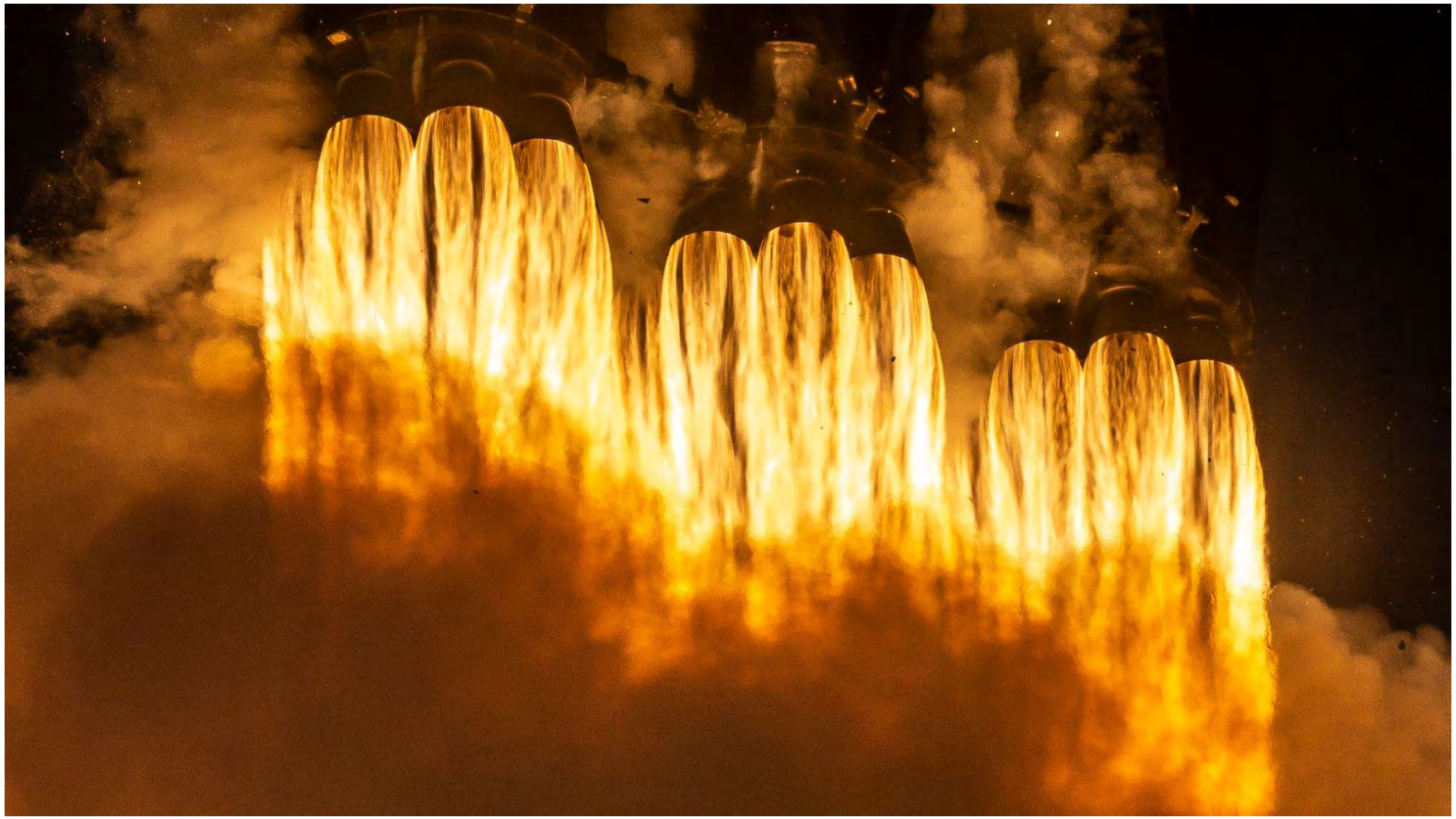
# Tracker of emissions of air pollutants and $CO_2$ from launches and re-entries

**Connor Barker**
with Jonathan McDowell

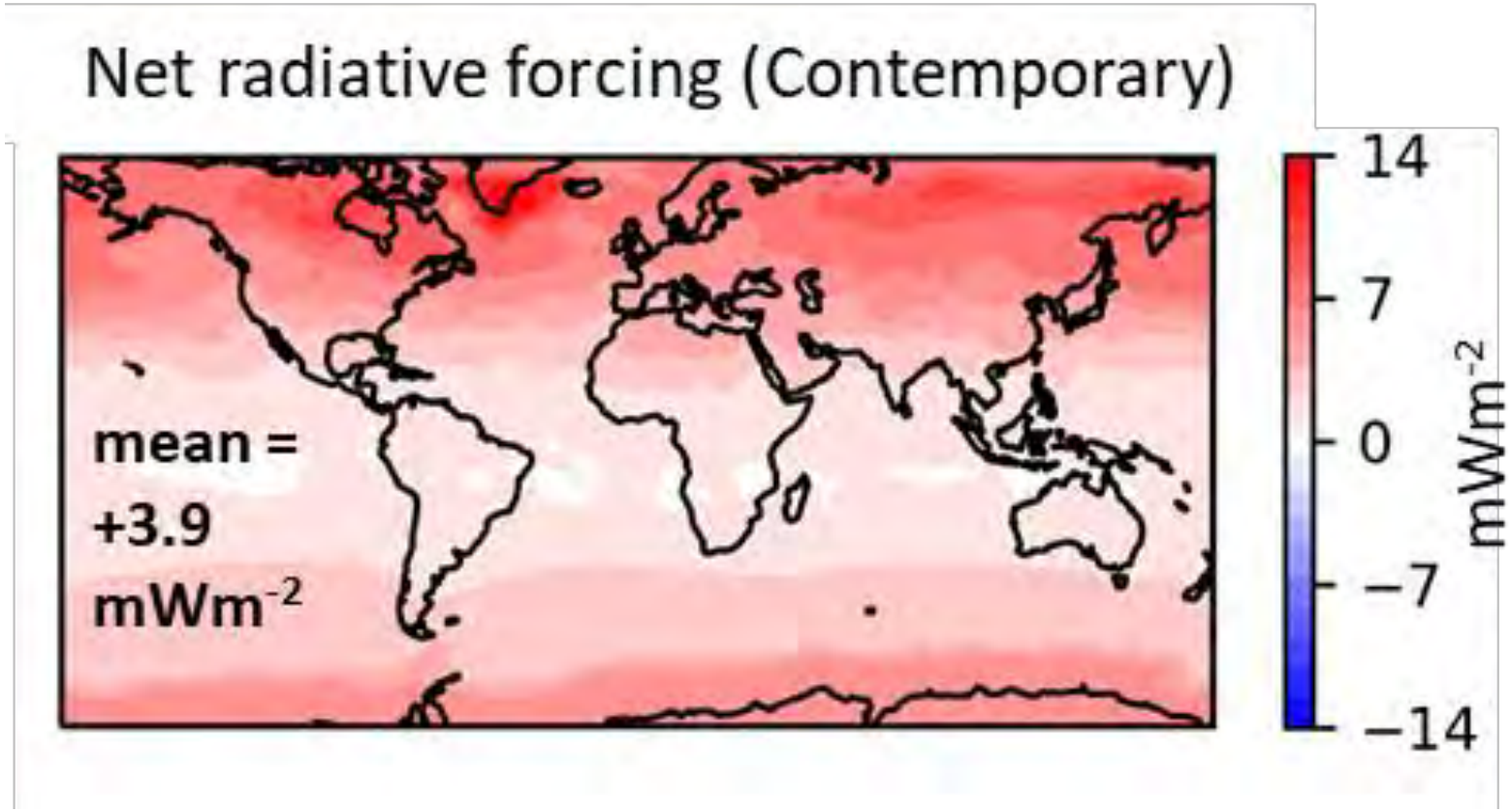
Starting Grant



2nd Workshop on Atmospheric Impacts of Spacecraft Launch and Re-entry, 25 September 2025
**Eloise Marais**, e.marais@ucl.ac.uk, https://maraisresearchgroup.co.uk/

