Environmental Impacts of Spacecraft <u>Launches</u> and Re-entries

Eloise A. Marais, COSPAR-26-PEDAS.1, 3 August 2026

UCL

Advanced Research + Invention Agency ARIA

Launch and Re-entry Emissions and Impacts

Launches (0 km to orbit)

Hydrogen
Kerosene
Methane
Hypergolic
Solid
Bio-propellants

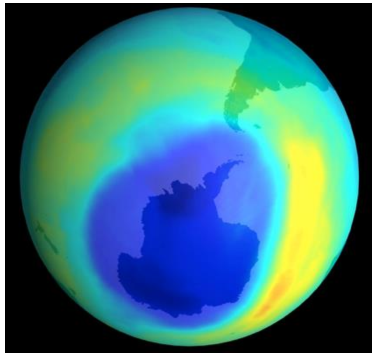
Re-entries (60-80 km)

Payloads
Components
Capsules
Rocket Bodies
Debris

H_2O
Al_2O_3

BC
NO_x
Chlorine
Metal oxides

Stratospheric Ozone Loss



Affected by all emitted compounds

Instantaneous Climate Forcing

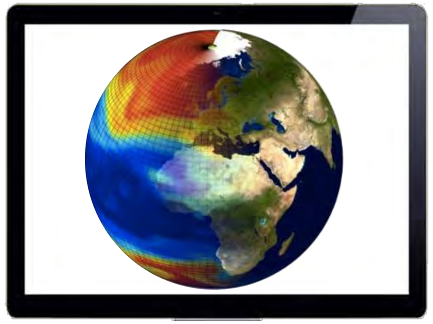
BC | Al_2O_3 | Stratospheric clouds

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

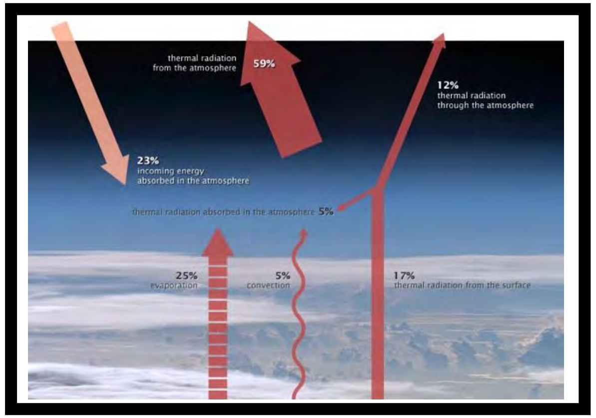
Reliance on Models to Quantify Global Impacts

3D launch and re-entry emissions

GEOS-Chem



Chemistry Transport Model



Radiative Transfer Model

Impact on atmospheric composition (e.g., ozone loss)

Impact on climate

Calculate emissions for 2020-2022 and project to end of decade for input to GEOS-Chem

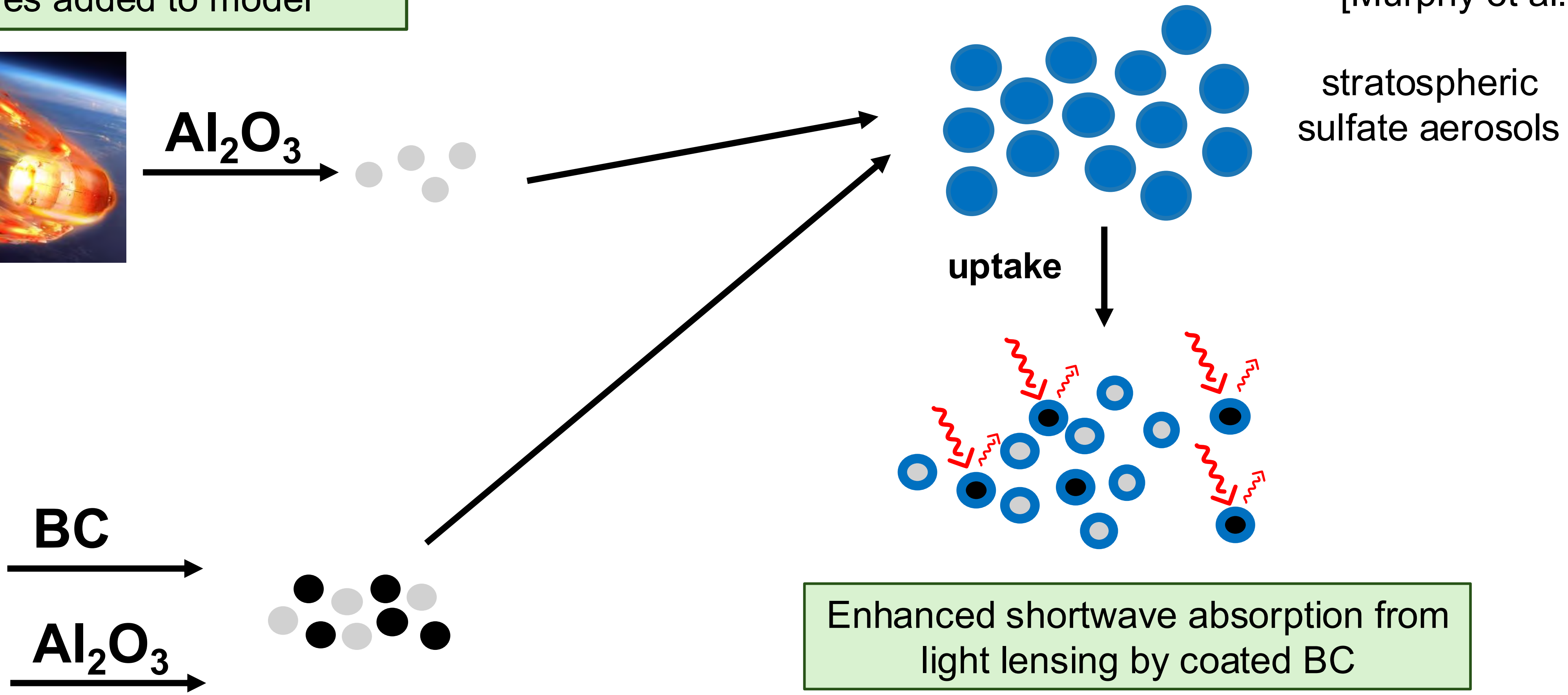
UCL Modelling Studies using GEOS-Chem: Ryan et al. (2022), Barker et al. (2026)

Update GEOS-Chem Model with Latest Science

Alumina (Al_2O_3) from launches and re-entries added to model

Prompt uptake of BC and Al_2O_3 to stratospheric sulfate

[Murphy et al., 2023]



Enhanced shortwave absorption from light lensing by coated BC

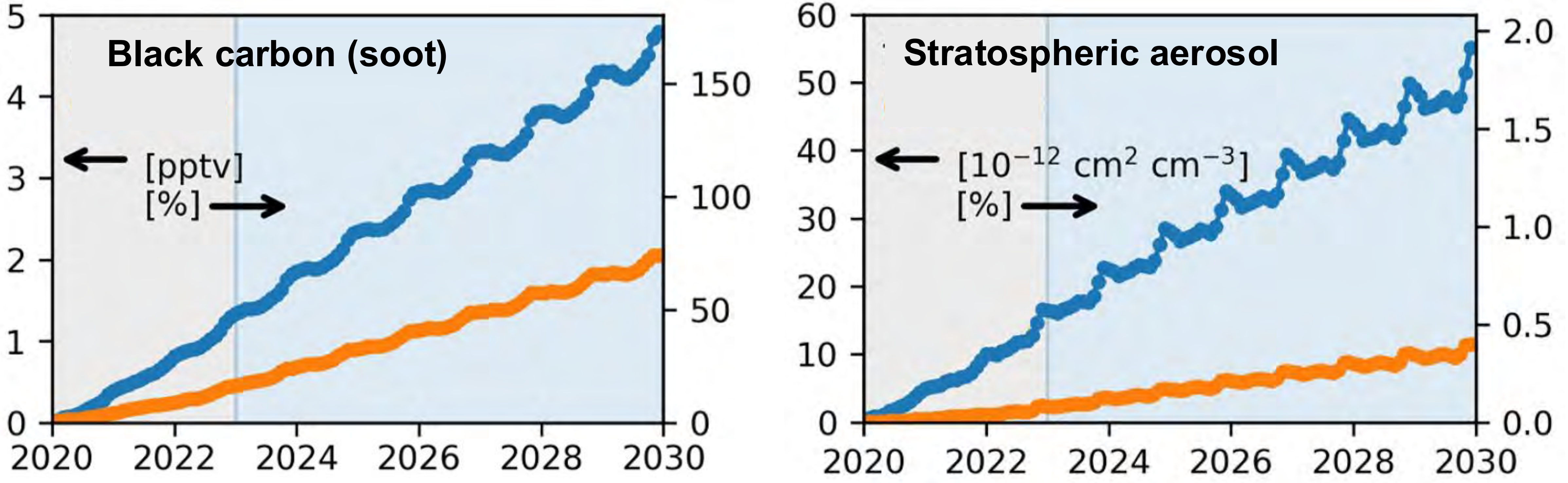
not to scale

Many more compounds formed during re-entry. Depends on material re-entering.

