Observing plumes from rockets: The next frontier in air pollution

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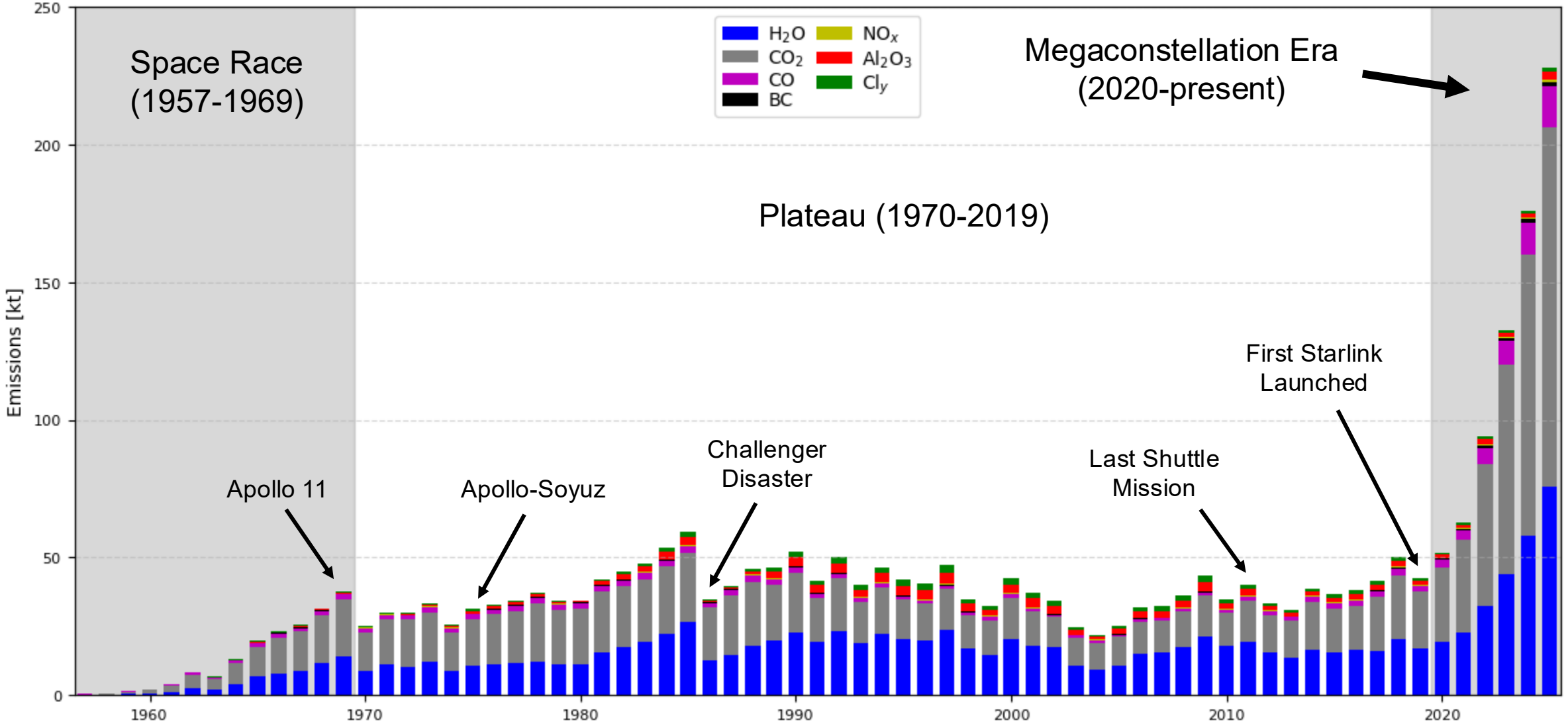
Seven Decades of Rocket Launch Emissions

Air Pollutant and CO_2 Emissions from Rocket Launches 1957-2025



New pollution era from recent exponential increase in emissions due to megaconstellations

Atmospheric Harm of Rocket Launches

Launches (0 km to orbit)

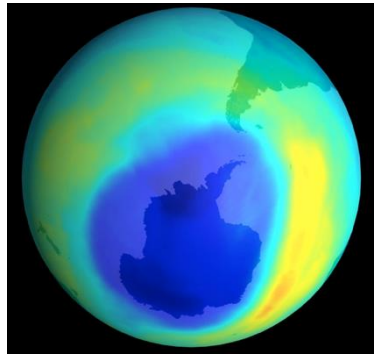
Propellant Types:

Hydrogen
Kerosene
Methane
Hypergolic
Solid
Bio-propellants

Major pollutants:

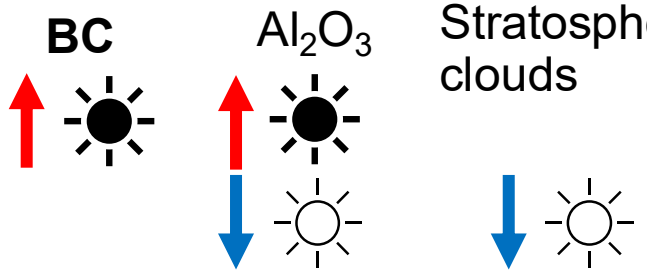
H_2O (all)
Al_2O_3 (solid)
BC (all except hydrogen)
NO_x (all)
Chlorine (solid)