# Climate Impact of Contemporary Rocket Launches

Ryan, Marais et al. [2022], https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002612:

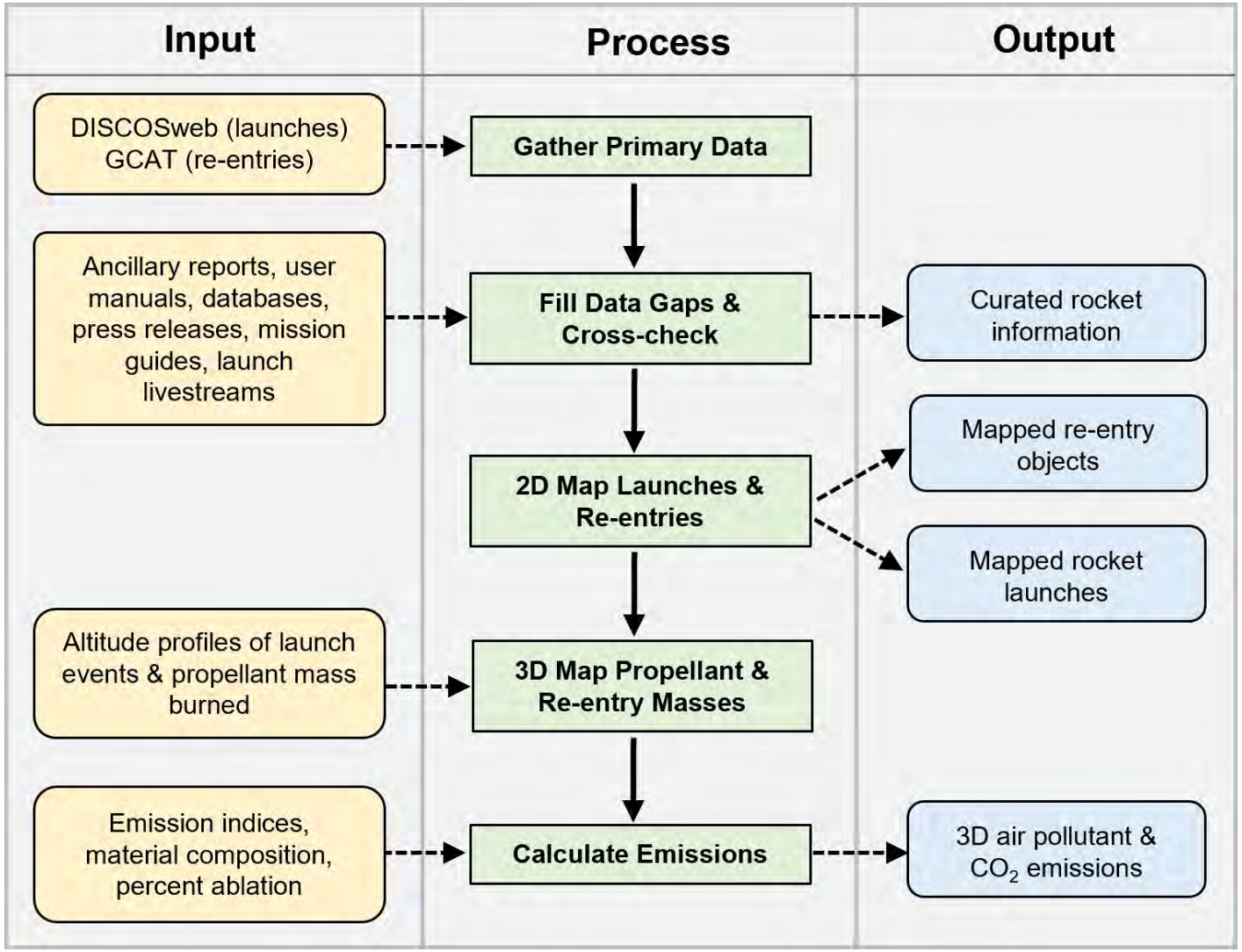



**Rocket black carbon per-mass radiative forcing 500-times more than Earth-bound sources**

But … we projected a decade of growth relative to 2019 far more modest (~6% per year) than is occurring (megaconstellations)

# Emissions inventory processing pipeline

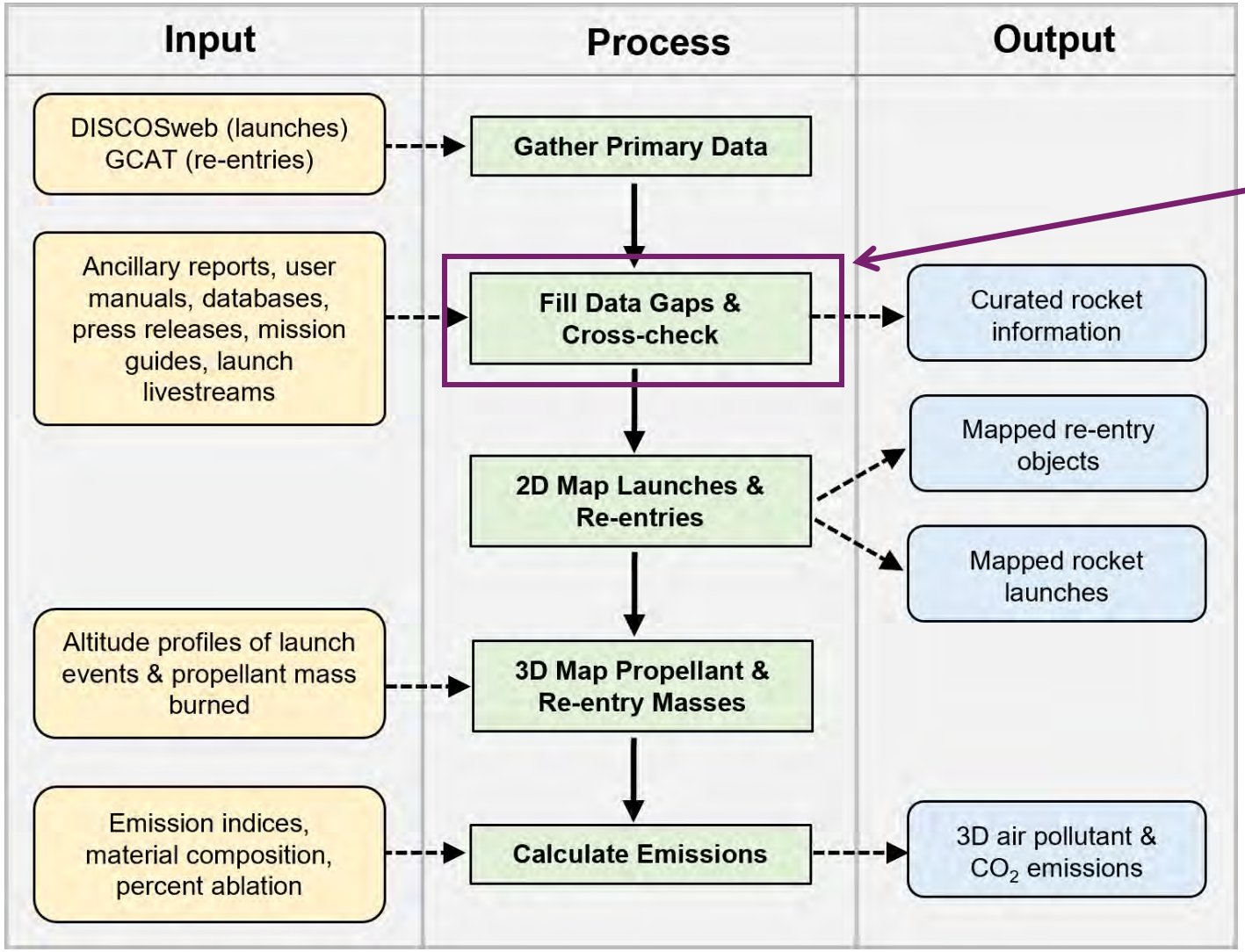
Initial inventory developed for **2020-2022** grounded in peer reviewed research