[Barker et al., 2026]

Effects on Stratospheric Composition

Model changes in global monthly mean stratospheric black carbon and liquid aerosols



Orange: Megaconstellation missions
Blue: All types of missions

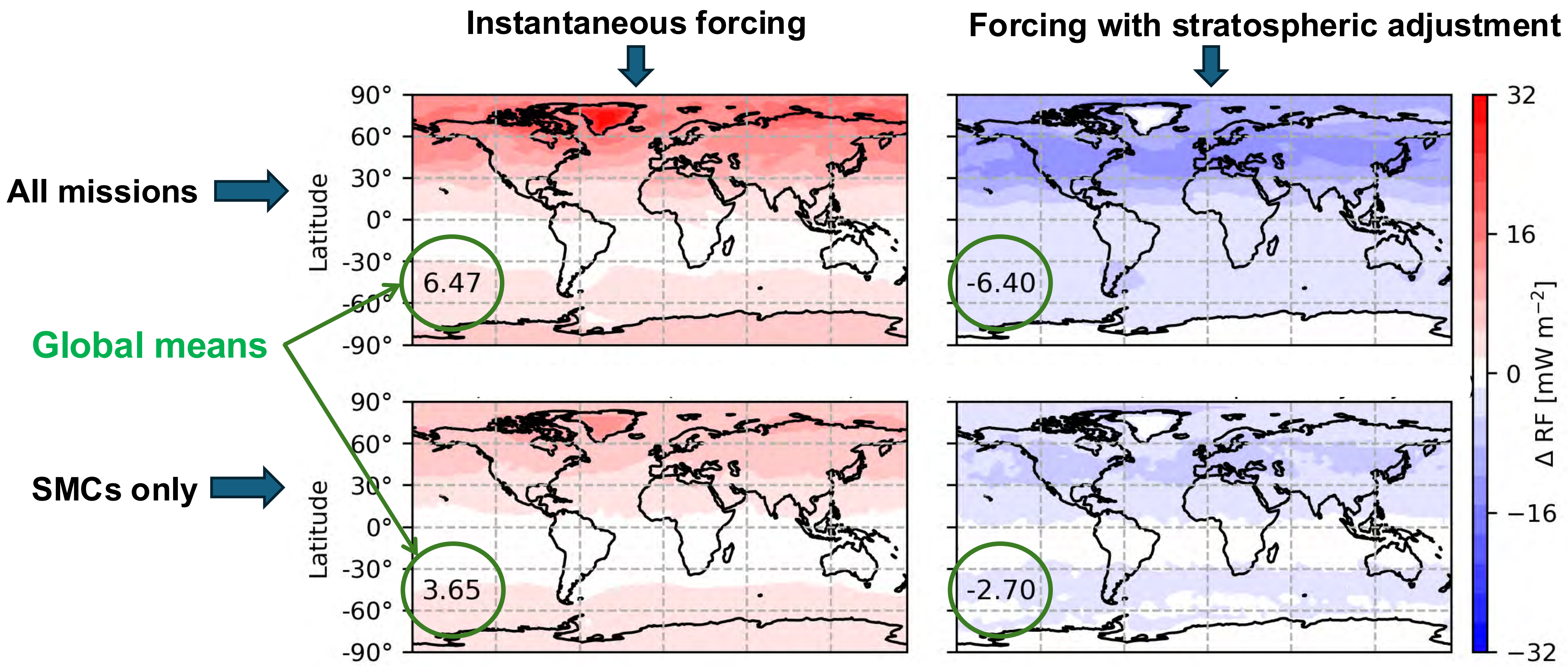
Megaconstellations ramp up from 38% of BC in 2020 to 44% by 2029

Stratospheric liquid aerosols (precursors to stratospheric clouds) increase mostly due to uptake of launch and re-entry alumina (Al_2O_3)

[Barker et al., 2026]

Global Climate (Radiative Forcing) Changes

Annual mean radiative forcing by 2029 calculated with the coupled radiative transfer model

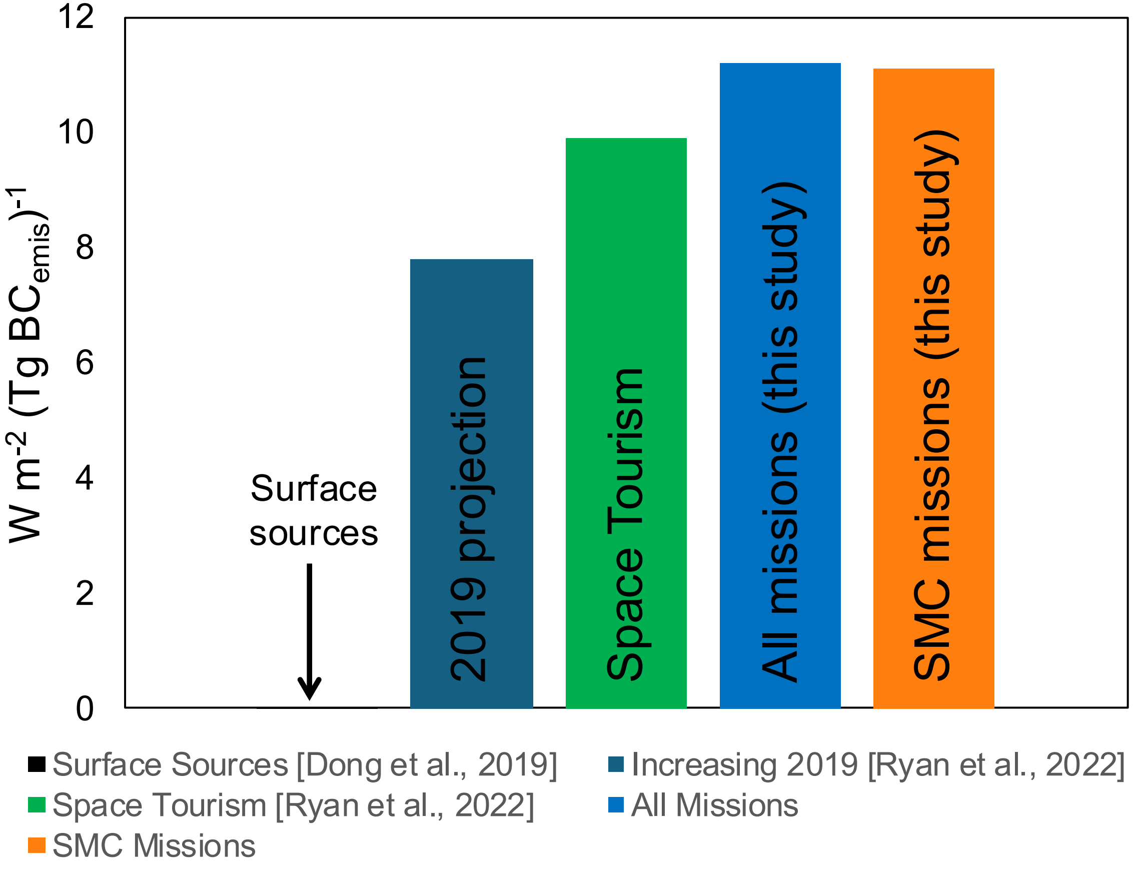


Instantaneous positive from absorption of incoming sunlight by aerosols in the stratosphere

Decline in incoming sunlight reaching the troposphere leads to negative stratospherically adjusted values

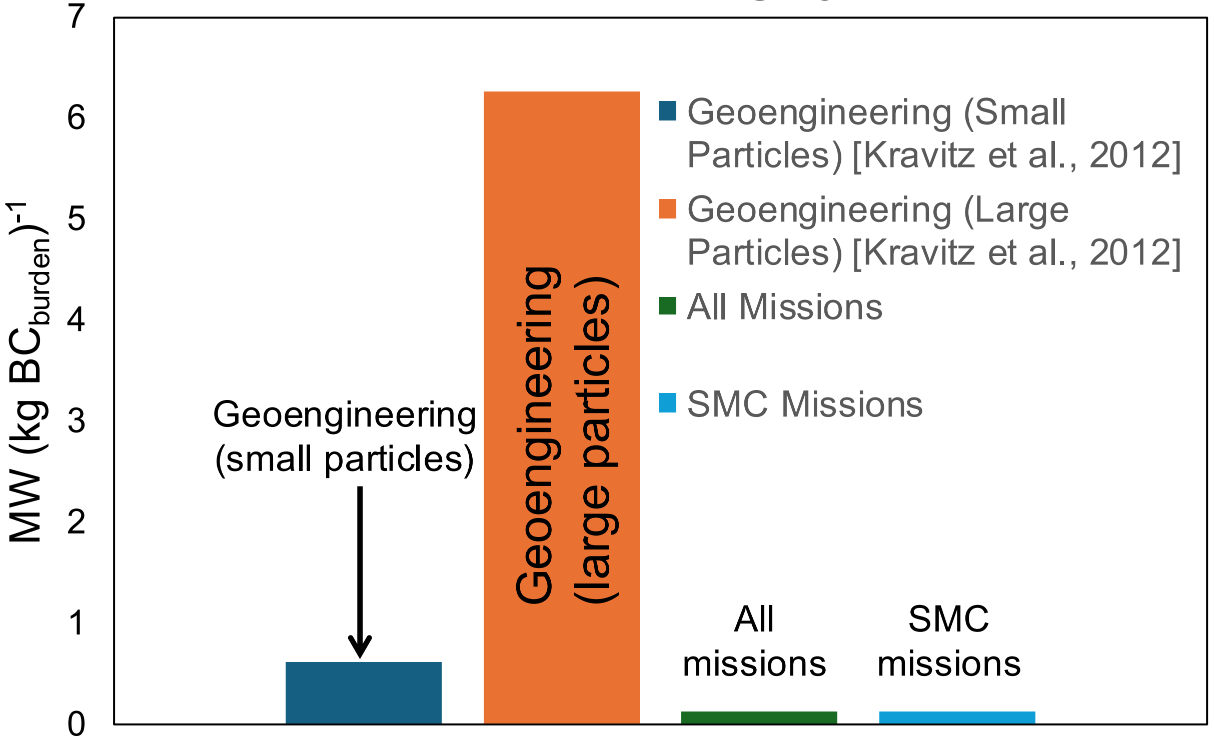
Contextualizing Spacecraft Radiative Forcing