Stratospheric Ozone Loss



Affected by all emitted chemicals

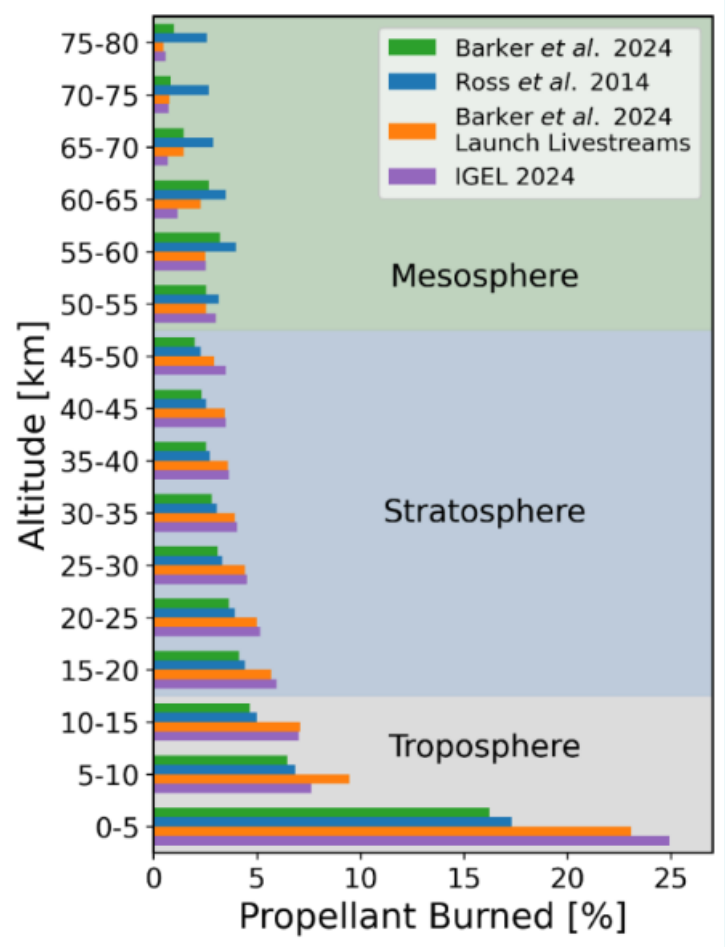
Instantaneous Climate Forcing



Al_2O_3: alumina; **BC**: black carbon (soot); **NO_x**: Nitrogen Oxides (NO + NO_2)

Bottom-up Rocket Launch Emissions Estimates

Propellant Consumed



Calculated using literature profile or launch trajectories

[Herberhold et al., in review]

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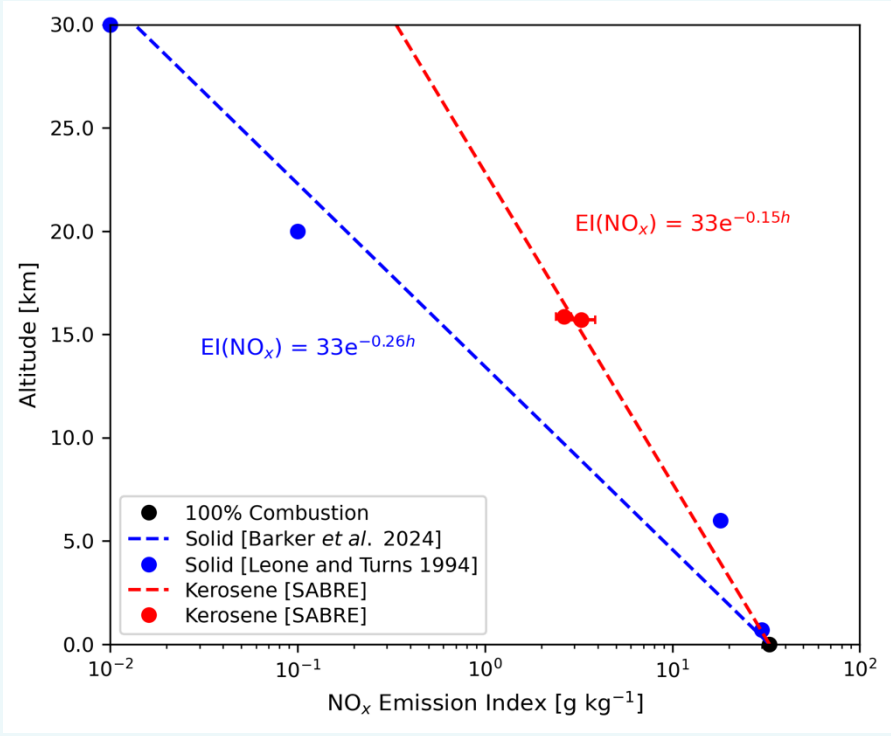
Emission Indices



Obtained from literature or calculated with in-engine modelling

[Barker et al., 2026]