[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

# Emissions inventory processing pipeline

Inventory grounded in peer reviewed research




Critical step:

- Data gaps
- Incorrect data
- Inconsistent data
- Obviously wrong data

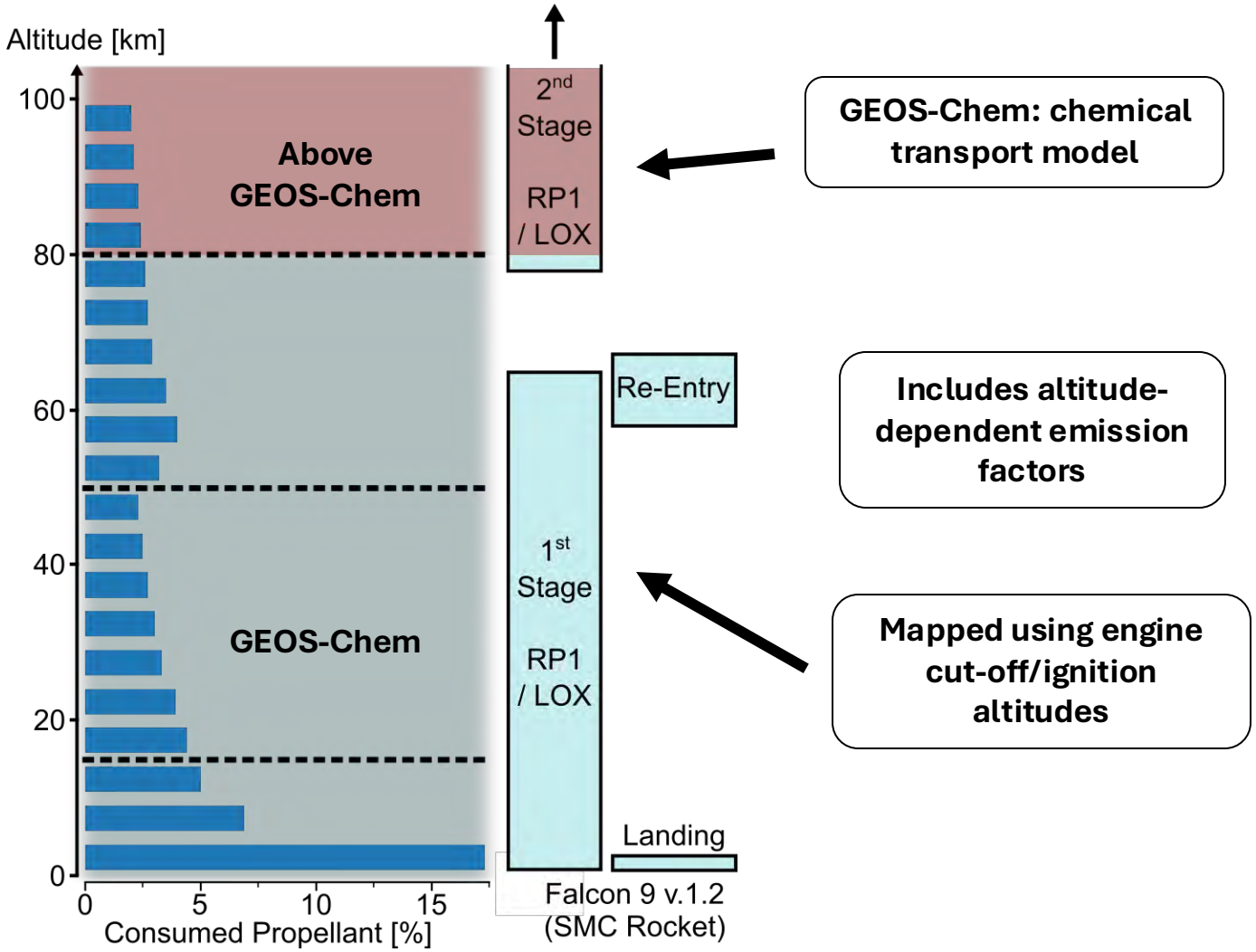
Bonus:

Categorize activities as megaconstellations

[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

# Vertical Distribution of Launch Emissions

Example vertical mapping of Falcon 9 kerosene rocket

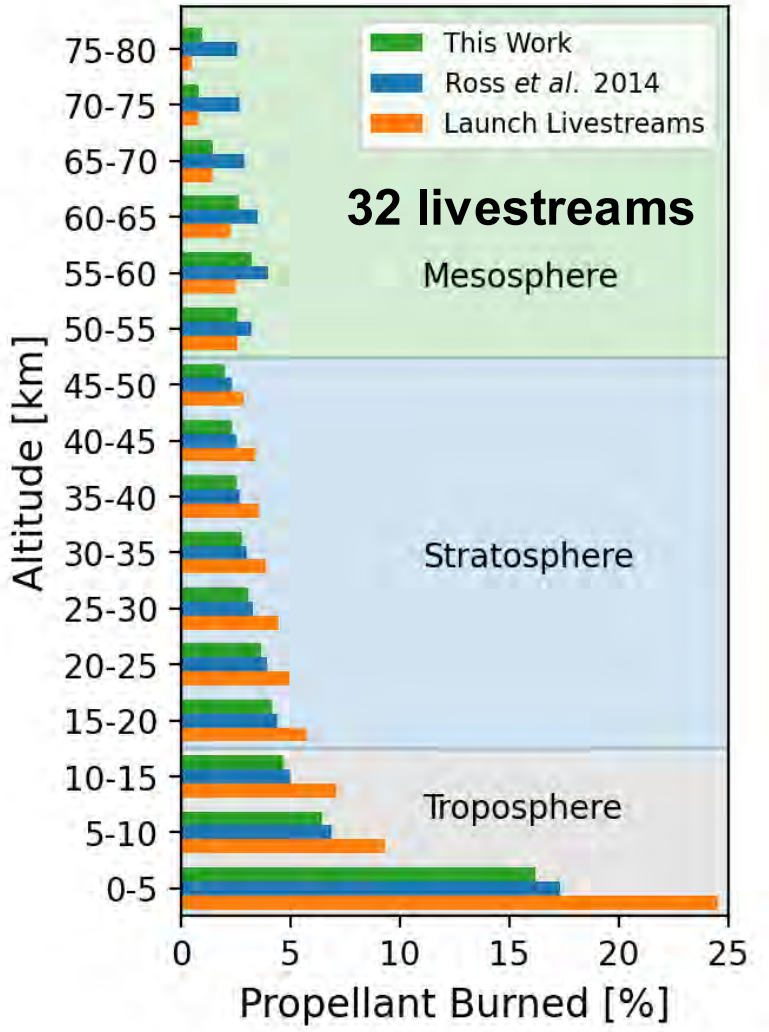



**GEOS-Chem: chemical transport model**

**Includes altitude-dependent emission factors**

**Mapped using engine cut-off/ignition altitudes**

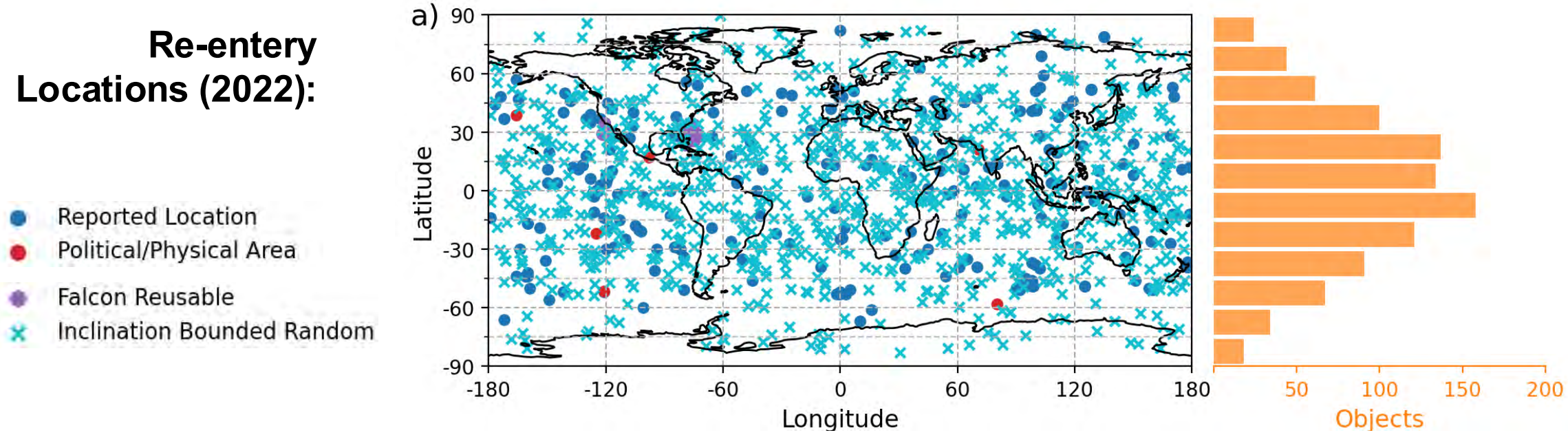
Assessment against other constraints



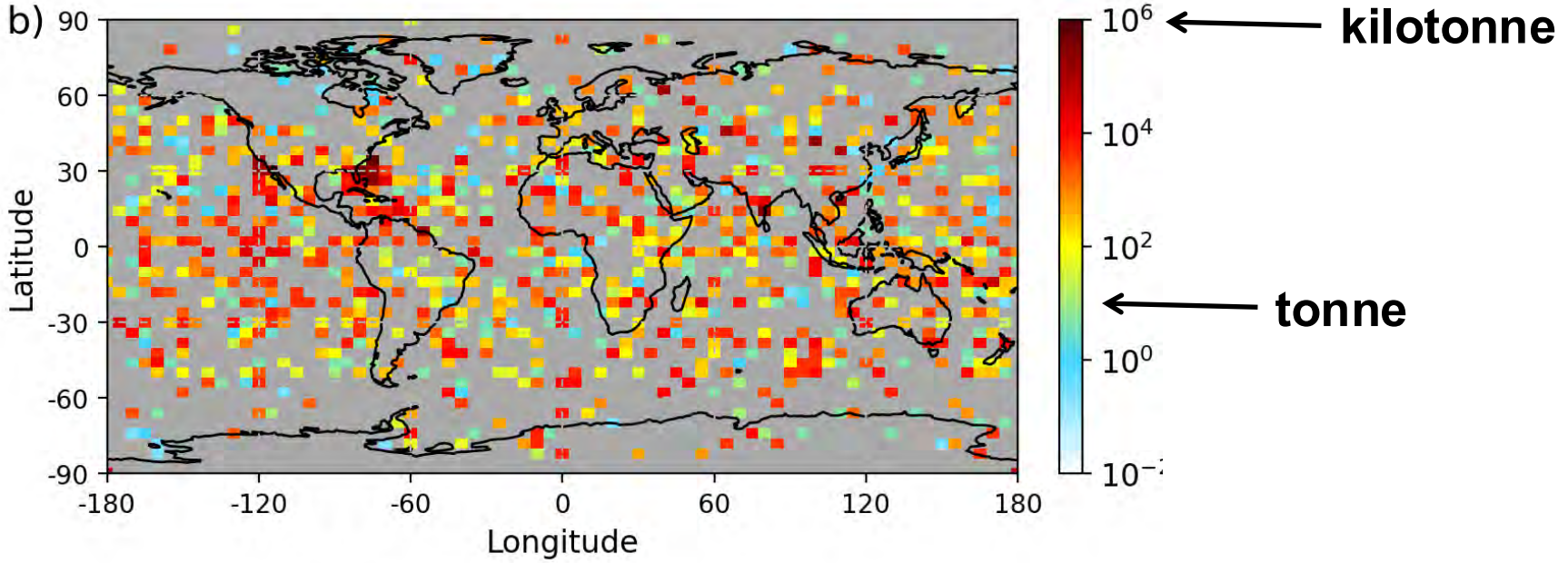

**Annual propellant consumption increased from 36 kilotonnes in 2020 to 63 kilotonnes in 2022**

# Location and Mass of Reusable and Discarded Re-entries

**Re-entery Locations (2022):**

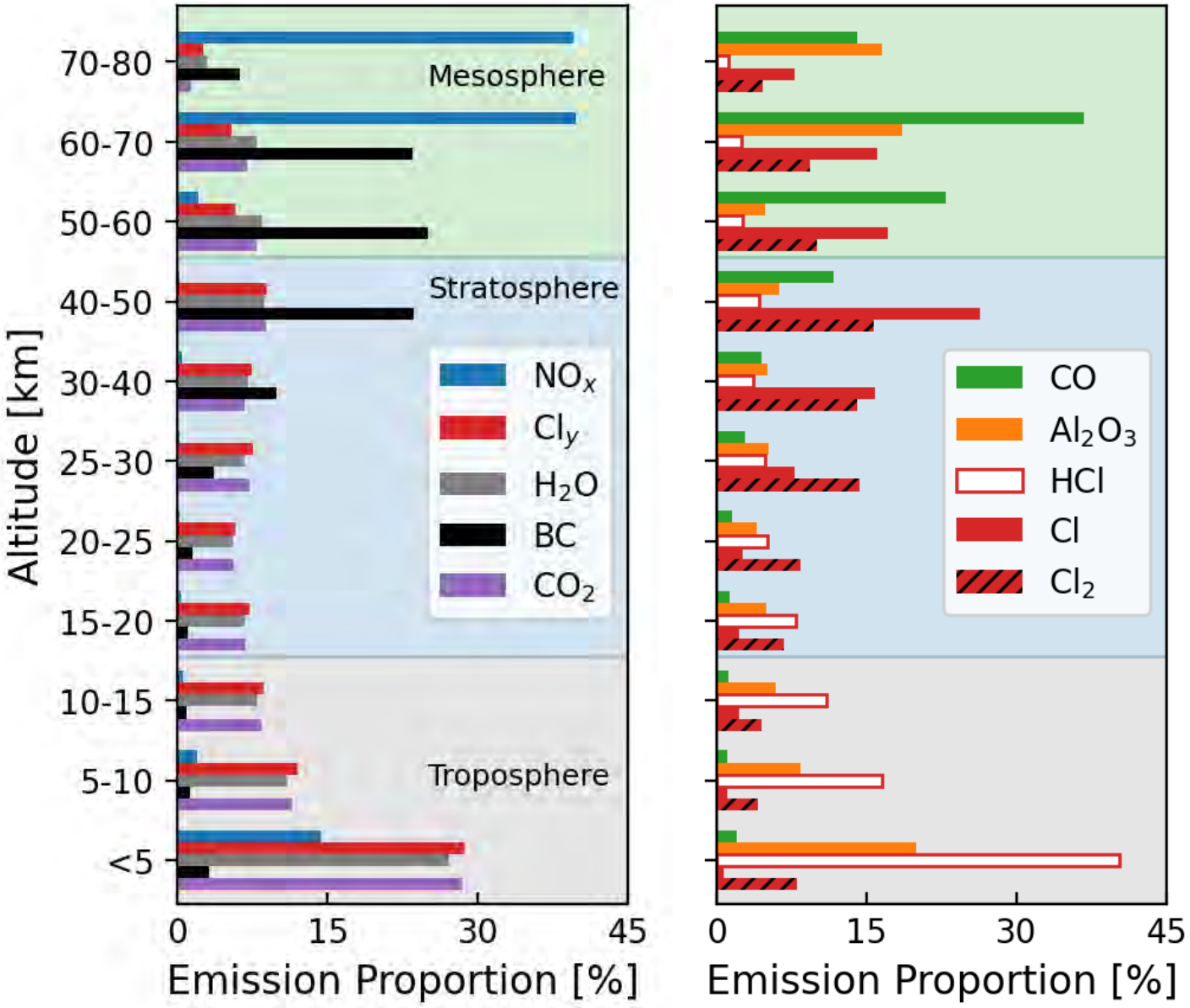