Emissions Normalized Instantaneous Radiative Forcing by BC



Emissions normalized forcing is ~540 times more than all Earth-bound sources, as BC persists for longer higher up

Burden Normalized Instantaneous Radiative Forcing by BC



Burden normalized forcing less than geoengineering model experiments with 3 orders of magnitude more BC released to the stratosphere than is emitted by spacecraft

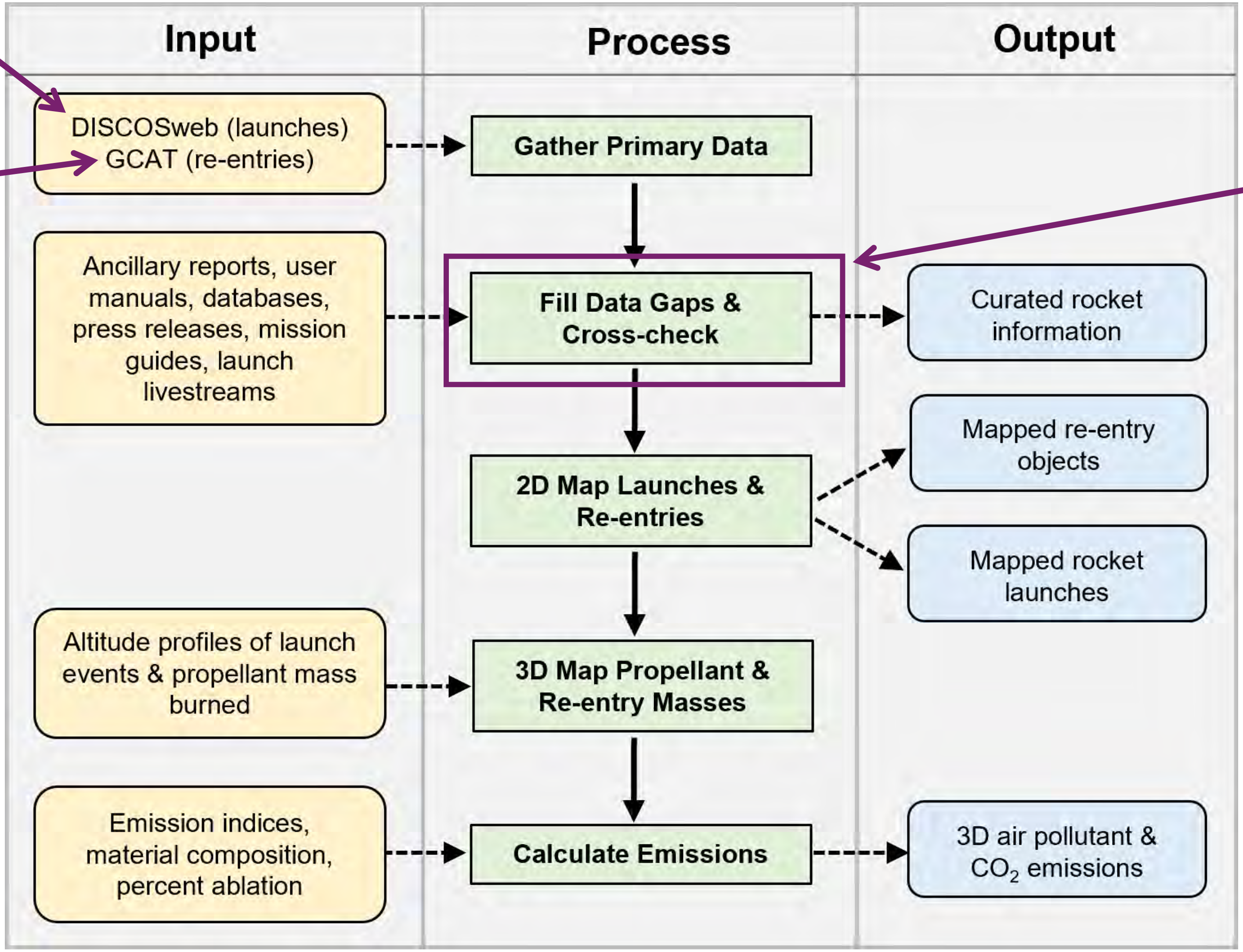
SMC: satellite megaconstellation

UCL Emissions Inventory Development

Initial inventory developed for **2020-2022** and legitimized by peer review

ESA database

Catalogue maintained by Jonathan McDowell



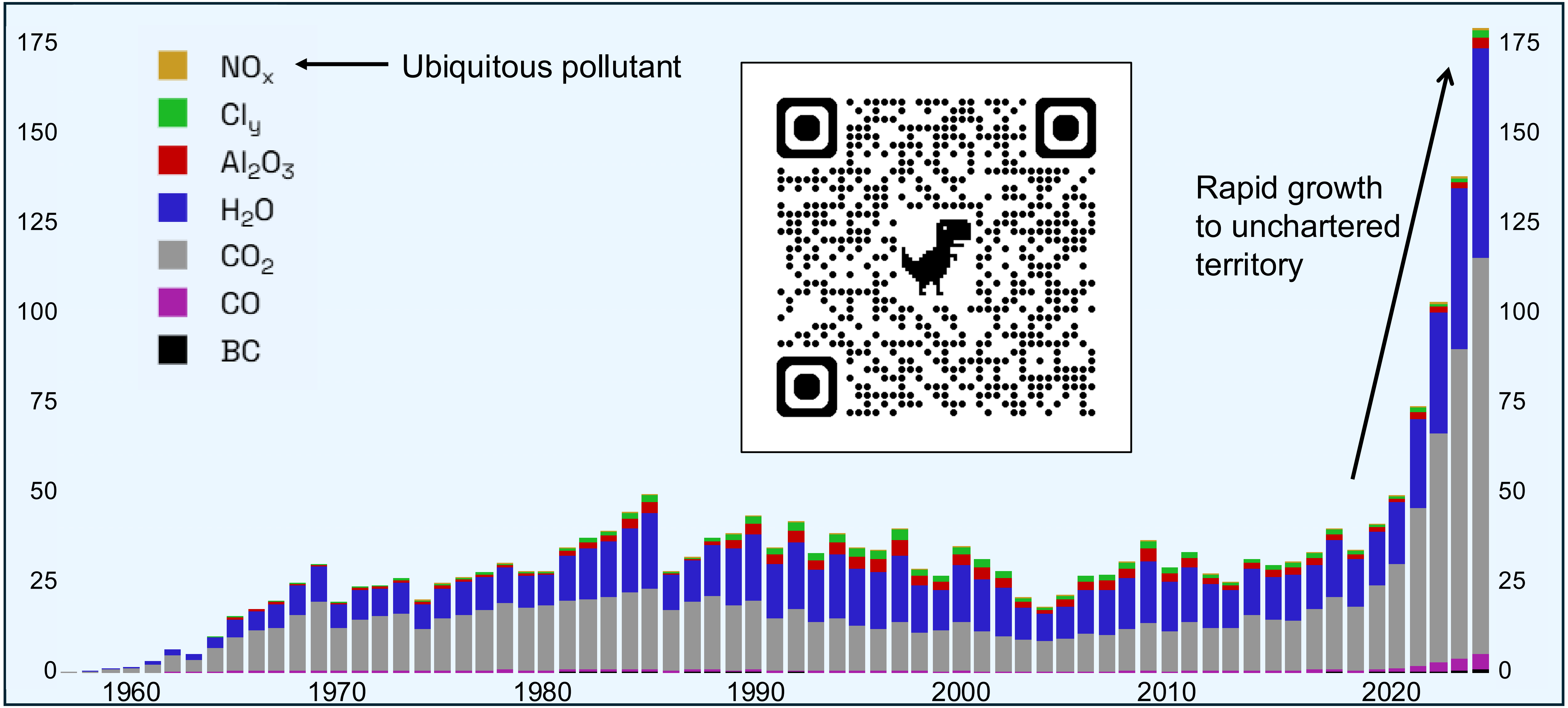
Critical step:

- Data gaps
- Incorrect data
- Inconsistent data

[Barker et al., 2024]