→ Exhaust Chemicals

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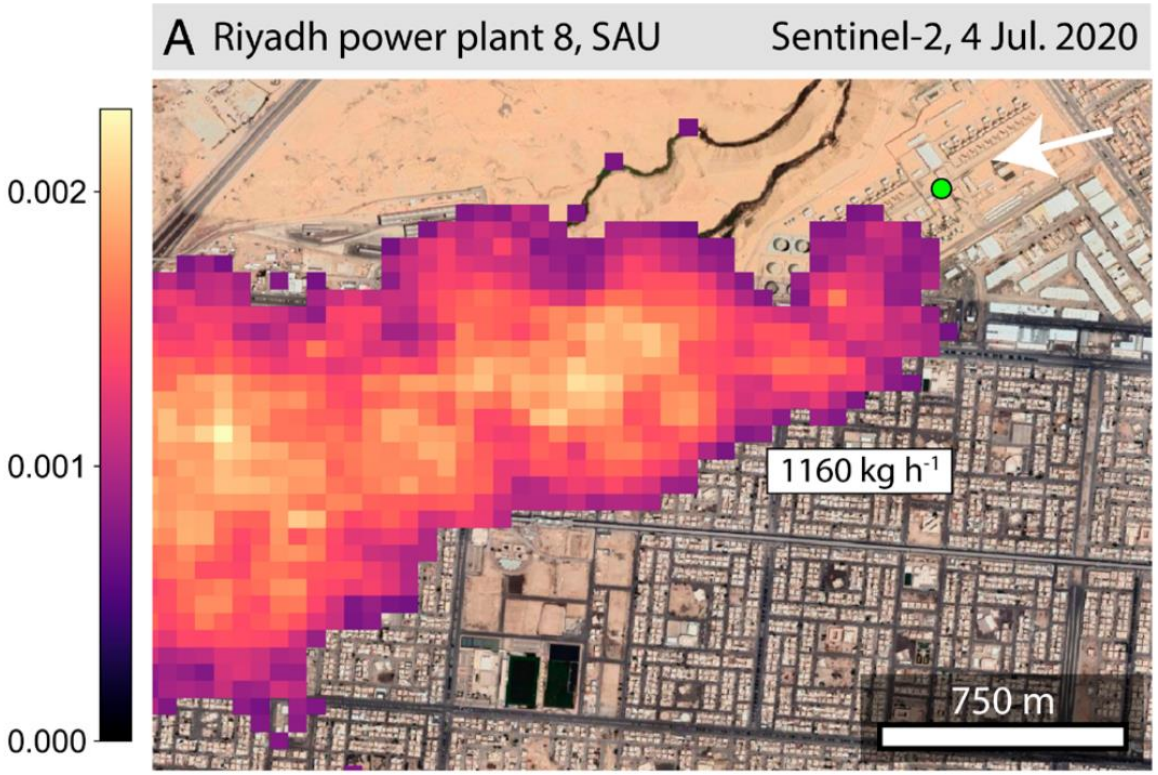
Validation?

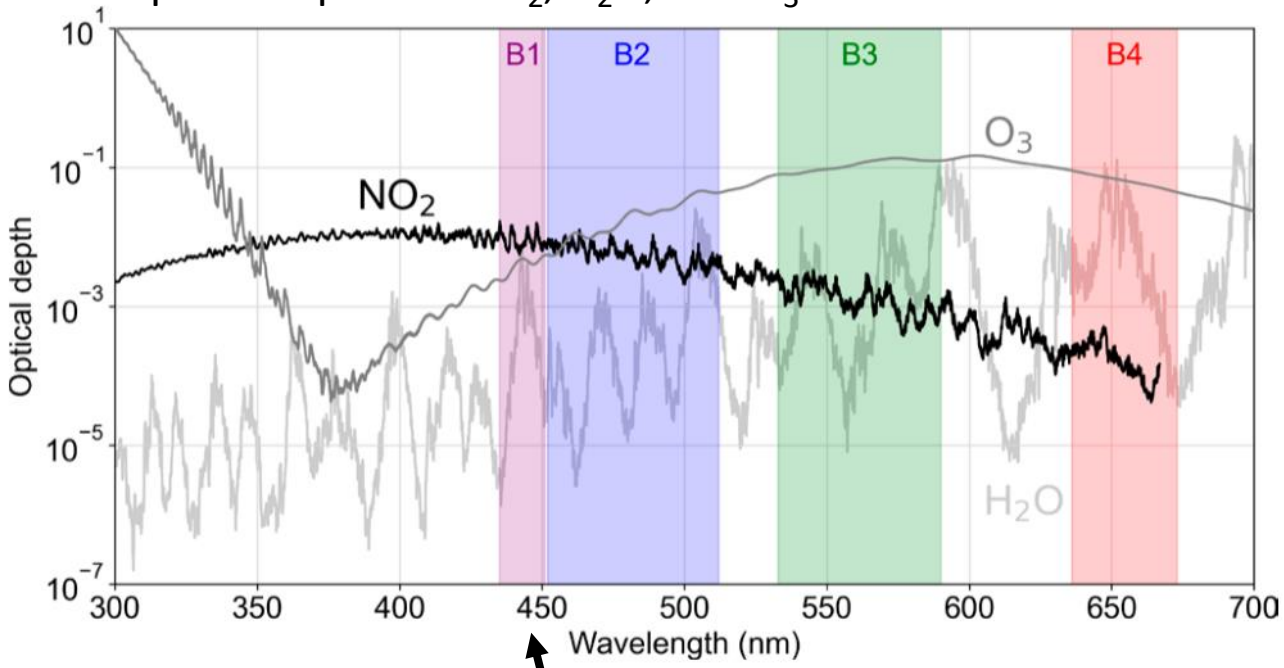
Power Plant NO_x Plumes Detected with Optical Imagers

Retrieved plume NO_2 enhancement [mol m^{-2}]



Paper demonstrated use of broadband sensors (Sentinel-2, Landsat) to retrieve NO_2 plumes at high resolutions (10-60m).

