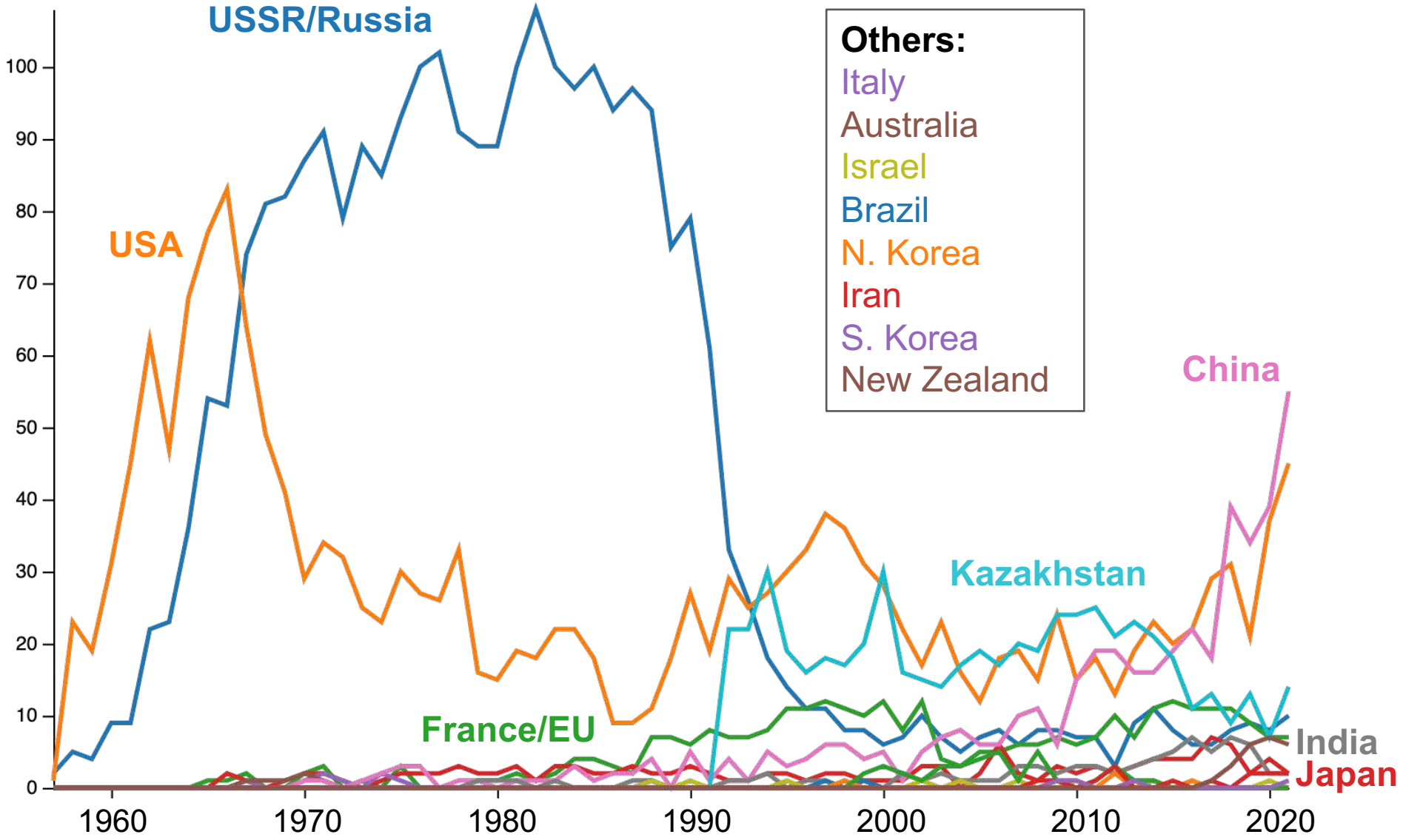
Hazardous effects of a burgeoning space industry on the environment