**Re-entry Mass (2022):**

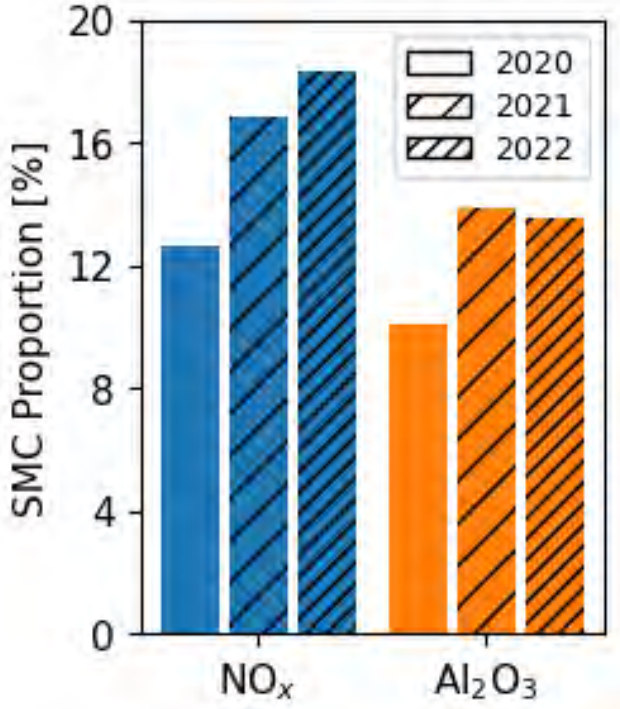


# Vertical Profiles of $CO_2$ and Pollutants

Relative distributions for 2022



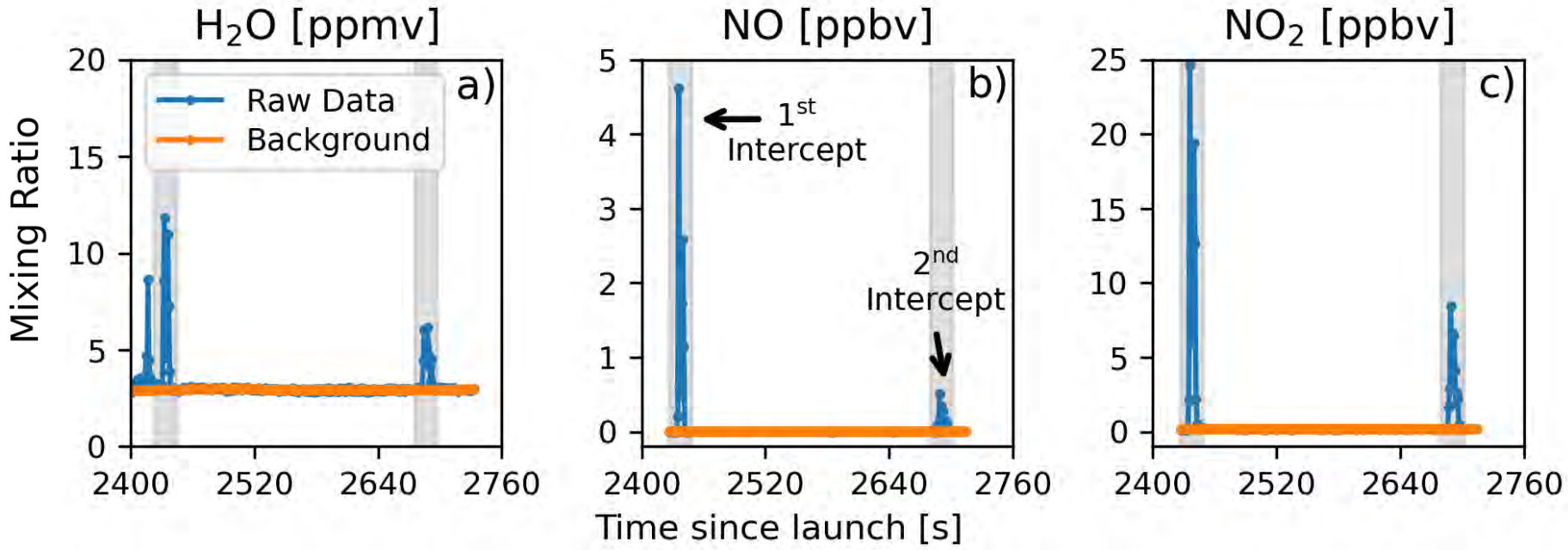

**Re-entry $NO_x$ and $Al_2O_3$ dominant in mesosphere.**




**SMC contribution to re-entry $NO_x$ increases from 13% in 2020 to 18% in 2022**

# Rare Opportunity to Evaluate Emissions

SABRE 2023 campaign measurement by researchers at NOAA and NASA:
G. S. Diskin, J. P. DiGangi, Y. Choi, A. W. Rollins, E. Waxman, T. P. Bui, C. K. Gatebe, J. Dean-Day, R. Poudyal




