}{\Delta\mathrm{p}} \times \frac{k_B g}{R_{\mathrm{air}}}$$

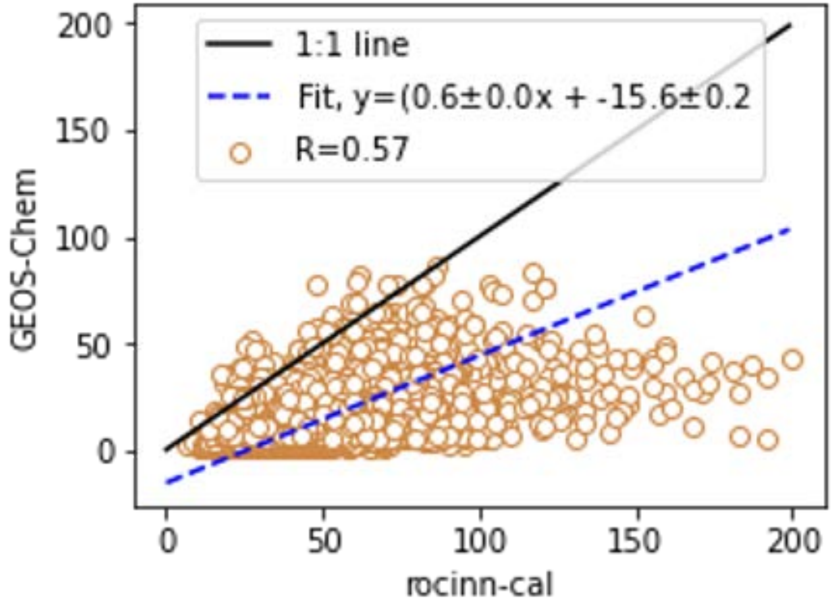
Cloud-sliced observations vs GEOS-Chem

ROCINN-CAL cloud sliced product



Ratio: TROPOMI / GEOS-Chem





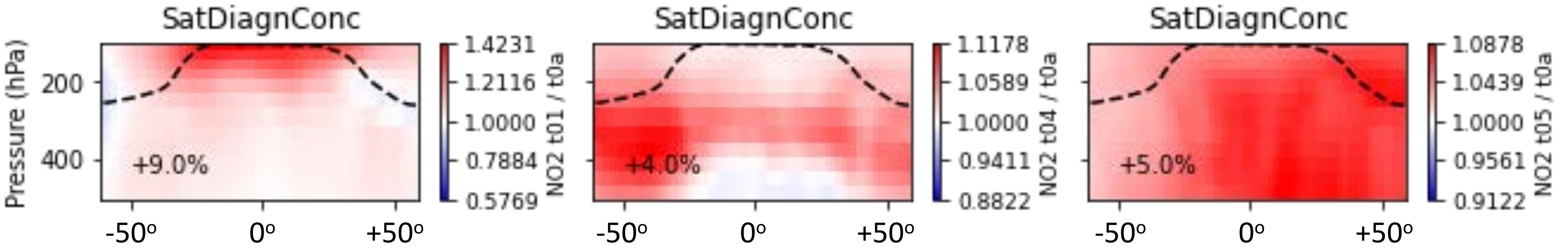
- GEOS-Chem underestimates TROPOMI U.T. NO_2 by about half on average
- Greatest agreement over tropical and sub-tropical land
- Greatest agreement in areas of very high lightning flash rate
- Large discrepancy over remote ocean, especially tropics, and areas of moderate-low lightning flash rate