IES Webinar **Eloise Marais** (e.marais@ucl.ac.uk) **22 Nov 2022**

More diverse space sector than the original space race

Number of rocket launches per country in each year

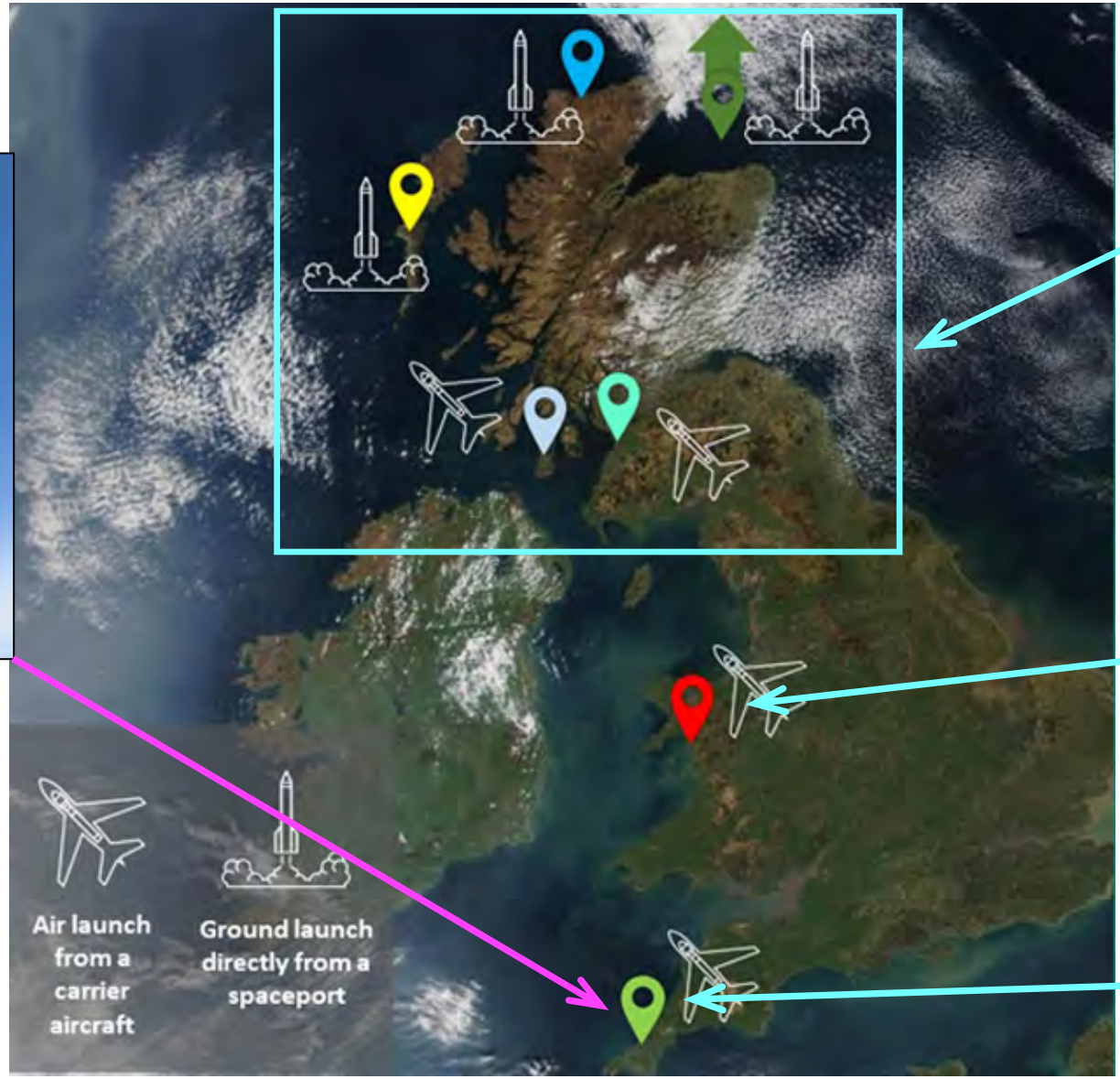


Even the UK has joined the modern space race

From zero to 7 ports: 4 air launch, 3 ground launch

First UK launch from Cornwall

Likely 30 launches each year



5 in Scotland

1 in Wales

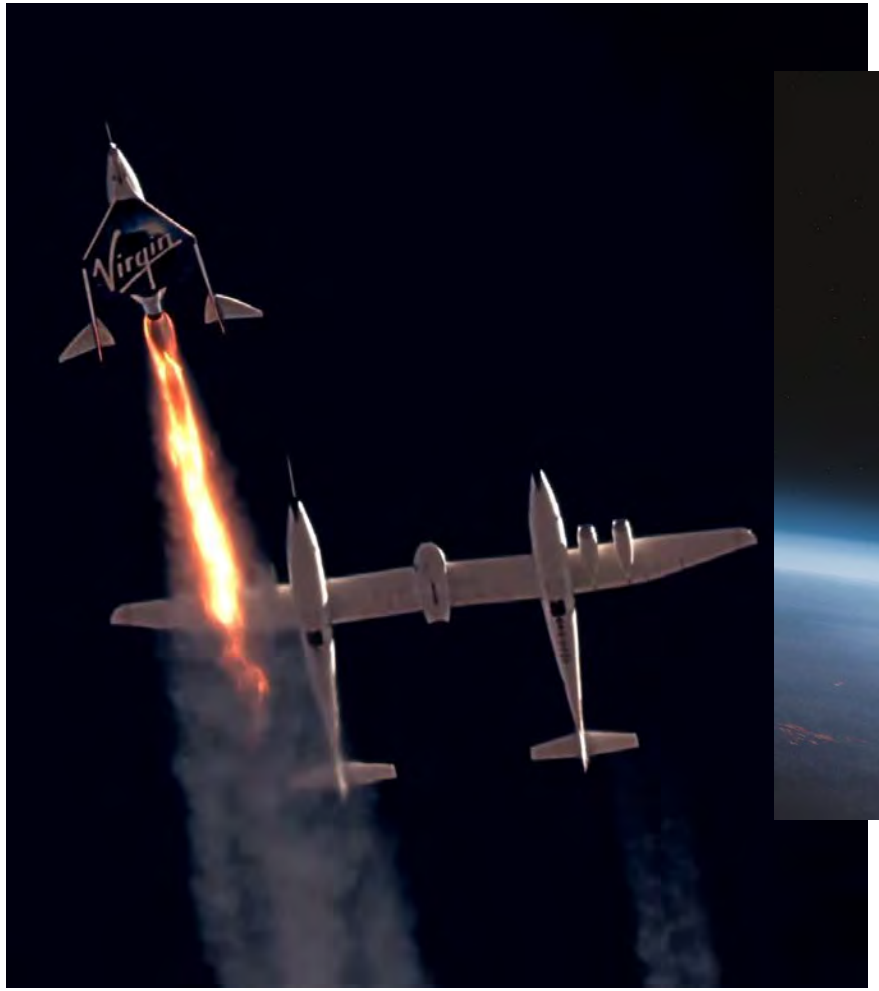
1 in England

[UK Space Agency]