Optical depths of NO_2, H_2O, and O_3 with Landsat bands



NO_2 absorbs strongly in the "ultra-blue" band (~430-450 nm)

Launch NO_x emission rates far exceed power plant NO_x emissions, but launches are transient

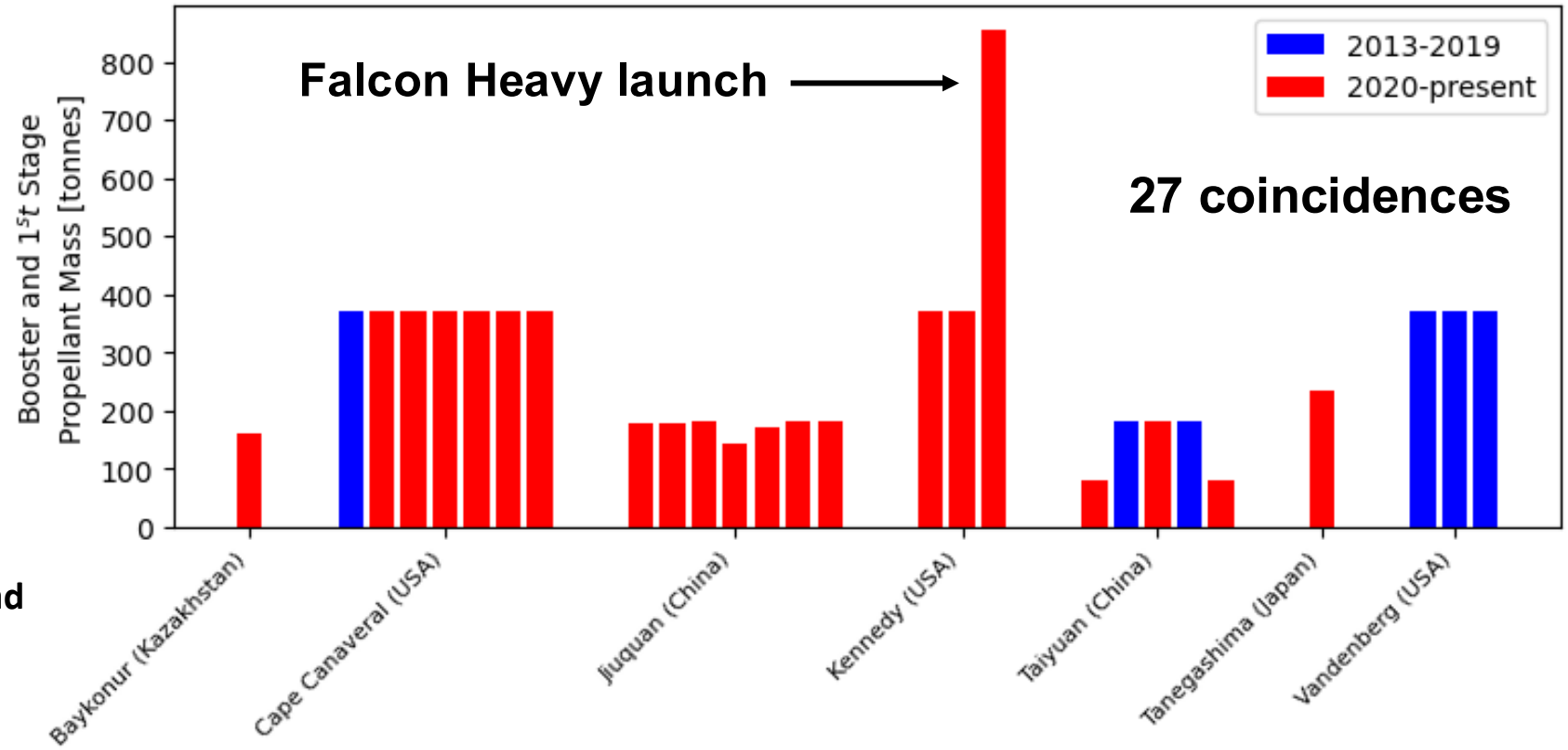
[Varon et al., PNAS, 2024]

Coincidence is a Challenge with Rocket Launches

Sentinel-2 (2A, 2B, 2C)
60m resolution (UB)
5-day revisit time
Since 2015

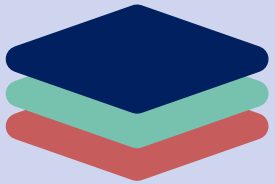
Landsat 8-9
30m resolution
8-day revisit time
Since 2013

Landsat and Sentinel-2 cloud-free launch-overpass coincidences



Adapt Power Plant Retrieval Method

1 Build the Reference



Identify reference scenes for average ‘idealized’ reference

2 Obtain Normalized Reflectance Ratio

scale factor

target

$$r = \frac{c\,R_i}{R_j}$$

reference

Used ratio approach to isolate plume signal

3 Calculate NO_2 Vertical Column

$$\Delta\Omega_V = -\frac{\ln(r)}{\sigma \times AMF}$$

scattering air mass factor

absorption cross-section

Convert ratio to the NO_2 vertical column.