Spun out into Emissions Tracker: orbitalemissions.org

Rocket launch air pollutant and CO_2 emissions in kilotonnes from 1957 to 2025

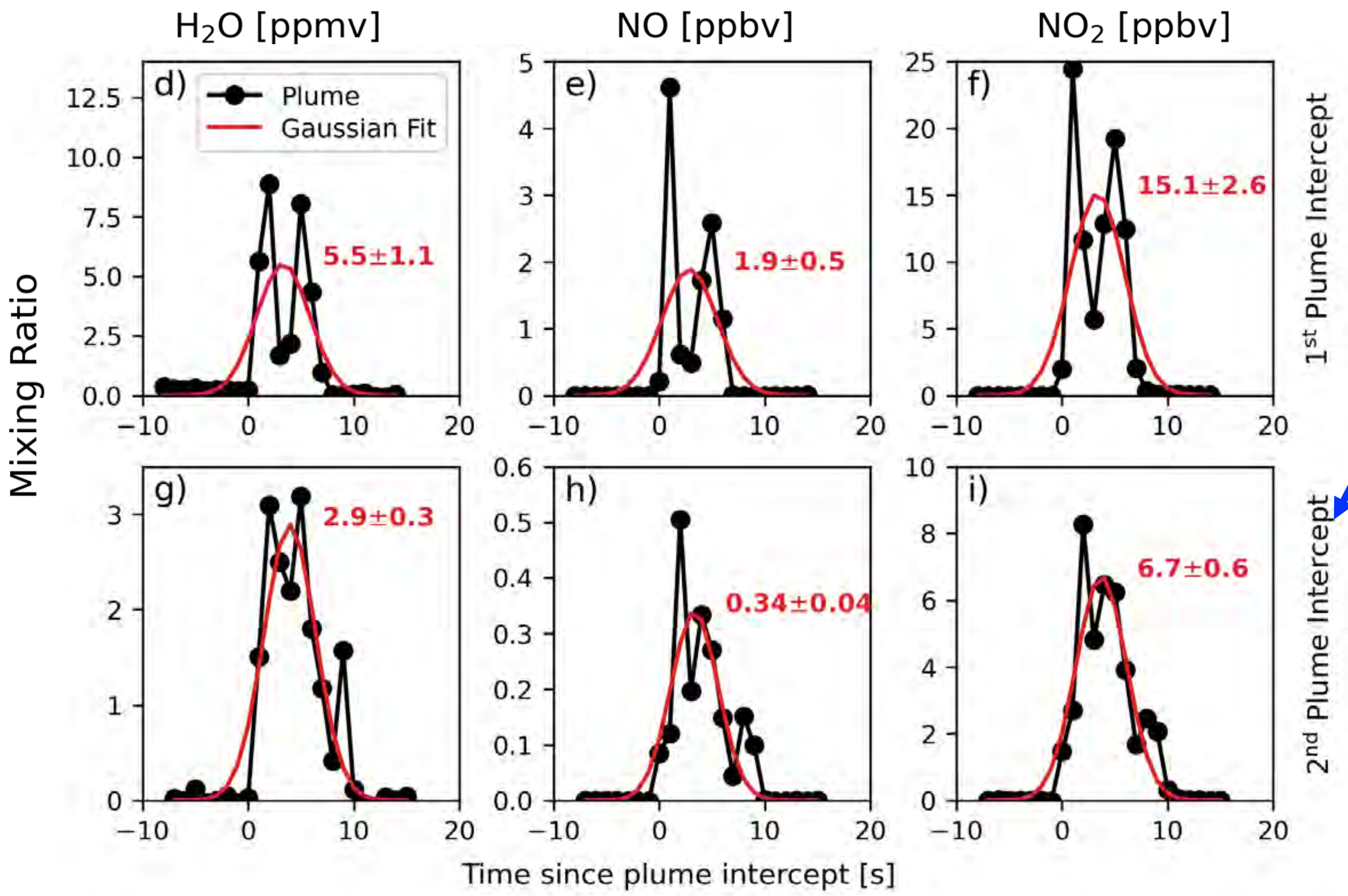


[https://orbitalemissions.org/launches.html]

Emissions data are uncertain, outdated, under-validated. Urgent need for observational constraints!

Evaluation Against In Situ Aircraft Measurements

Gaussian fit to Falcon 9 plumes measured during SABRE 2023 aircraft campaign



1st intercept

2nd intercept

Both intercepts at ~16 km

Measurements:

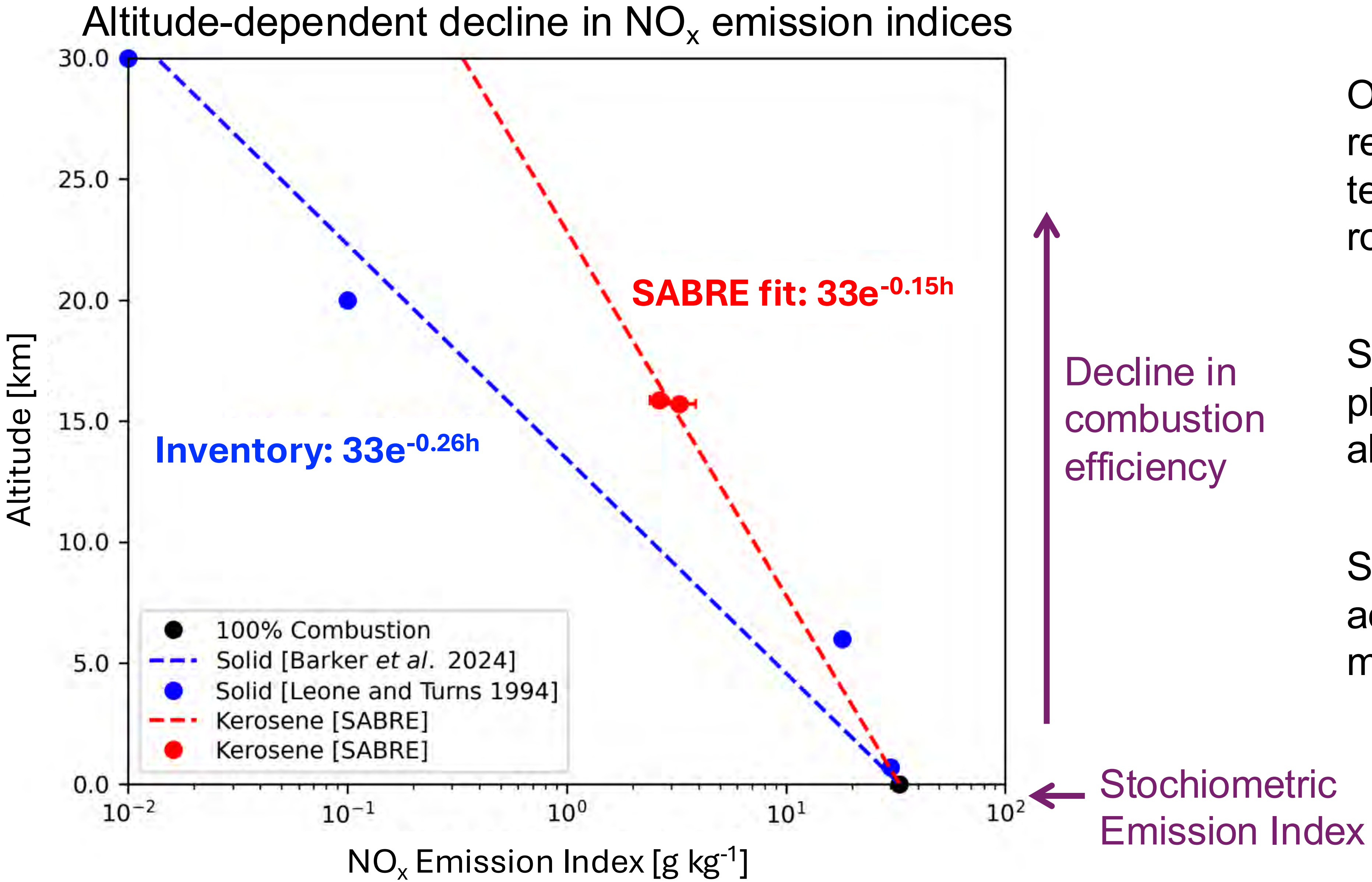
$\Delta NO_x/\Delta H_2O$ = 6-8 ppb ppm^{-1}

Inventory:

$\Delta NO_x/\Delta H_2O$ = ~1 ppb ppm^{-1}

Use H_2O rather than CO_2, as H_2O is conserved with altitude. Similar results if integrate under plume