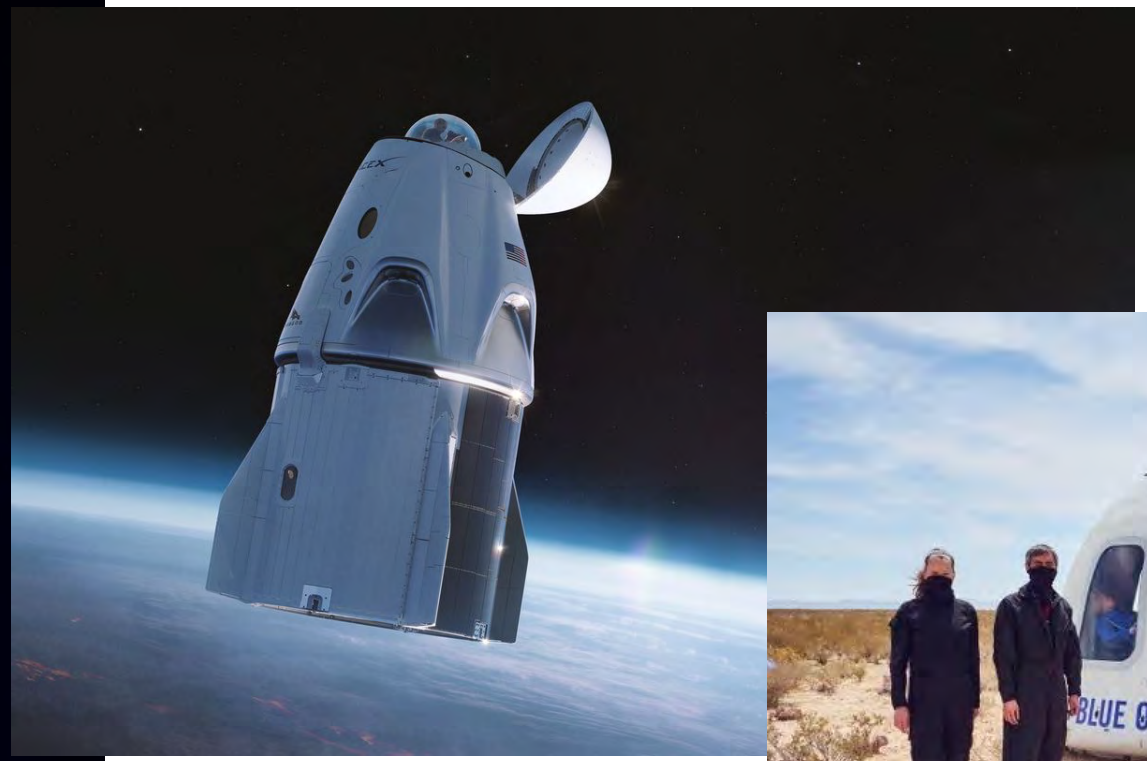
Advent of a space tourism industry

3 demonstrations by each in 2021, additional launches by Blue Origin, nothing much since