4 Mask the Plume

Smooth and use percentile filter to mask plume

5 Second Retrieval

Refine estimate by repeating with plume pixels removed

6 Calculate Emissions

$\Delta\Omega_V \rightarrow$

Use Integrated Mass Enhancement (IME) method

Plume from Sentinel-2 at Chinese Launch Site

Launch plume NO_2 at the Jiuquan Satellite Launch Centre in Northwest China

Launch on 29 July 2021

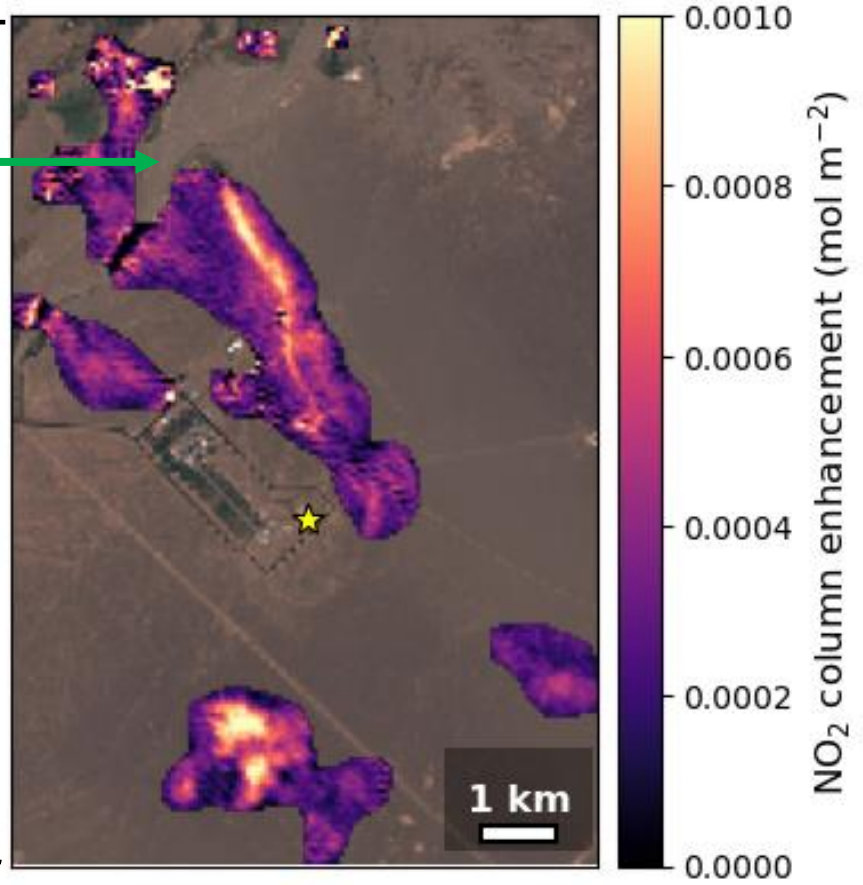
Sentinel-2 overpass 15 min after liftoff

Rocket burns 183 tonnes hypergolic propellant

Sentinel-2 RGB image of the launch site

Surface water may "break up" the plume.

NO_2 enhancement retrieved from Sentinel-2



Plume from Landsat at Kazakhstan Launch Site

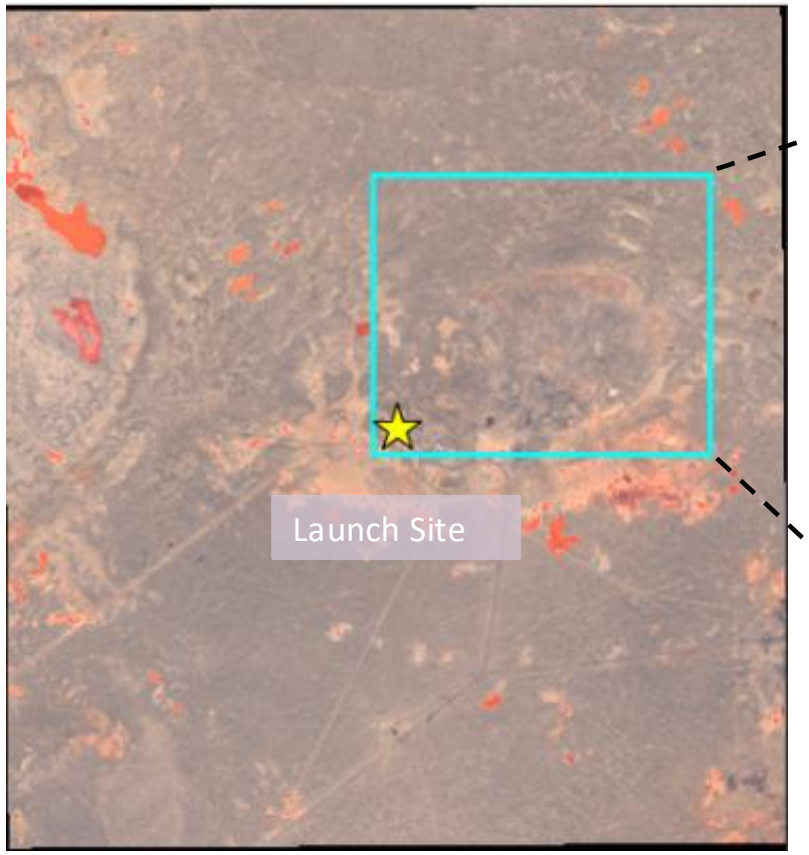
Launch plume NO_2 at the Baikonur Launch Centre in Kazakhstan