2 intercepts of a SpaceX **Falcon 9** kerosene fuelled rocket on 18 February 2023

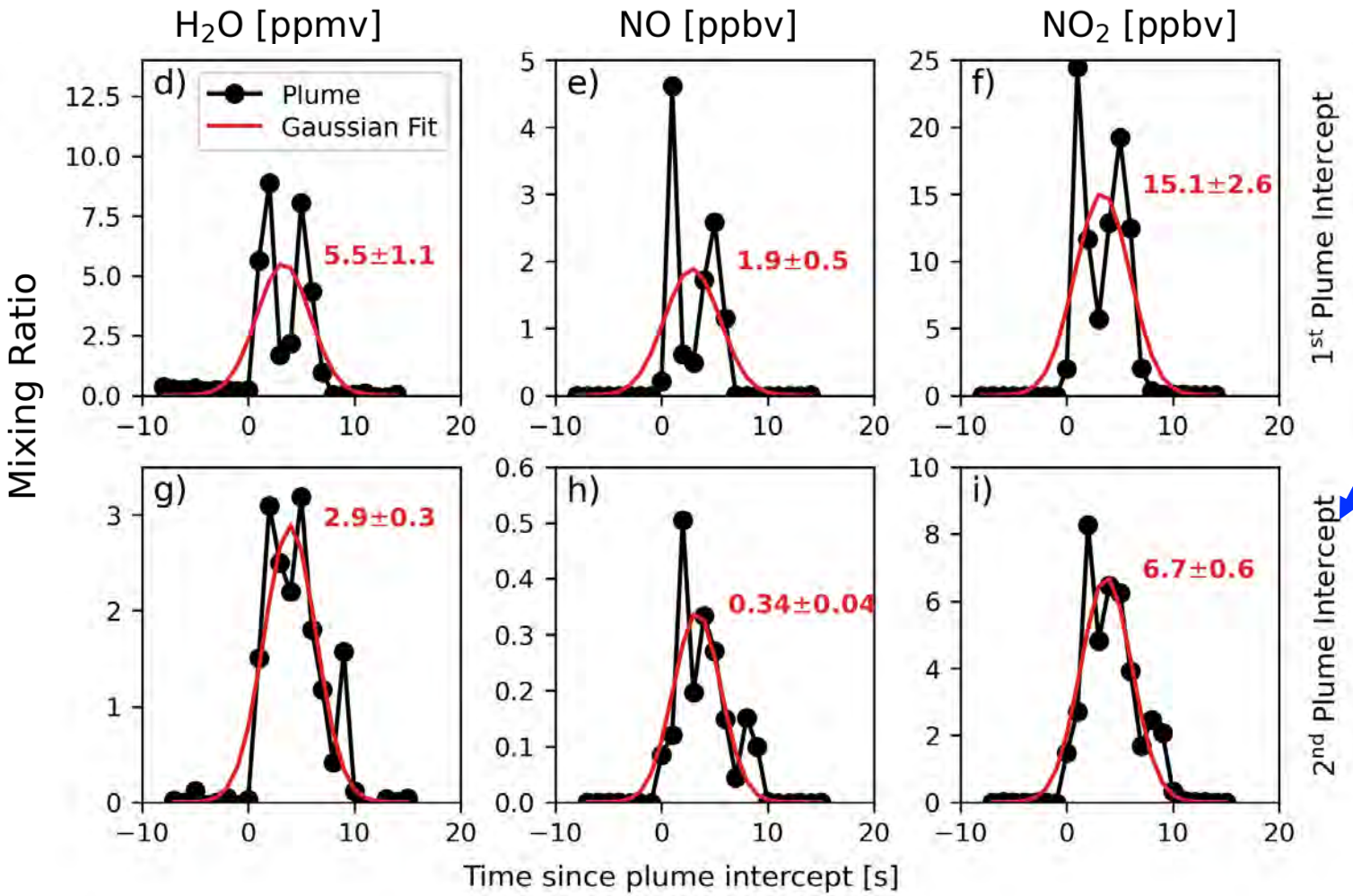
41-45 min after launched at ~16 km altitude (lower stratosphere)

$NO_x$ ($NO + NO_2$) and $H_2O$ preserved (long-lived in the stratosphere)

[Barker et al., submitted, 2025]