Virgin Galactic



SpaceX



Blue Origin

Remained nascent

Rockets getting bigger and burning more fuel

NASA launches largest booster ever on 16 November 2022

NASA Space Launch System (SLS)
Propellant mass: ~1300 tonnes

India Space Research Organization rocket
Propellant mass: 410 tonnes

More payloads launched into space

SpaceX and other megaconstallation programmes

StarLink

Falcon 9

26 tonnes

60 satellites/launch

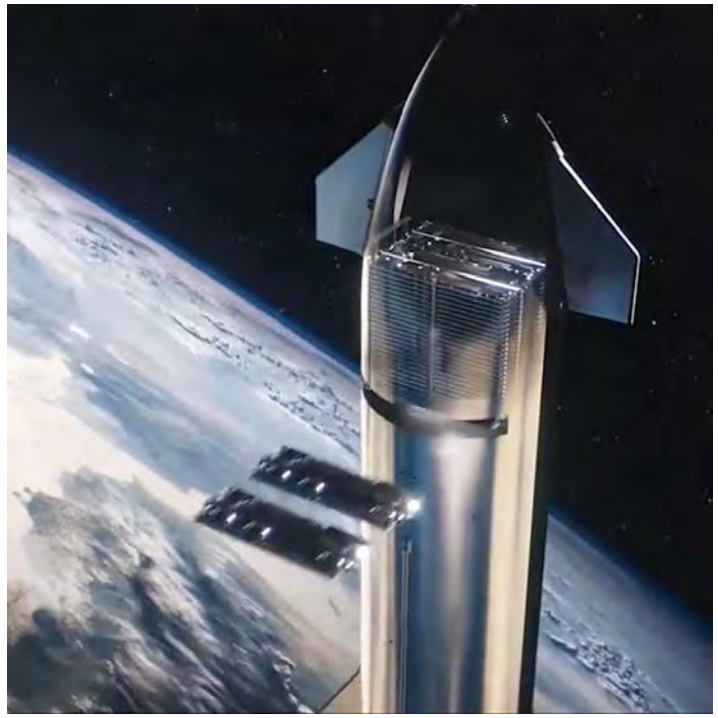
3,558 launched to date

318 already deorbited

StarShip

Raptor

~200 tonnes



Ambition is 3 launches per day and total launch of 30,000 satellites

Dramatic increase in objects in space

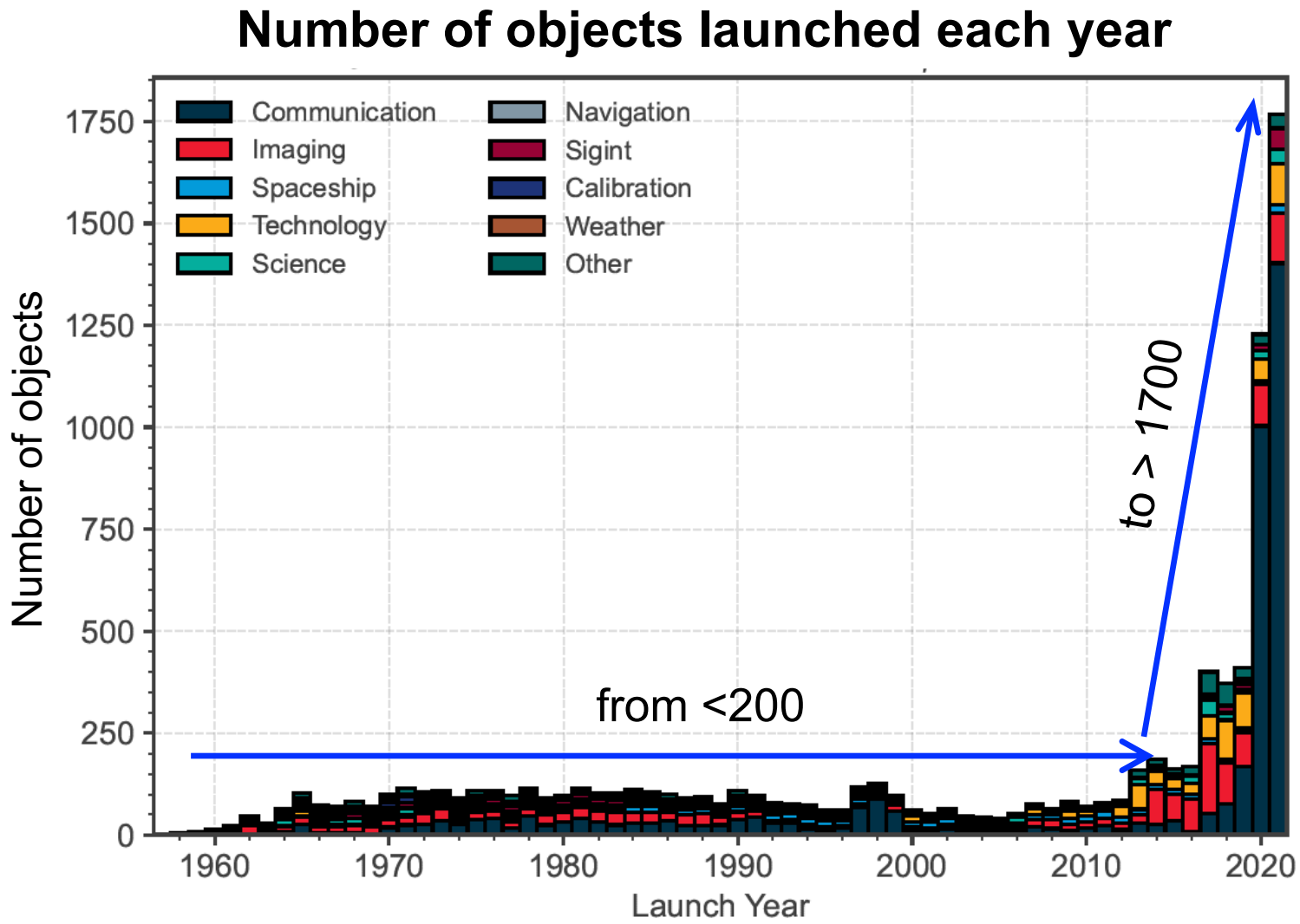
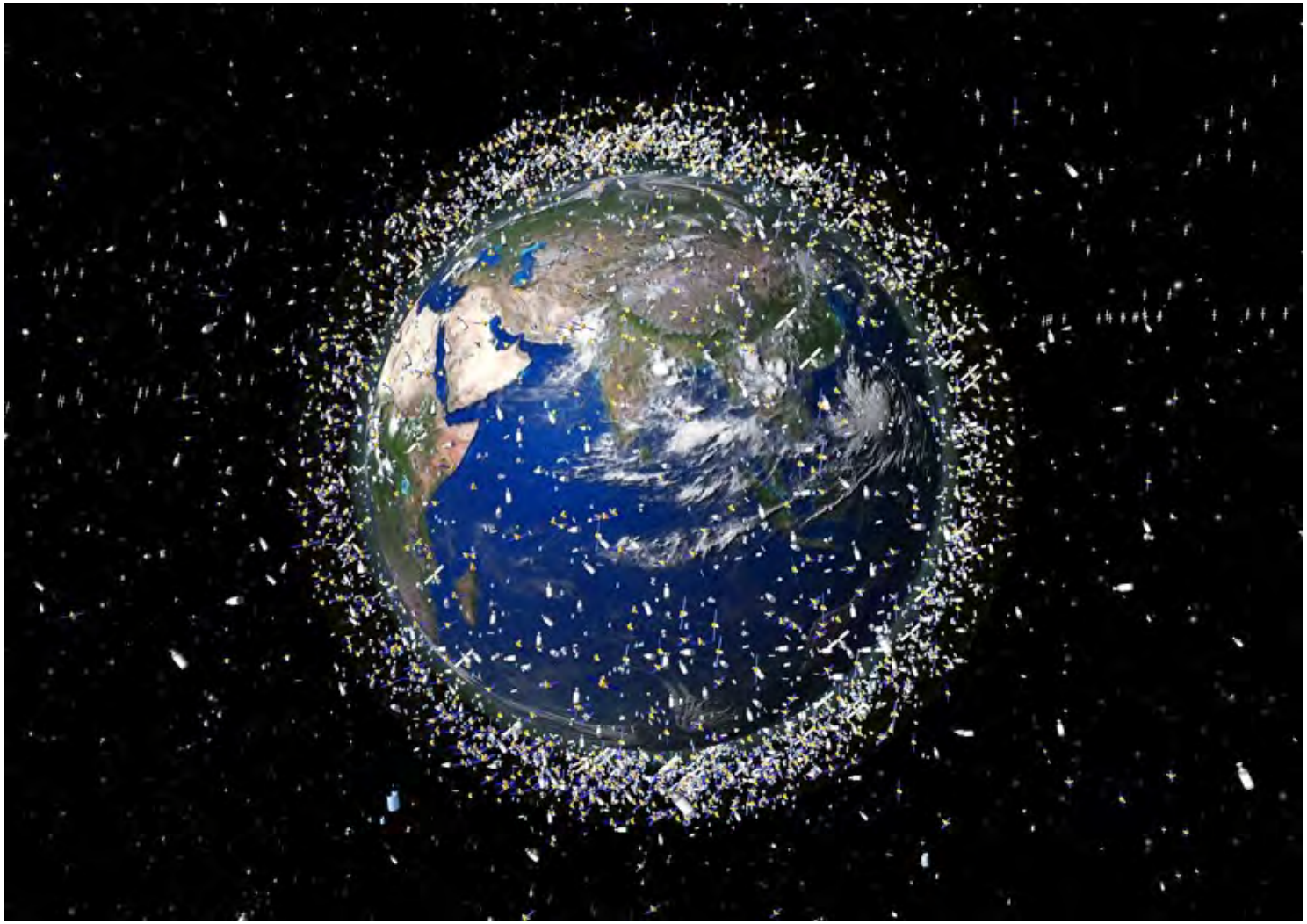


Image from ESA's Annual Space Environment Report, 2022

From fewer than 200 before 2017 to >1700 in 2021

Cluttered Skies

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



Only viable disposal method is complete burn up by re-entering Earth’s atmosphere