Launch on 8 April 2025

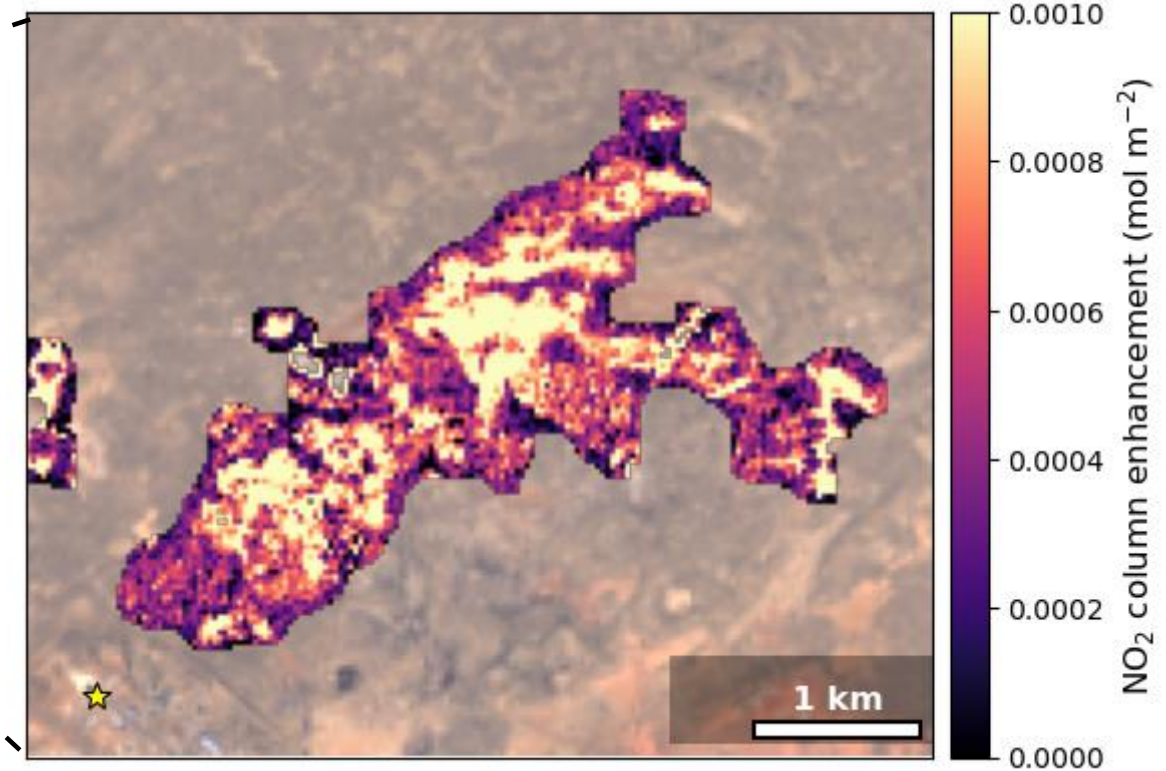
Landsat overpass 41 min after liftoff

Rocket burns 162 tonnes kerosene propellant

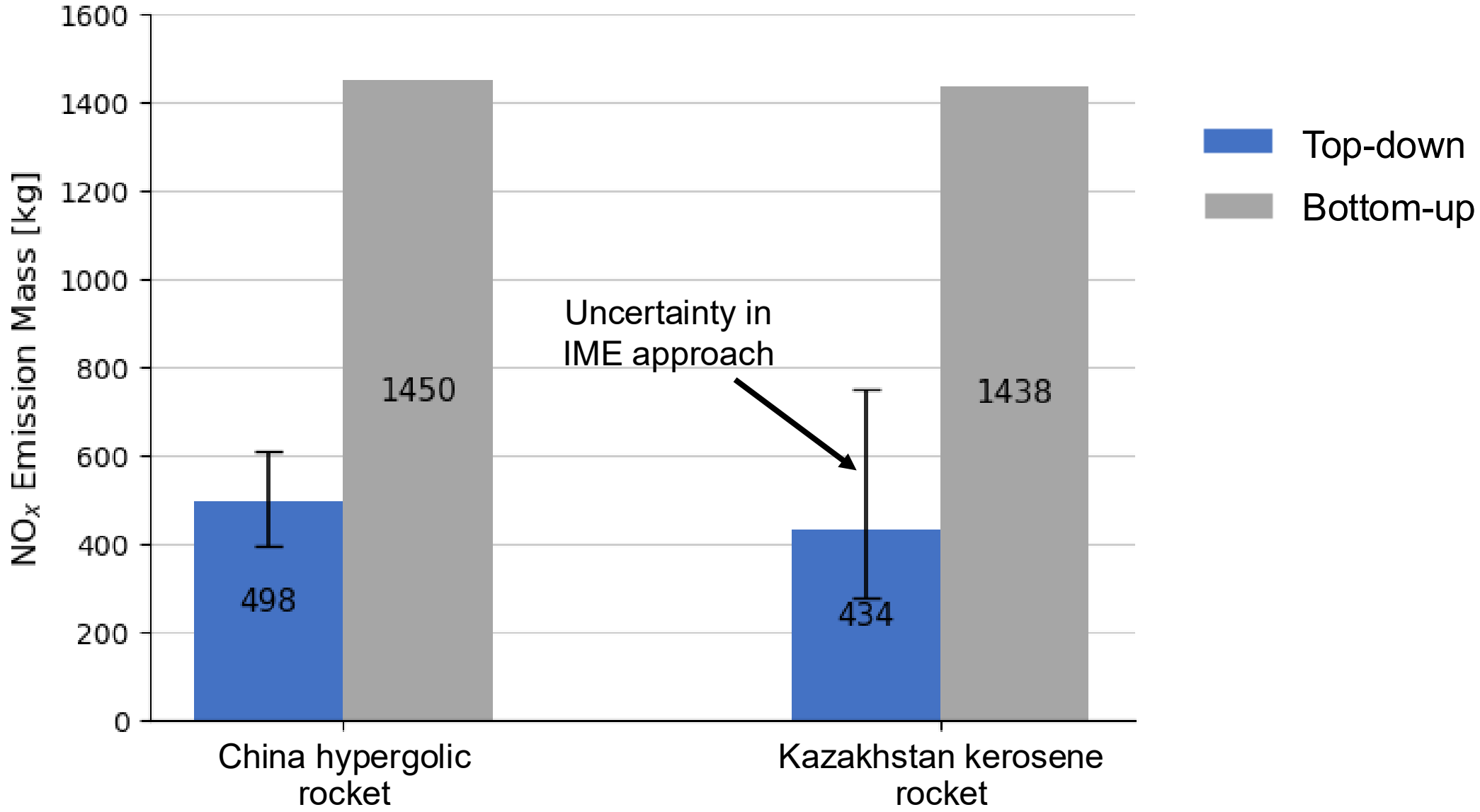
Landsat RGB image of the launch site



NO_2 enhancement retrieved from Landsat



Top-down versus Bottom-up NO_x Emissions



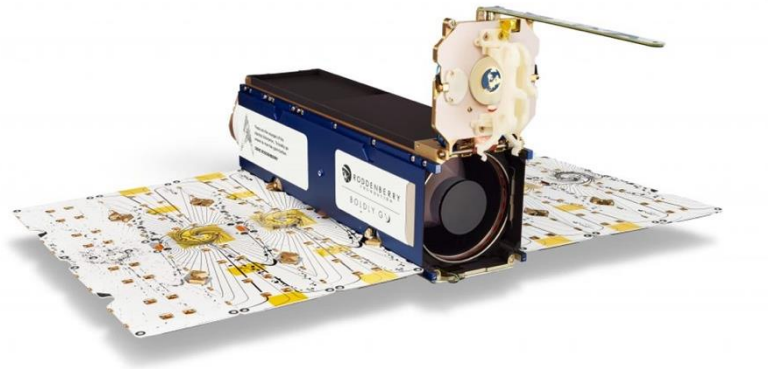
Top-down NO_x emissions are consistent with each other, but much less than bottom-up estimate