Measured vs Inventory Vertical Emissions Profiles



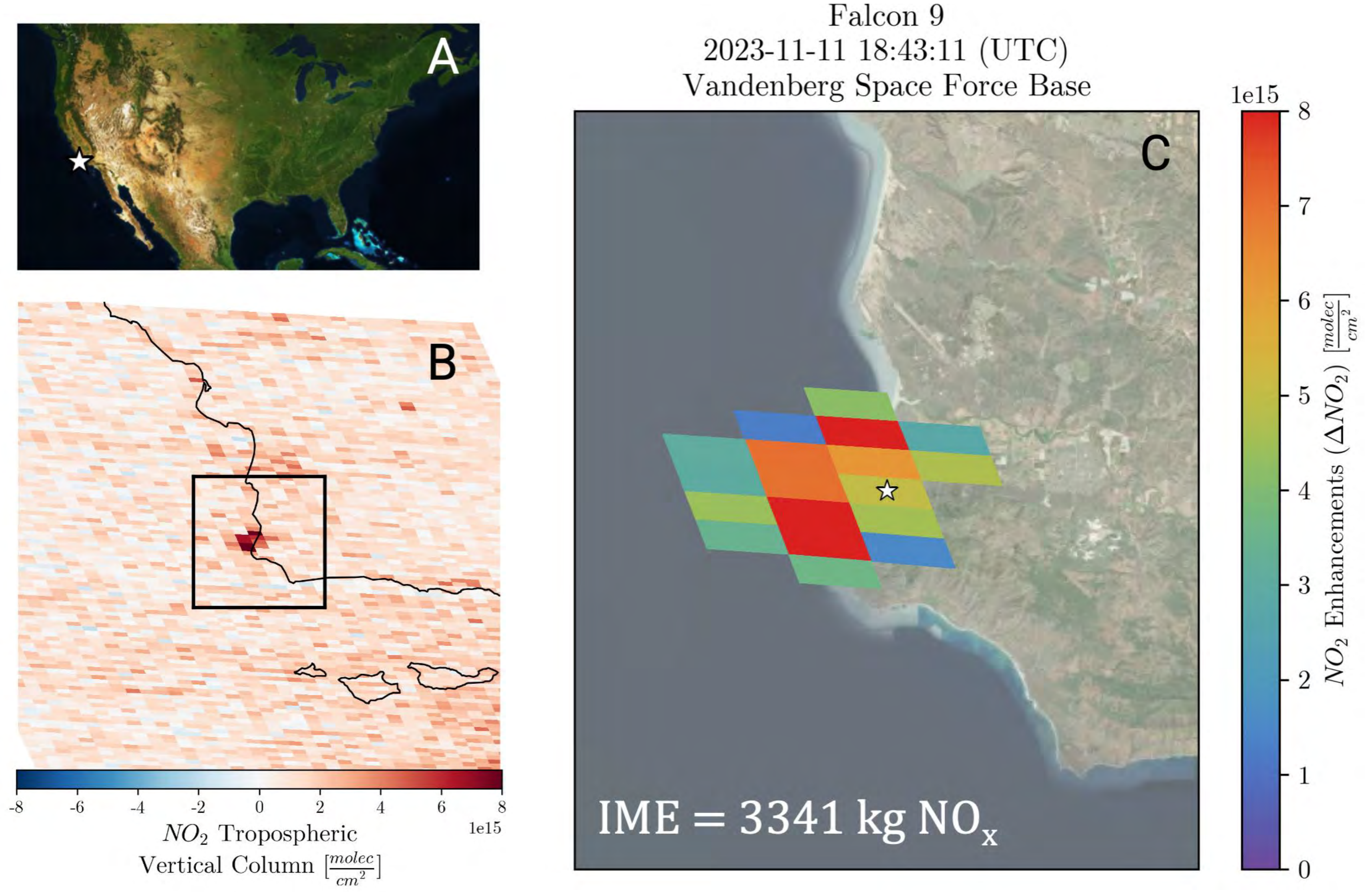
Original profile from 1994 report of outdated rocket technologies (mostly solid rockets)

SABRE only intercepted plume twice at same altitude

Shows what could be achieved with more measurements!

Decline in combustion efficiency with altitude more gradual than assumed in the inventory

NO_x Emissions Derived with Satellite Observations



Convert integrated tropospheric columns of NO_2 from TEMPO into NO_x emissions

Detects plumes from rockets burning at least 500 tonnes propellant (Falcon 9 1st stage)

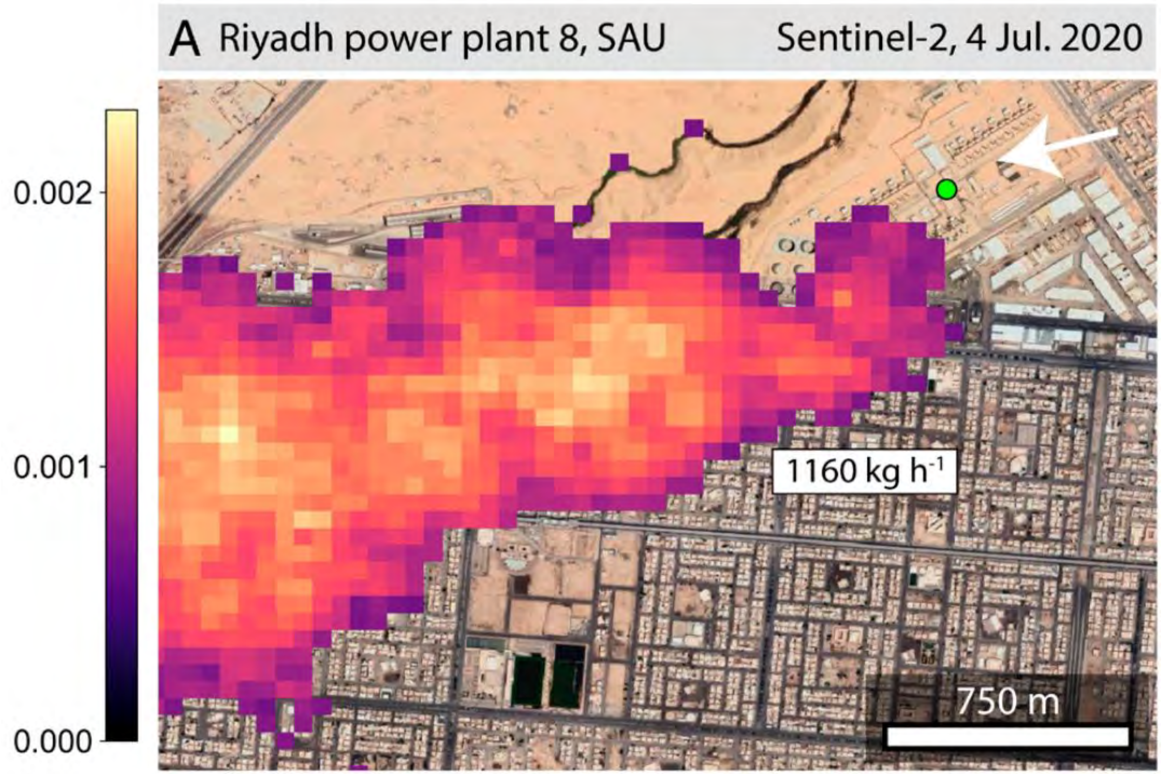
Plume resolved to ~2-3 km at best

18 plumes detected and quantified with this approach; mostly Falcon 9 rockets

[Palmo et al., GRL, *in review*]

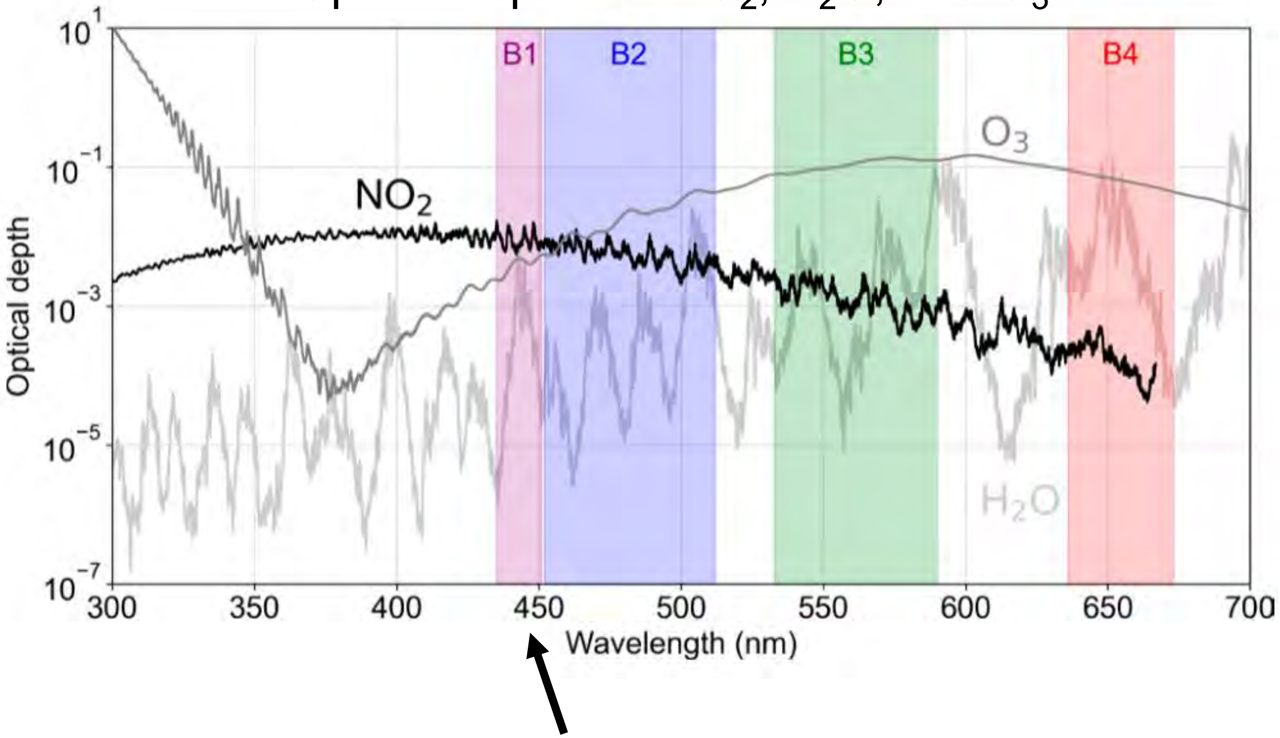
NO_x Emissions Derived with Satellite Observations