Air pollutant emissions from rocket launches

Depends on propellant burned

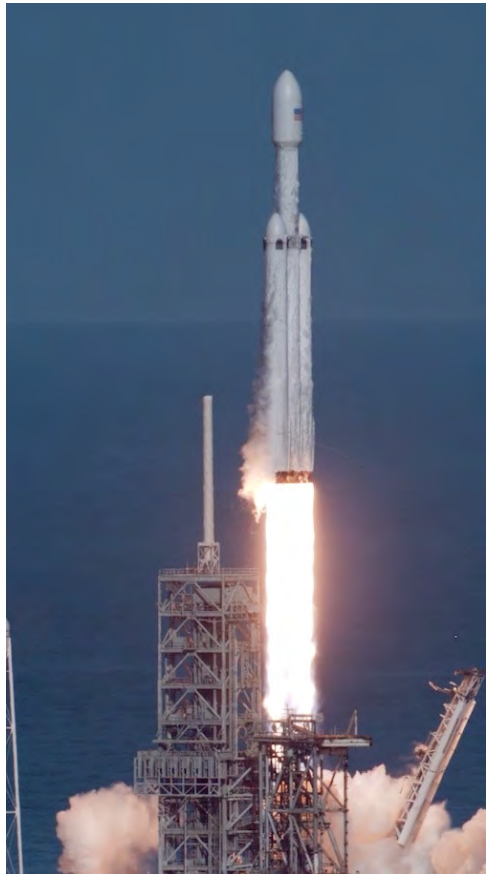
Solid

NO_x
HCl+Cl
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

BC: black carbon
NO_x: nitrogen oxides

Black carbon (BC) or soot particles

Historic and modern era pollutant from burning carbon-based fuels

Dark → strong absorbers of sunlight → warms the atmosphere

Pollutants that impact climate

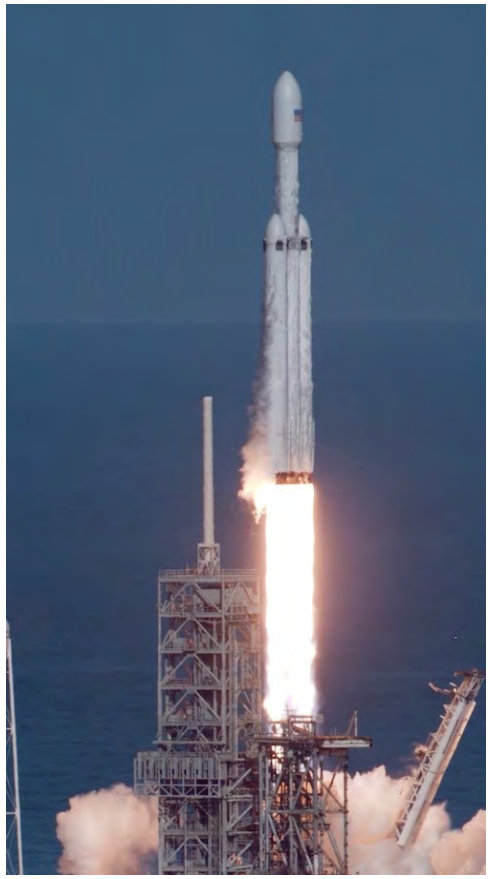
Solid

NO_x
HCl+Cl
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

Climate concern

Pollutants that deplete stratospheric ozone

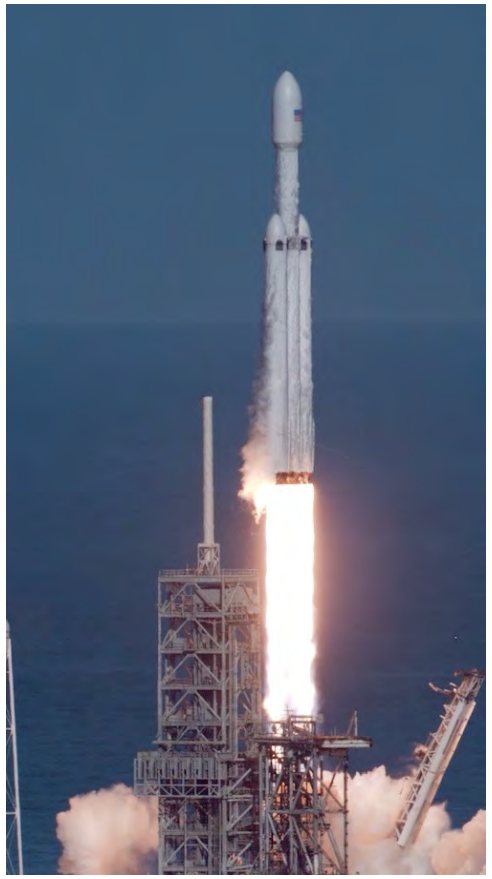
Solid

NO_x
HCl+Cl