Conclusions and Next Steps

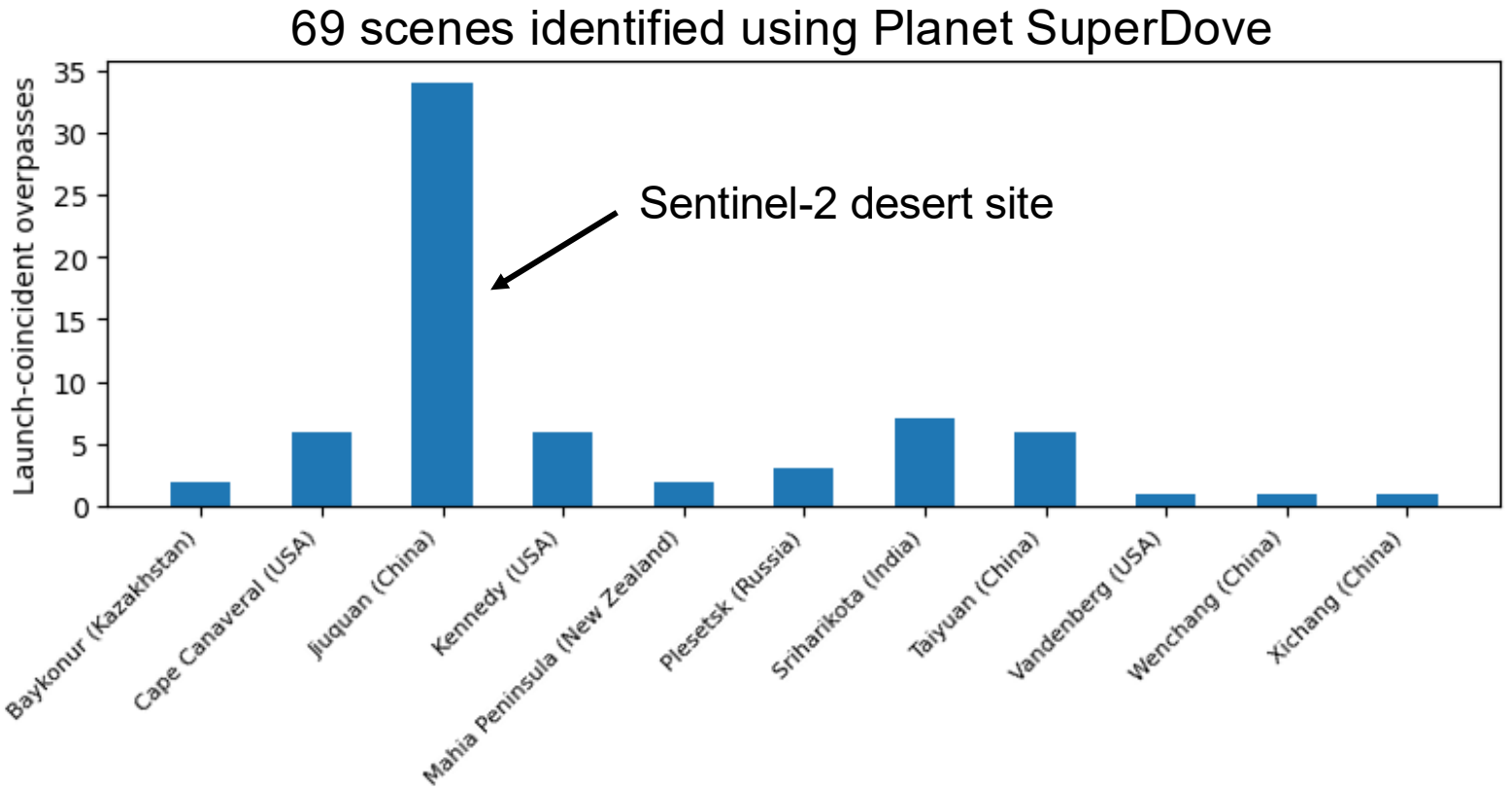
- Initial results demonstrate potential of space-based sensors to calculate rocket launch NO_x emissions.
- High-resolution broadband retrievals are currently limited to barren desert scenes.
- 3-fold underestimate consistent with use of TEMPO instrument to estimate rocket launch NO_x emissions