Reaction rate tests in GEOS-Chem

Speed up rate of $NO + O_3 \rightarrow NO_2 + O_2$

Slow down rate of $NO_2 + HO_2 \rightarrow HNO4$

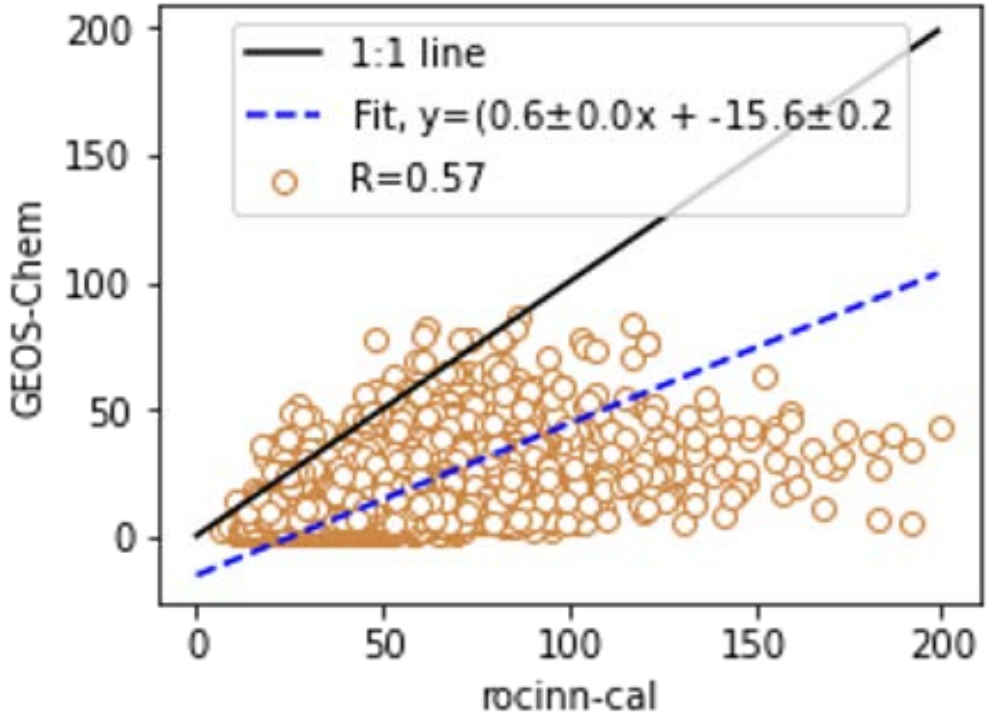
Slow down rate of $NO_2 + OH \rightarrow HNO_3$



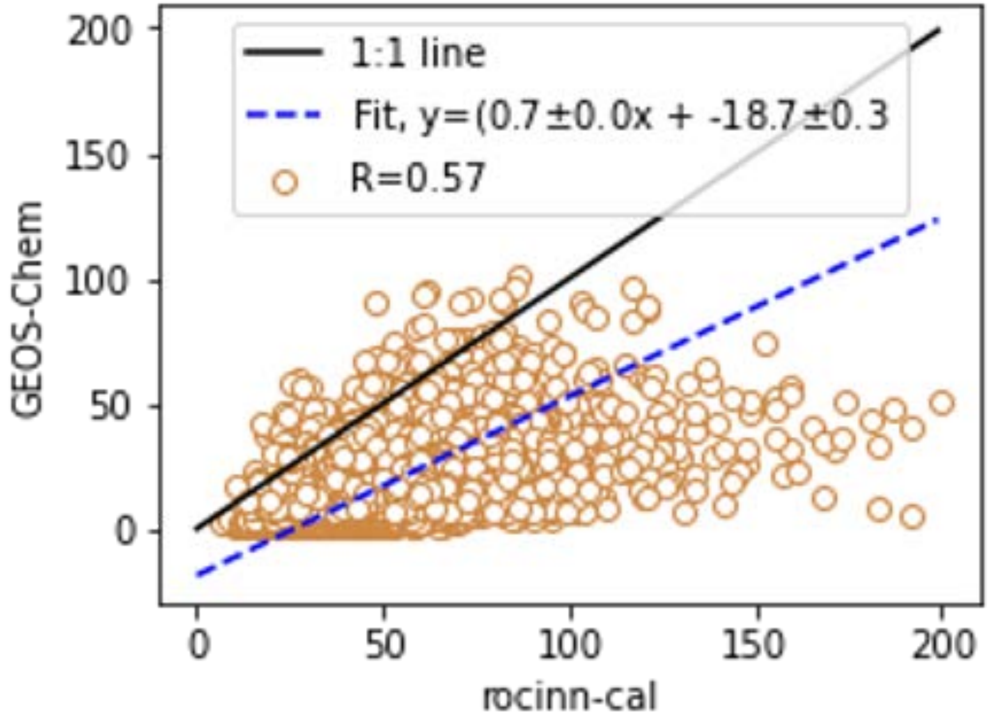
- GEOS-Chem U.T. NO_2 increased by updating reaction rates for NO-NO_2 cycling
- We also found that U.T. peroxypropionyl nitrate (PPN) is over-represented in GEOS-Chem by about 60 % because photolysis and OH-reaction sinks were missing.

Reaction rate tests in GEOS-Chem

Original simulation



All reaction rate tests combined



- Comining all reaction rate tests improves the comparison by about 10 %.
- Next steps: address uncertainties in the way NO_x from lightning is parameterised in GEOS-Chem