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene



NO_x
H_2O
BC

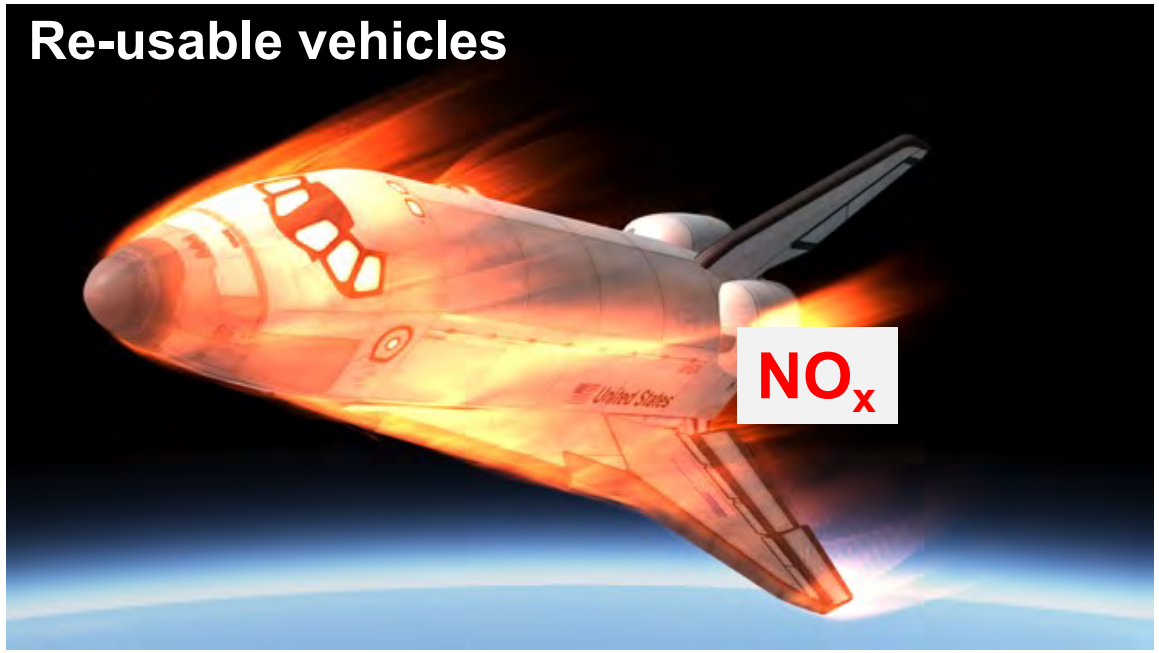
Cryogenic

NO_x
H_2O

Ozone depletion

Air pollutant emissions from re-entry

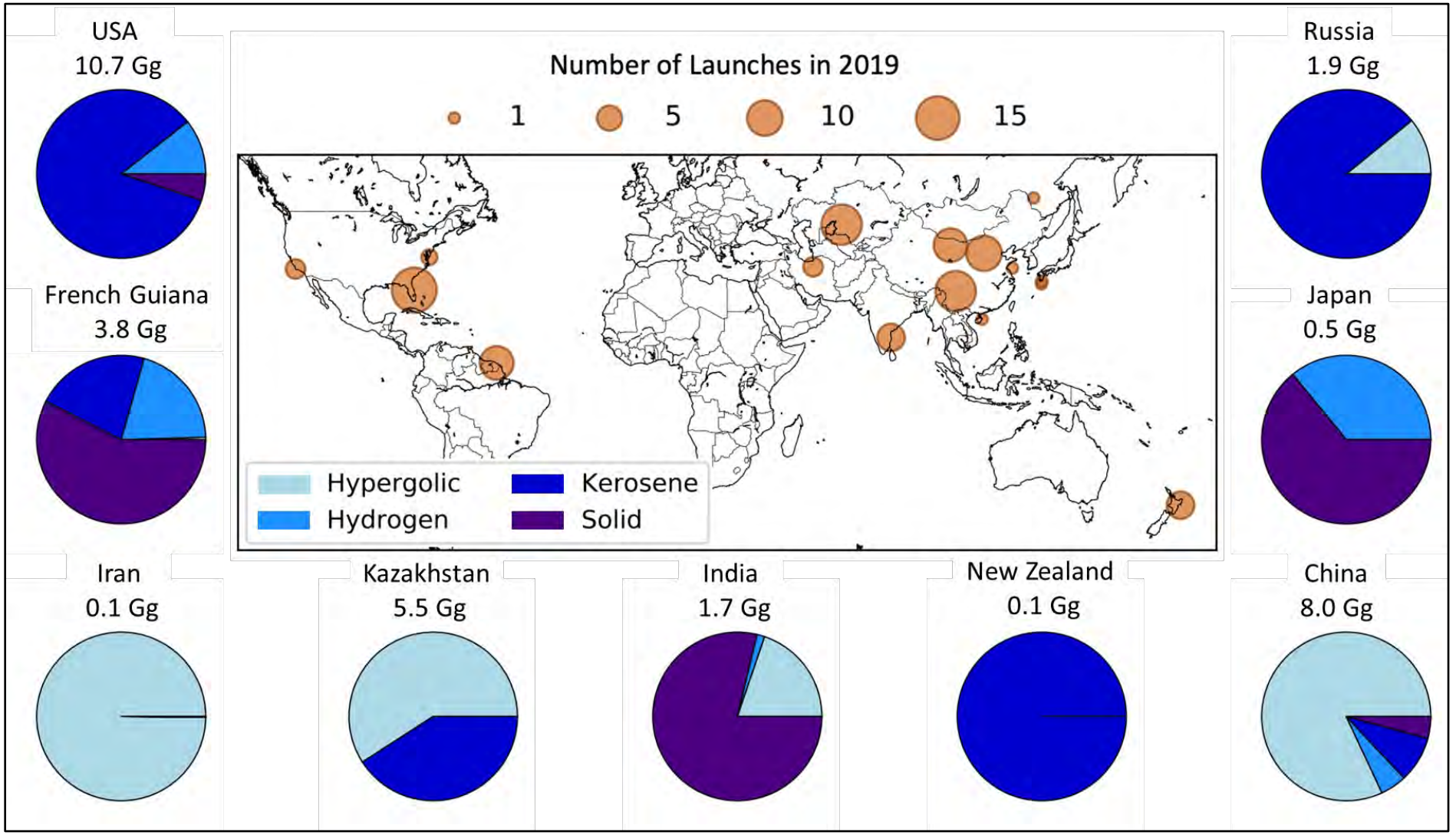
Depends on mass and composition of returning object



Natural source:

2-40 Gg NO_x per year

Calculate and map a year of emissions



Annual Emissions:

H_2O: 11 Gg
BC: 0.5 Gg
Al_2O_3: 2 Gg
HCl: 1 Gg
Launch NO_x: 0.2 Gg
Re-entry NO_x: 2 Gg

Gg = kilotonnes

Artificial NO_x similar to lower end estimate of natural NO_x

~100 successful launches in 2019

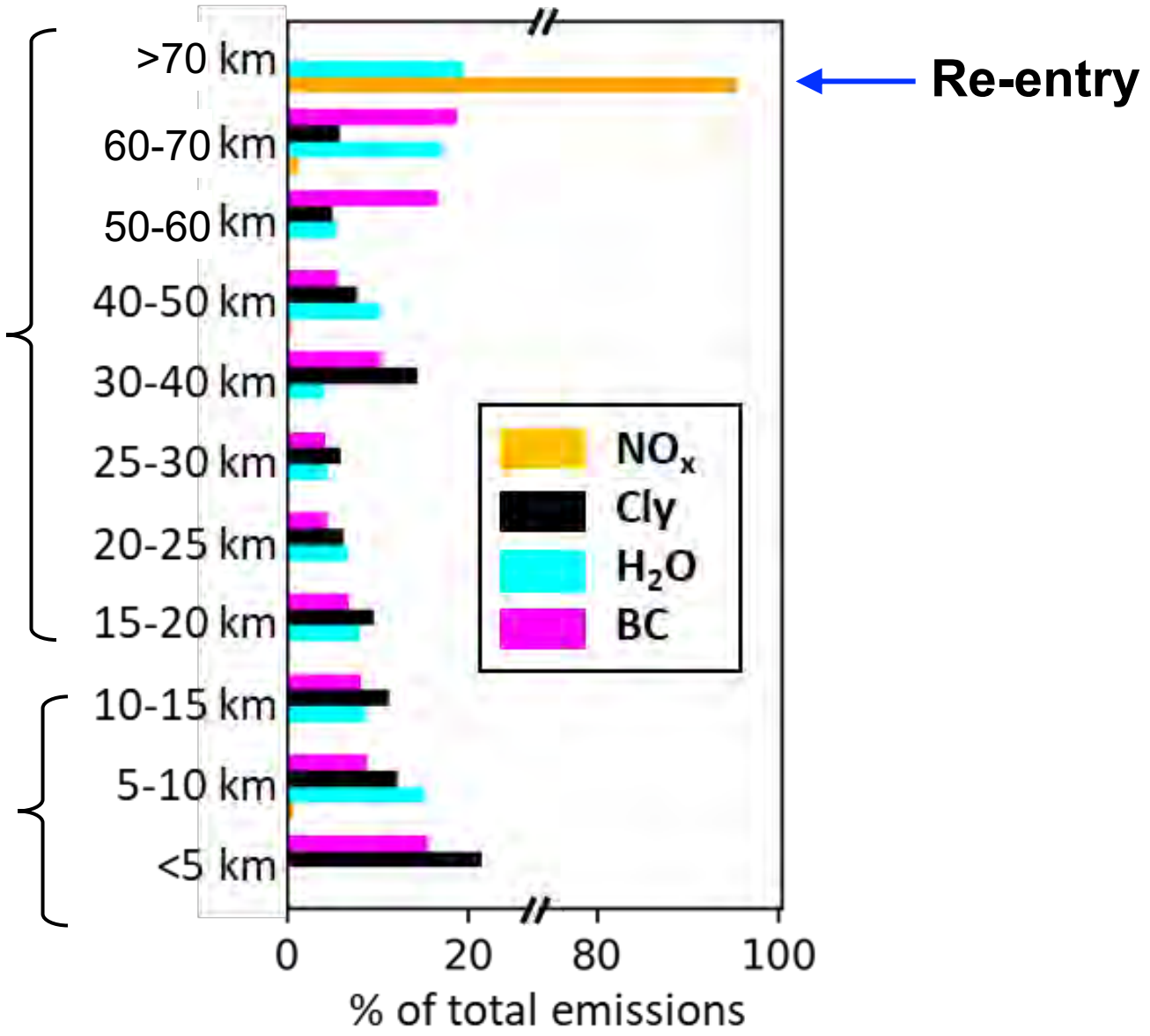
Reaches 135 in 2021. Already 161 in 2022.