Next steps:

- Explore potential to use Planet SuperDove constellation (3 metre resolution, daily revisits).

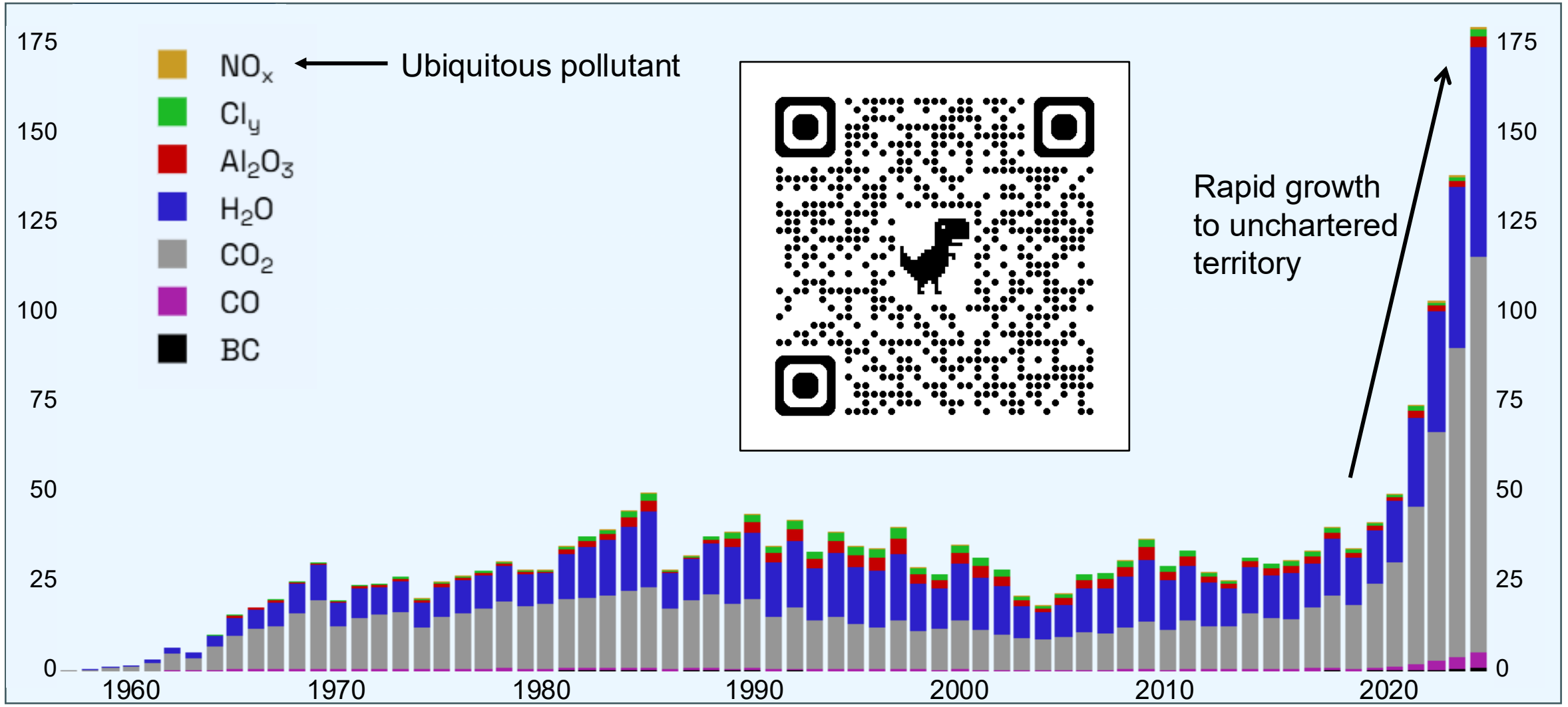


Planet SuperDove satellite



Interactive Emissions Tracker: orbitalemissions.org

Track rocket launch emissions [in kilotonnes] since the first orbital launch



Also tracking re-entry emissions: https://orbitalemissions.org/reentries.html