Plume NO_2 enhancement [mol m^{-2}] from Sentinel-2



Paper demonstrated use of broadband sensors to retrieve NO_2 plumes at high resolution (10-60m)

Optical depths of NO_2, H_2O, and O_3



NO_2 retrieval requires ultra blue band

[Varon et al., PNAS, 2024]

Launch NO_x emission rates (>5,000 kg h^{-1}) far exceed power plant NO_x emissions, but launches are transient

Launch and Broadband Sensor Coincidences

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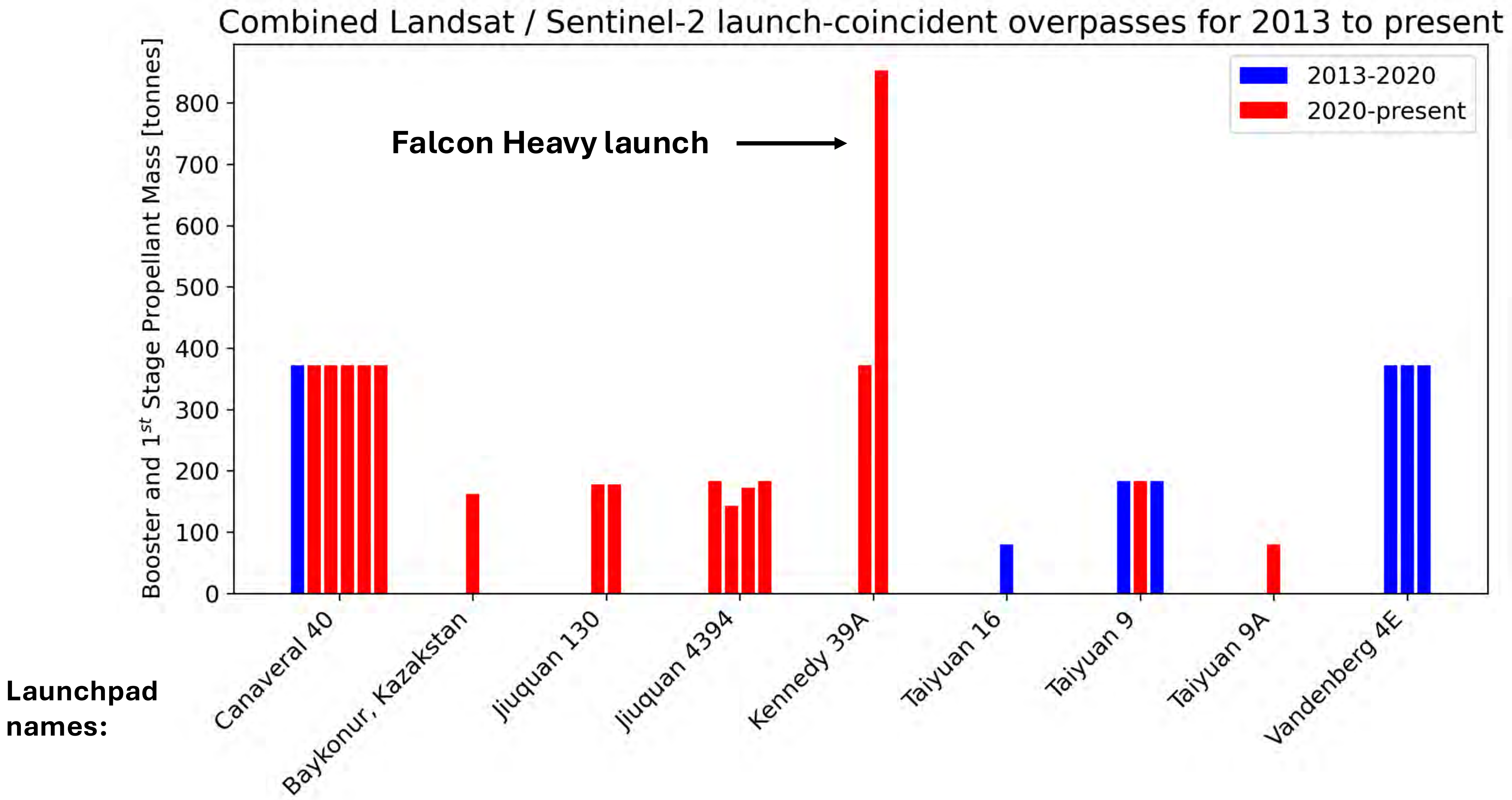
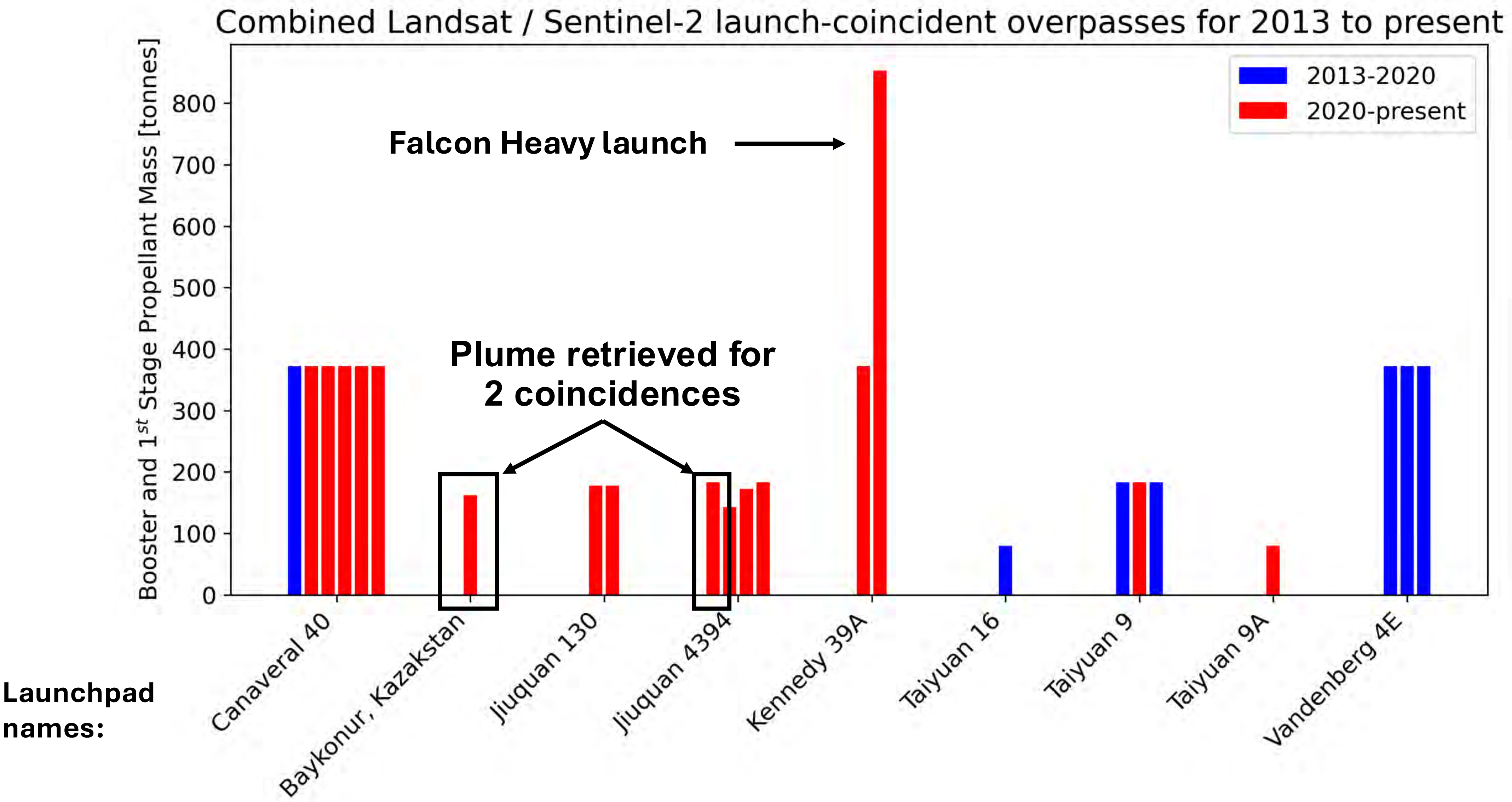


23 launch-coincident cloud-free overpasses detected
in the US, China, and Kazakhstan since 2013, mostly since 2020

Launch and Broadband Sensor Coincidences



23 launch-coincident cloud-free overpasses detected
in the US, China, and Kazakhstan since 2013, mostly since 2020