Implement emissions in 3D chemistry model

Model extends to **80 km**

Stratosphere & mesosphere:
lifetime >2 years
(*gravitational settling*)

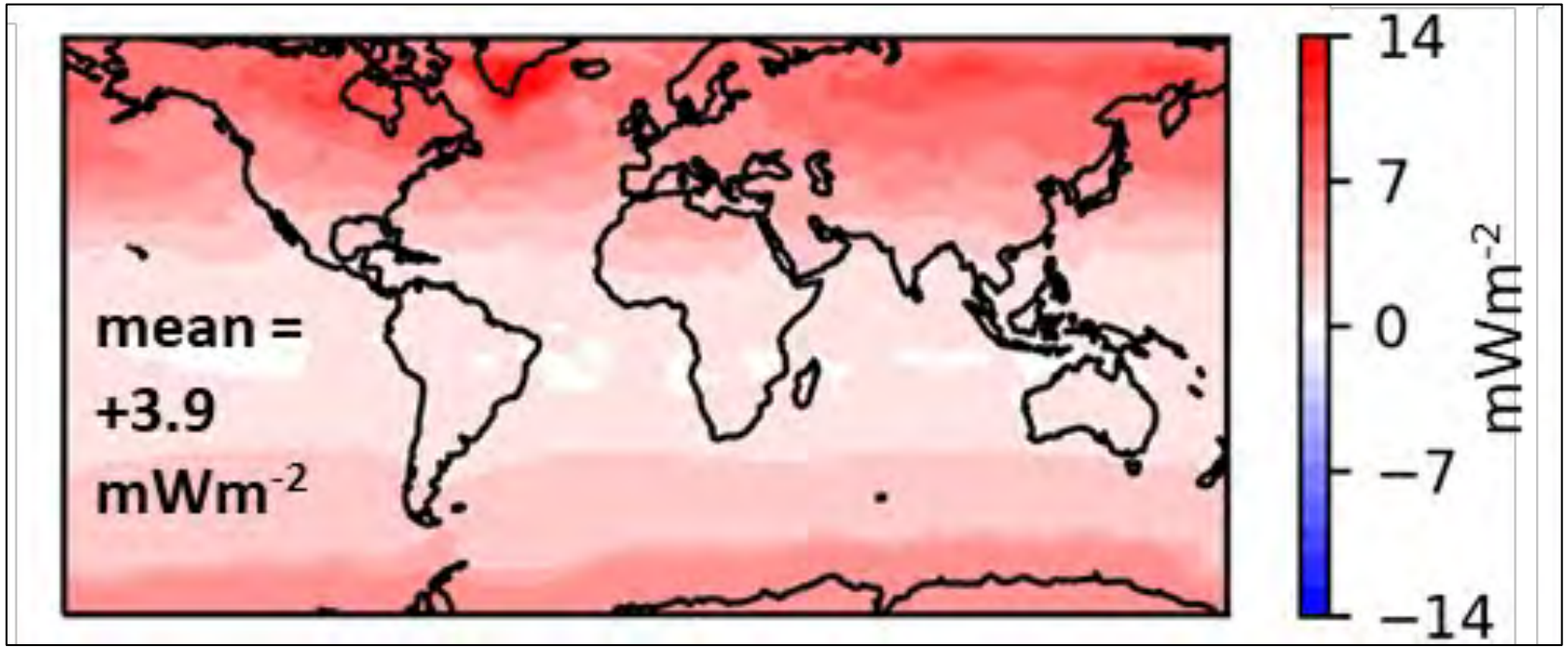
Troposphere:
lifetime weeks to months
(*wet and dry deposition, subsidence, chemical losses*)



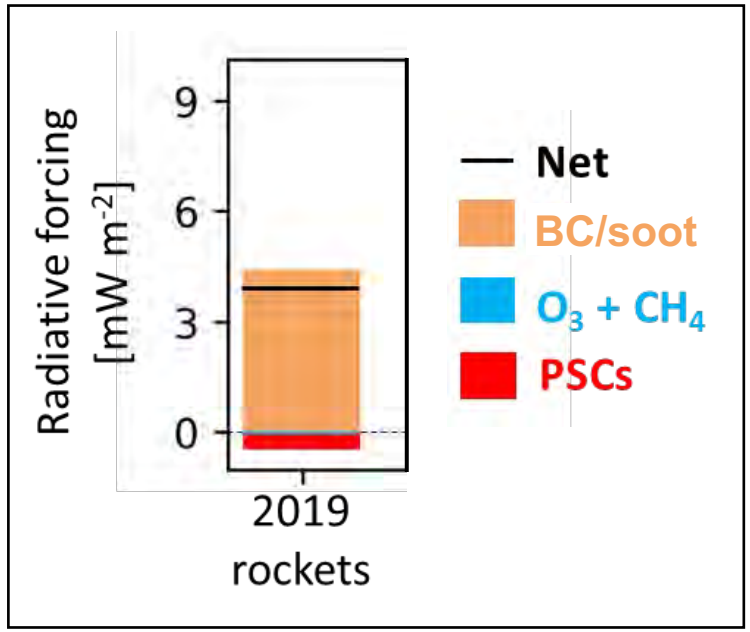
Model includes estimate of radiative forcing