# Measured vs Inventory Emission Indices

Gaussian fit to plume to calculate mixing ratios in plume




**1st intercept**

**2nd intercept**

<u>Measurements:</u>

$\Delta NO_x/\Delta H_2O$ = 6.1-7.6 ppb $ppm^{-1}$

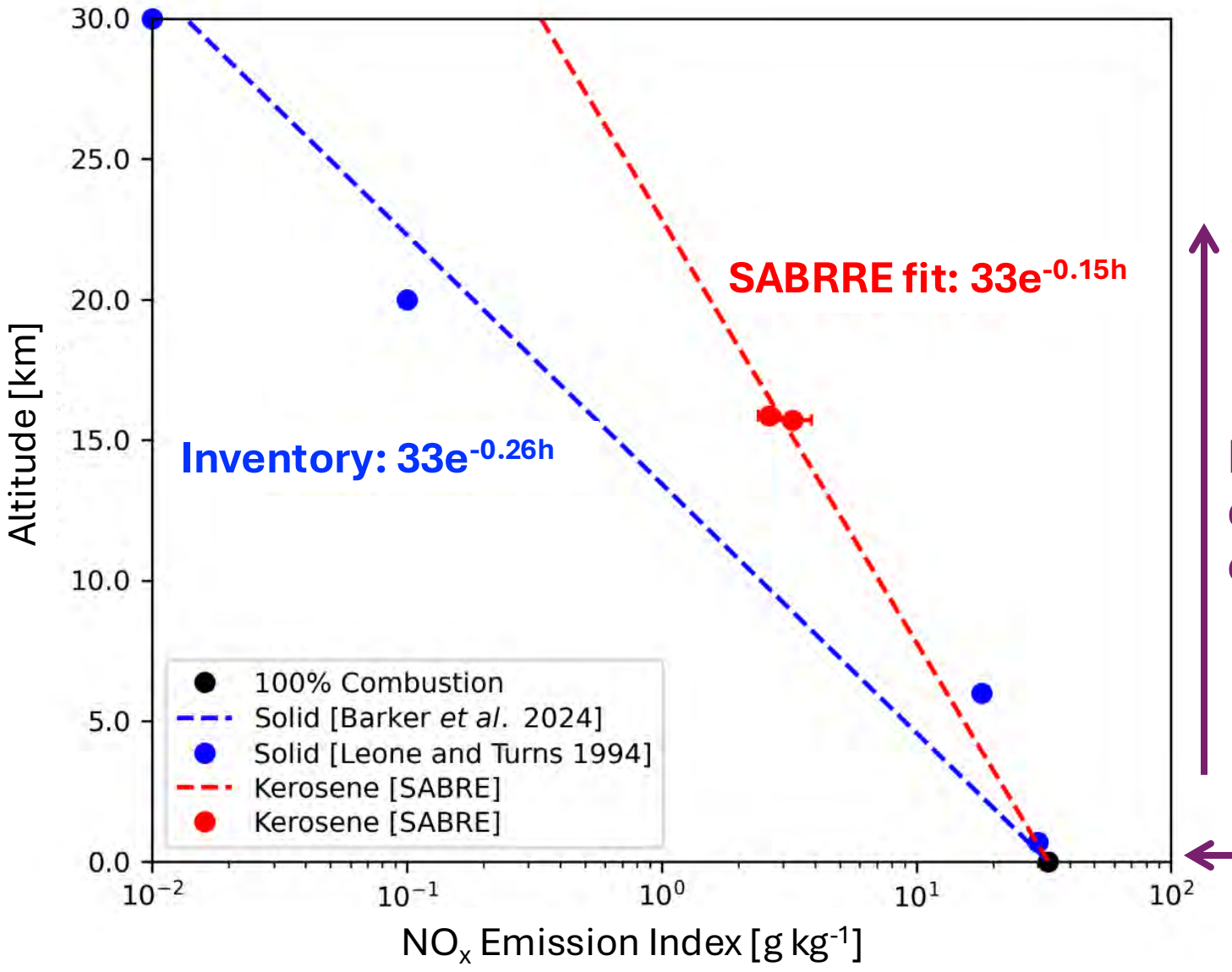
<u>Inventory:</u>

$\Delta NO_x/\Delta H_2O$ = 1.2-1.3 ppb $ppm^{-1}$

Use $H_2O$ rather than $CO_2$, as $H_2O$ is conserved with altitude

# Measured vs Inventory Vertical Emissions Profiles

Altitude-dependent decline in $NO_x$ emission indices




Decline in combustion efficiency

← Stochiometric Emission Index

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

Only 2 plume intercepts

Better than currently using to constrain emissions

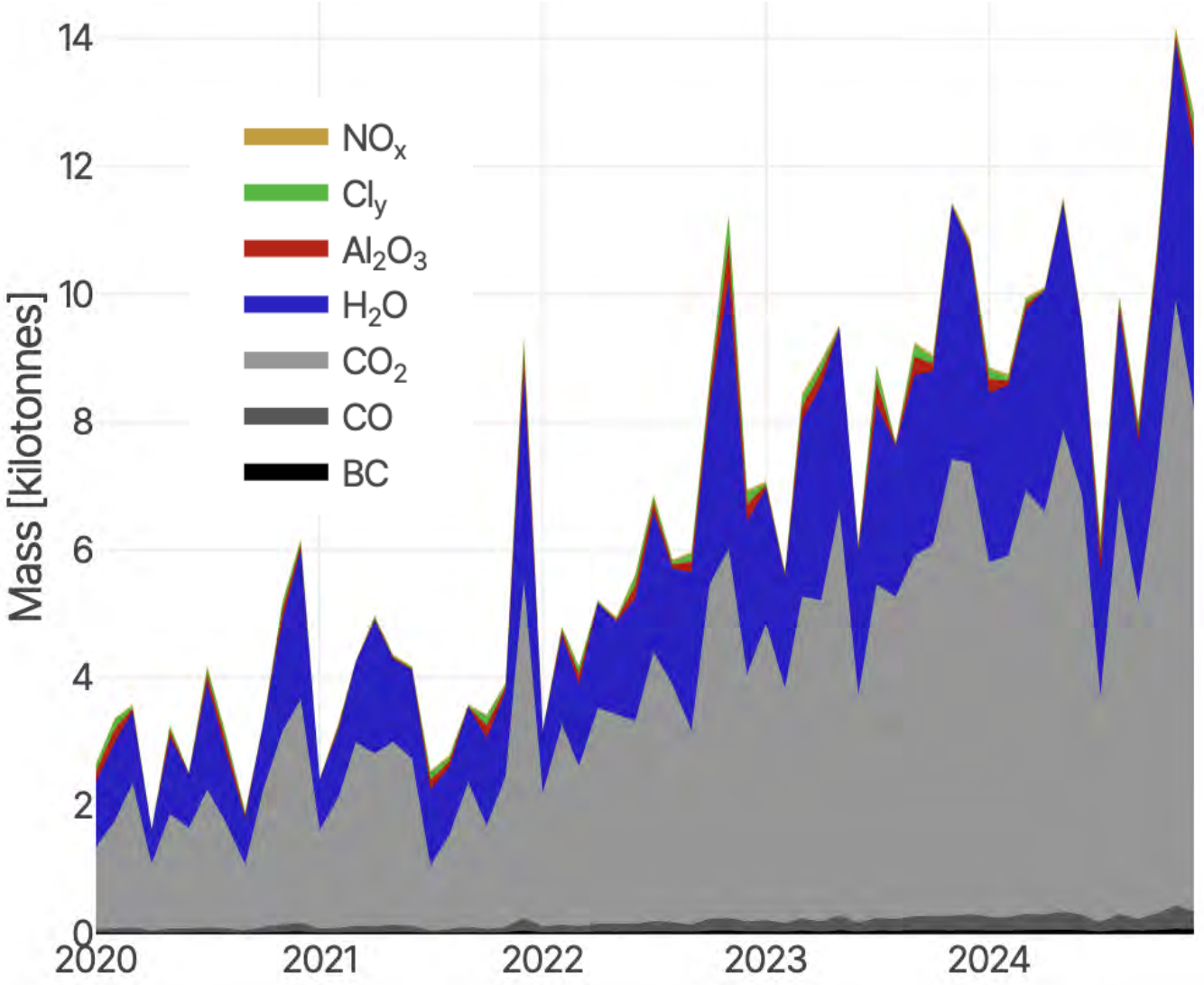
Shows what could be achieved with more measurements!

Comparison suggests decline in combustion efficiency much slower than assumed in the inventory

# Tracking Growth in Emissions from 2020 to 2024

Extended to include 2023-2024 by UCL Astrophysics summer research student, Eric Tan