Rocket Plume at Jiuquan Launch Site in China

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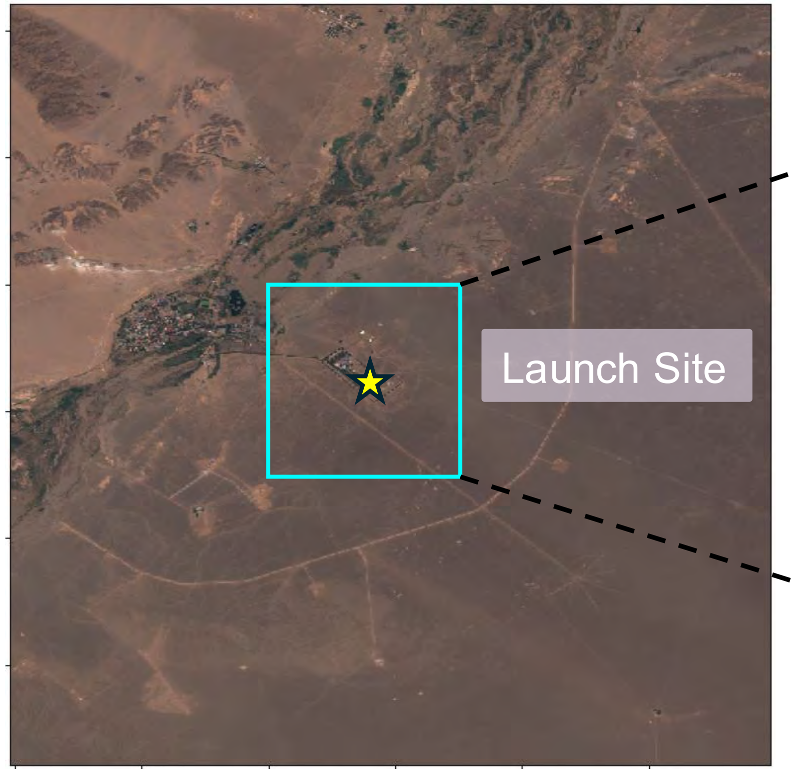
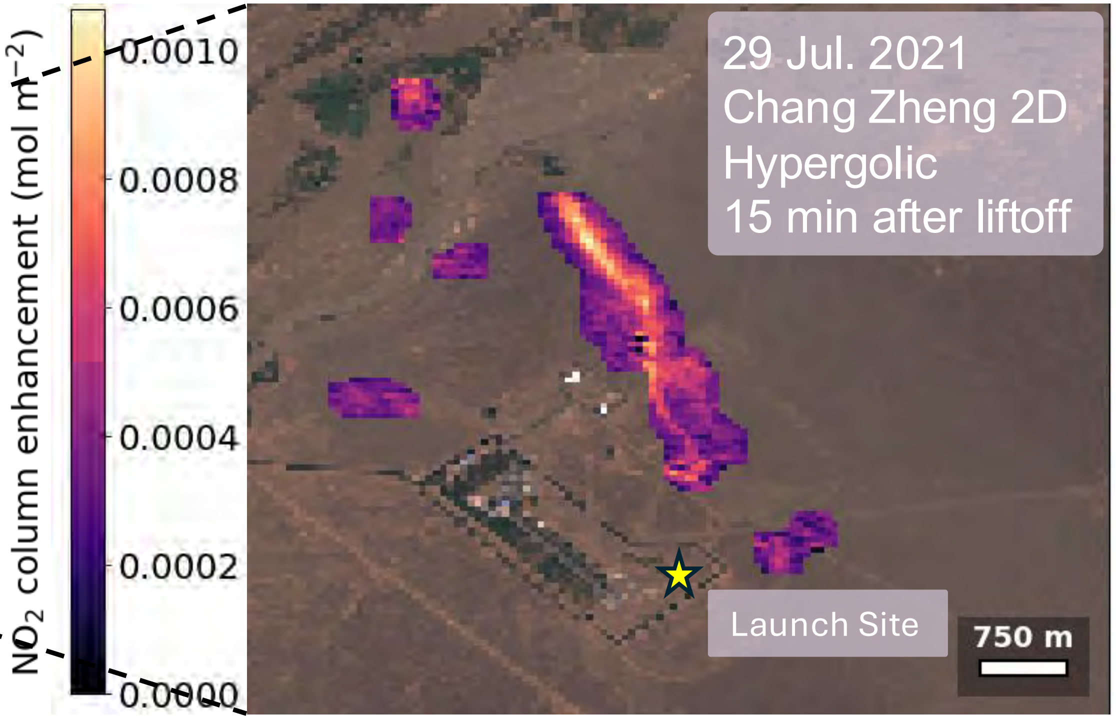
Detected an NO_2 plume at the Jiuquan Satellite Launch Centre in Northwest China:

Sentinel-2 RGB image of the launch site



NO_2 enhancement retrieved from Sentinel-2



Launch pad used for Chang Zheng (Long March) 2D rocket using hypergolic fuel (fuel banned in US)

****Early results**** of launch plume NO_2 from a small hypergolic propellant rocket in 2021

Surface water causes discontinuities in the plume

Rocket Plume at Baykonur Site in Kazakhstan

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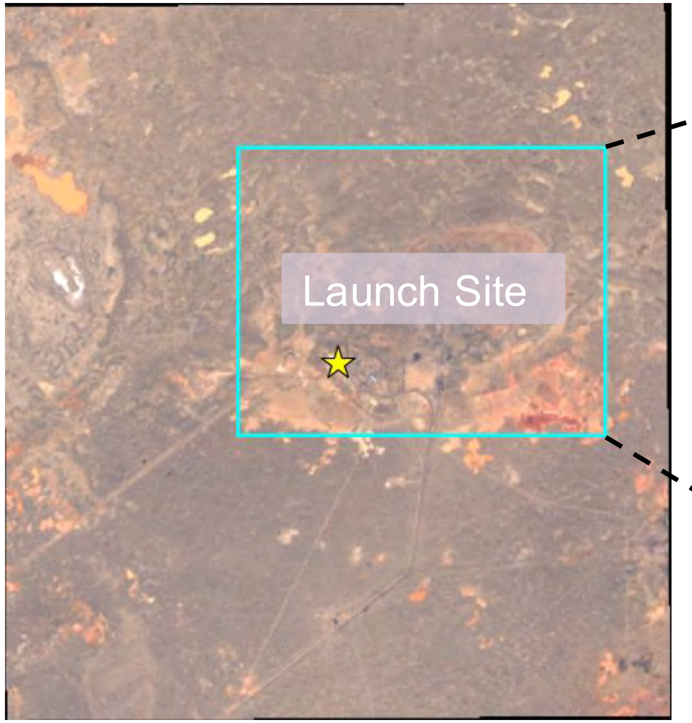
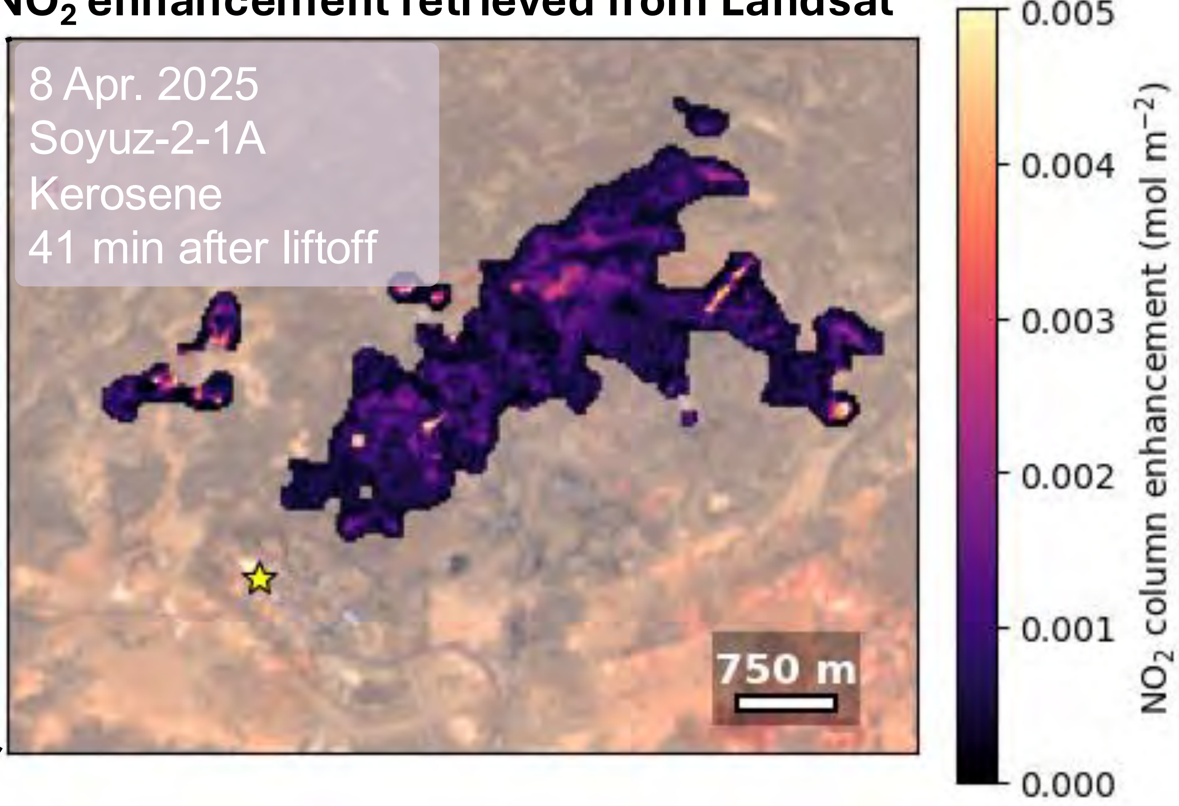
Detected an NO_2 plume at the Baykonur Launch Centre in Kazakhstan:

Landsat RGB image of the launch site



Launch pad used for Soyuz rockets using kerosene fuel (refined jet fuel)

NO_2 enhancement retrieved from Landsat

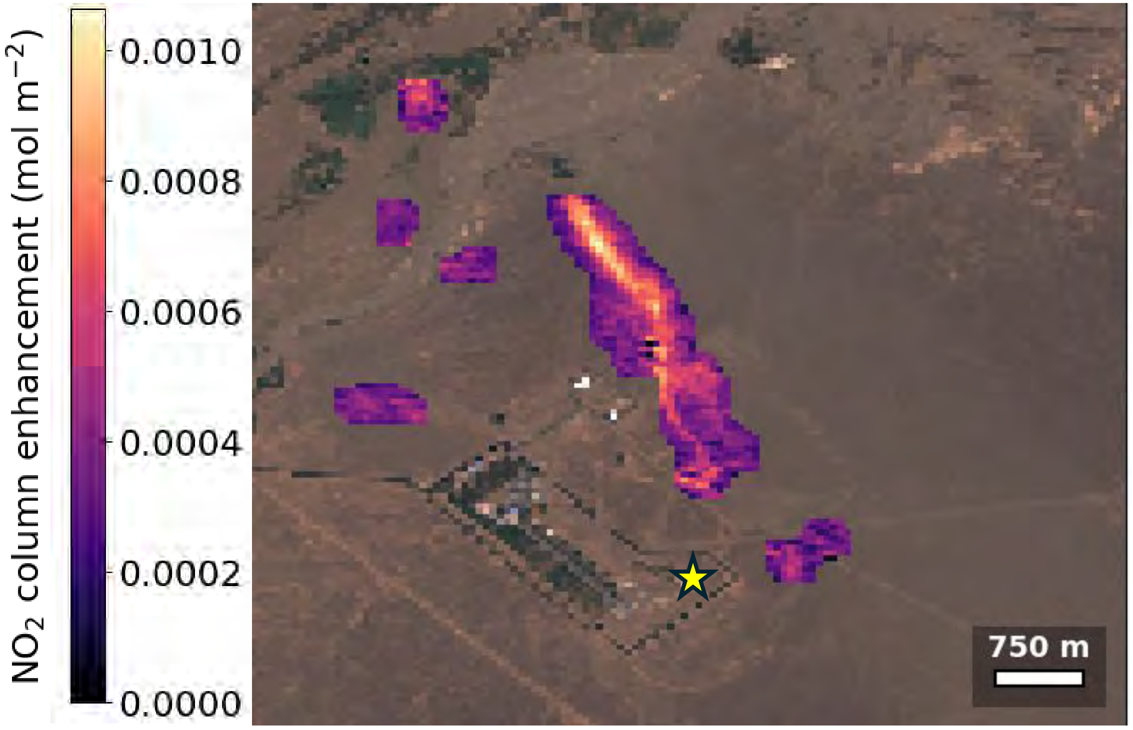


****Early results**** of launch plume NO_2 from a small kerosene propellant rocket in 2025

Both rockets yield plumes ~4-5 km long.

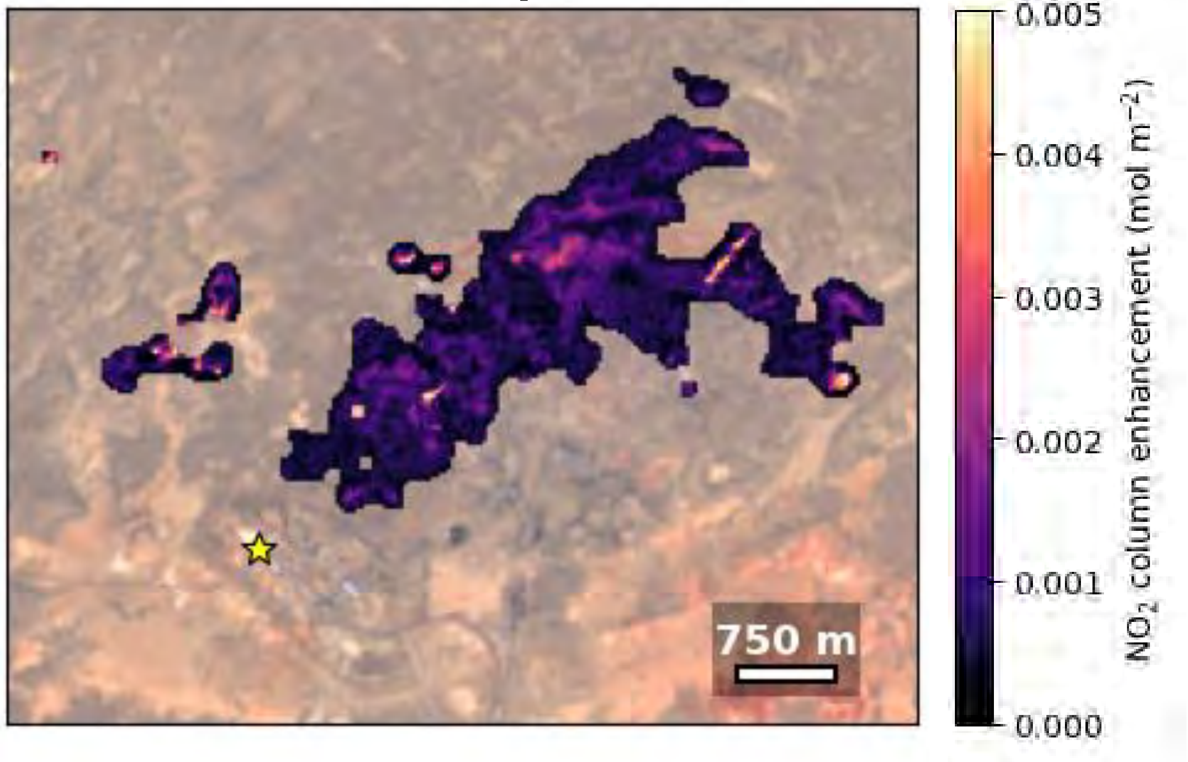
Plumes shown side-by-side

China launch pad:



Satellite-derived emissions: 448 (355-550) kg
Inventory emissions: 1450 kg
Propellant burned: 183 tonnes

Kazakhstan launch pad:



Satellite-derived emissions: 441 (350-542) kg
Inventory emissions: 1438 kg
Propellant burned: 162 tonnes

Achieve plume retrieval at launch sites over barren/desert land.

Variable surface reflectivity impacts retrievals at coastal launch sites.

Take-Home Messages and Next Steps

Megaconstellation mission emissions already half the climate effect of all launch black carbon emissions

Normalized radiative forcing of black carbon from spacecraft far surpasses that of Earth-bound emissions

Major climate effects are instantaneous warming in stratosphere and stratospherically adjusted cooling in the troposphere, but the size of the forcings are currently small

Inventory underestimate Falcon 9 NO_x emissions compared to emissions derived with aircraft observations

Space-based sensors demonstrate potential to calculate NO_x emissions from rocket launches, limited to large rockets for TEMPO, and limited to barren/desert scenes so far for broadband sensors.

Next critical steps:
→ Develop plume model to conduct synthetic retrieval and emissions inversion experiments
→ Apply retrieval to Planet sensors SuperDove and Tanager to increase chance of coincidences
→ Improve inventory estimates and project emissions due to anticipated growth

Details of Cited Sources

Ryan et al., Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate, Earth's Future, 10, e2021EF002612, doi:10.1029/2021EF002612, 2022.

Barker et al., Global 3D rocket launch and re-entry air pollutant and CO2 emissions at the onset of the megaconstellation era, Nature Scientific Data, 11, 1-15, doi:10.1038/s41597-024-03910-z, 2024.

Barker et al., Radiative forcing and ozone depletion of a decade of satellite megaconstellation missions, Earth's Future, 14, doi:10.1029/2025EF007229, 2026.

Palmo et al., Quantifying Rocket NO_x Emissions Using Geostationary Satellite Observations, Geophys. Res. Lett., in review, 2026.

Emissions Tracker: https://orbitalemissions.org/

Murphy et al., Metals from spacecraft reentry in stratospheric aerosol particles, PNAS, 120(43), doi:10.1073/pnas.2313374120, 2023.

More about the ARIA funded project can be found here: https://maraisresearchgroup.co.uk/rocket_emis.html and here: https://aria.org.uk/opportunity-spaces/scoping-our-planet/opportunity-seeds?cardId=unlocking-potential-to-quantify-spacecraft-pollution