Radiative forcing: measure of the change in energy balance of atmosphere

After 10 years of emissions assuming modest growth



Mostly due to soot particles



PSCs: polar stratospheric clouds

Ranges from +14 mW m^{-2} over the Arctic to +1-2 mW m^{-2} in the tropics

Majority due to black carbon (BC) or soot particles from rocket launches

Putting the climate effect of soot particles into context

Global rocket launches:

0.5-1.0 kilotonnes soot

Total Earth-bound sources (includes aircraft):

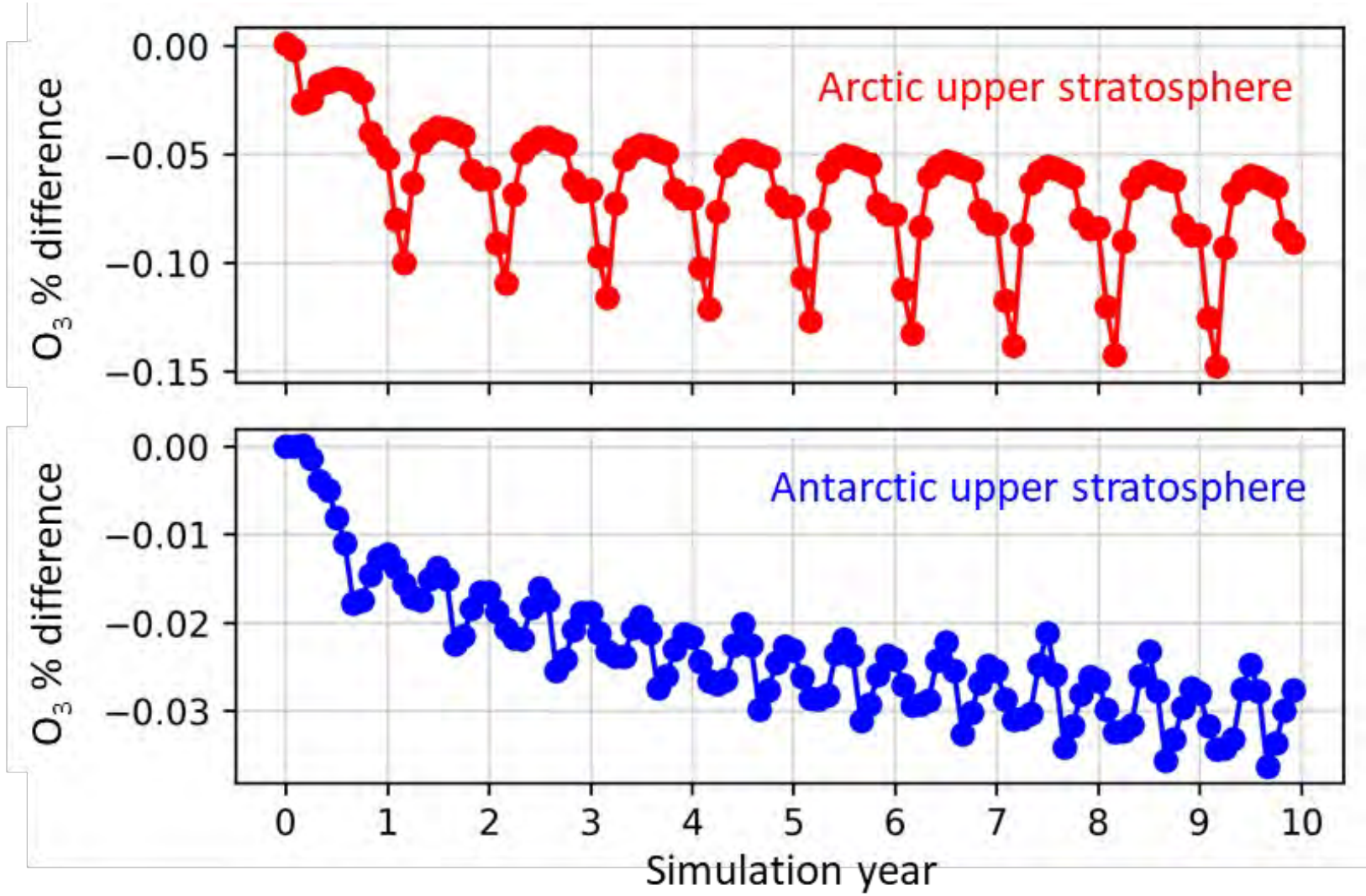
6700 kilotonnes soot

Rocket soot emissions only 0.01% of Earth-bound emissions, but 3% of climate effect

Soot from rockets **400-500 times greater radiative effect** than BC from Earth-bound sources

Depletion of stratospheric ozone

Percent change (decrease) in polar (60-90°) upper stratospheric (40-50 km) ozone



Peak decline in spring is
0.15% in the NH and
0.04% in the SH

50:50 contribution from
re-entry NO_x and **rocket launch chlorine**

@35 MONTREAL PROTOCOL

NH **~0.15%** depletion is ~10% of upper stratospheric ozone recovery attributed to Montreal Protocol

Concluding Remarks and Resources

- Largest environmental effect of space sector launches and re-entries is climate change due to soot particles
- Stratospheric ozone depletion is relatively small and local
- Climate effect of soot particles is large in relation to emissions, so anticipated growth in space sector is of great concern
- Other concerns not considered in our study: local air and noise pollution, supply chain emissions, cluttered skies
- Regulation and innovation urgently needed to mitigate harmful environmental effects
- Our study: https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021EF002612
- Research group website: https://maraisresearchgroup.co.uk/
- Contact details: e.marais@ucl.ac.uk