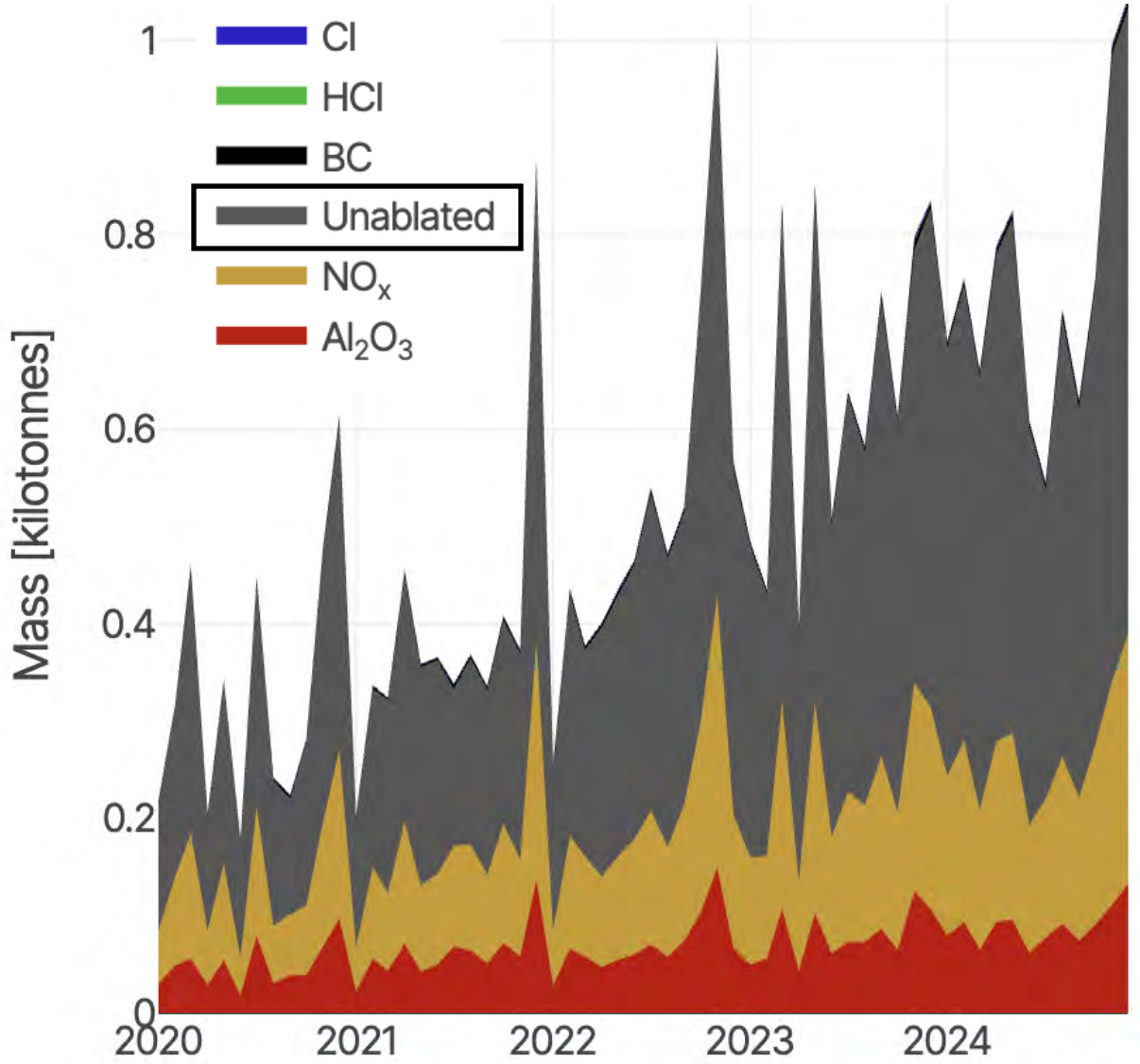
**Byproducts from launches:**




Propellant use for megaconstellations surpass propellant use for all other missions combined

# Tracking Growth in Emissions from 2020 to 2024

**Byproducts from re-entries:**

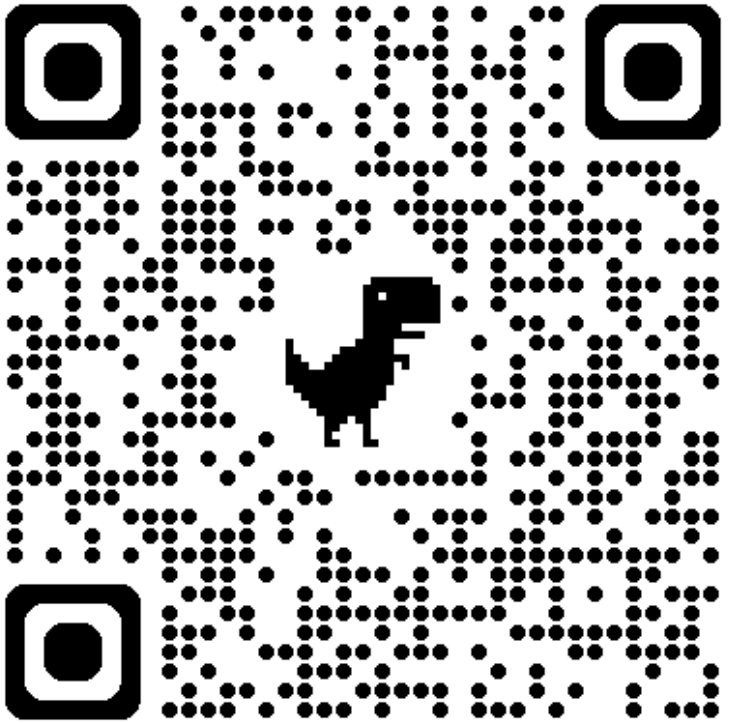



Includes BC and chlorine emissions from James Beck's lab work

# Give it a try!

## Launches byproducts

## Re-entries byproducts



Feedback is “Hey! That’s cool!” Lots of enthusiasm, but major challenge securing funding.

# Could Crowd Sourcing Funding Work?

## Fund Jonathan's Space Report Library Transition


Jonathan McDowell is organizing this fundraiser.

$115,510 USD raised

$186,000 goal · 842 donations

62%

Share

Donate now

Patrick O'Laughlin
**$10** MONTHLY · 22 hrs

Ken Howard
**$25** MONTHLY · 1 d

Anonymous
**$50** · 5 d

Anonymous
**$250** · 12 d

# Not Without a Following!

## Fund Eloise's rocket pollution tracker


Eloise Marais is organizing this fundraiser.

£400 raised

£2.6K goal · 9 donations

15%

Share

Donate now

Amir Hossein Souri
**£30** · 4 mos

Ms Donna J Marais
**£25** · 4 mos

Anonymous
**£25** · 4 mos

SANDRA MARAIS
**£100** · 5 mos

# Many New Developments on the Horizon

- Test effect of measurement-constrained afterburning on emissions estimates
- Extend time coverage
- Add missing air pollutants
- Add missing sources (e.g. in-orbit propulsion)
- Integrate in lifecycle assessment tools
- Improving our re-entry emission estimates using the ESA DRAMA re-entry model
- Improving representation of launch using a trajectory approach
- Migrate to dedicated website
- Establish near-real time data processing pipeline

# European Geophysical Union (EGU) 2026 Session

https://meetingorganizer.copernicus.org/EGU26/provisionalprogramme/5854

**Atmospheric impacts of spacecraft launches and re-entries: knowns, unknowns, and research priorities**

Conveners: Eloise Marais, Connor Barker[ECS], Christian Bach, Raphaela Guenther, Laura Revell

**Proposed** 11 September 2025 by Eloise Marais

**Session short summary:**

This session invites abstracts on planned, current, ongoing or recently completed research that advances knowledge and reveals new uncertainties that need to be resolved to characterise and mitigate atmospheric impacts of trace gas and aerosol emissions from spacecraft launches and re-entries.

Second year session running, following success of inaugural session in 2025

Abstract submissions open **22 October**

Want to be on the email list reminding you to submit an abstract?
Email me at **e.marais@ucl.ac.uk**