Abstract
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Dynamic lightning NO_x production rates obtained with space-based low-Earth orbiting and geostationary lightning imagers

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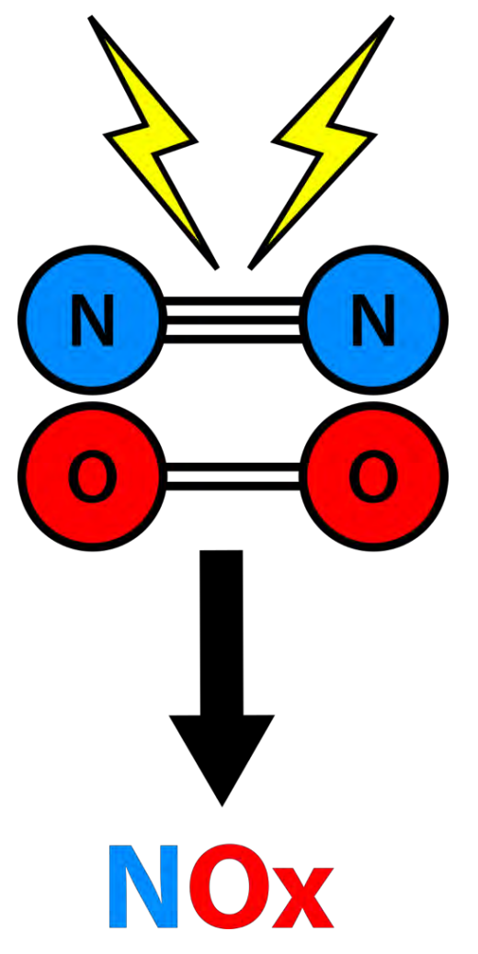
We derive spatially and hourly varying lightning NO_x production rates with satellite observations of lightning energies for improved representation of NO_x sources in models

1 NO_x formation from lightning

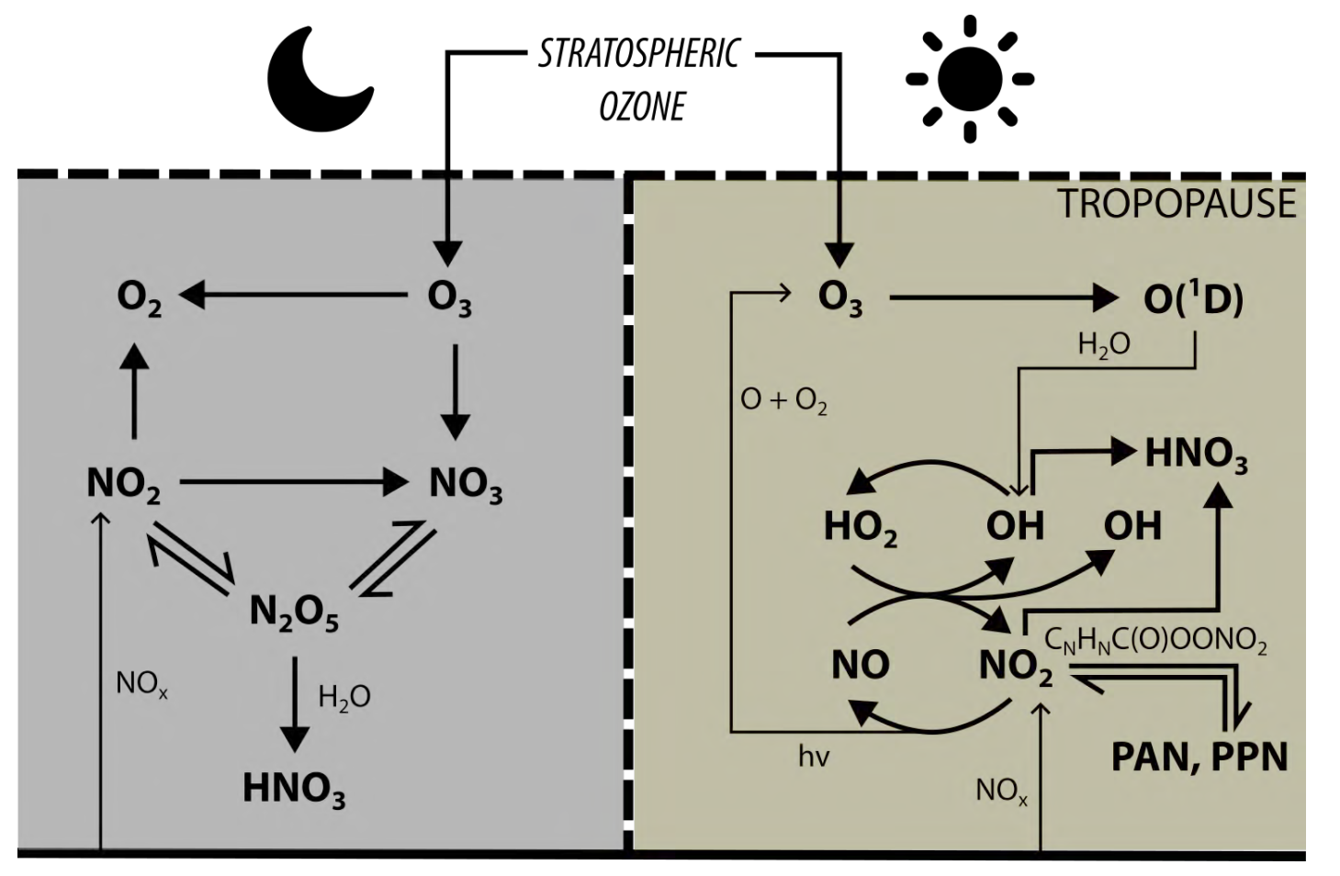
- Lightning-produced NO_x is the most dominant source of NO_x throughout most of the troposphere.
- High-energy lightning discharges break apart N_2 and O_2 molecules, that then recombine as NO, which rapidly reacts to form NO_2.



Lightning NO_x forms through N_2 and O_2 breakdown

2 Tropospheric NO_x chemistry and influence on O_3

The formation of tropospheric ozone

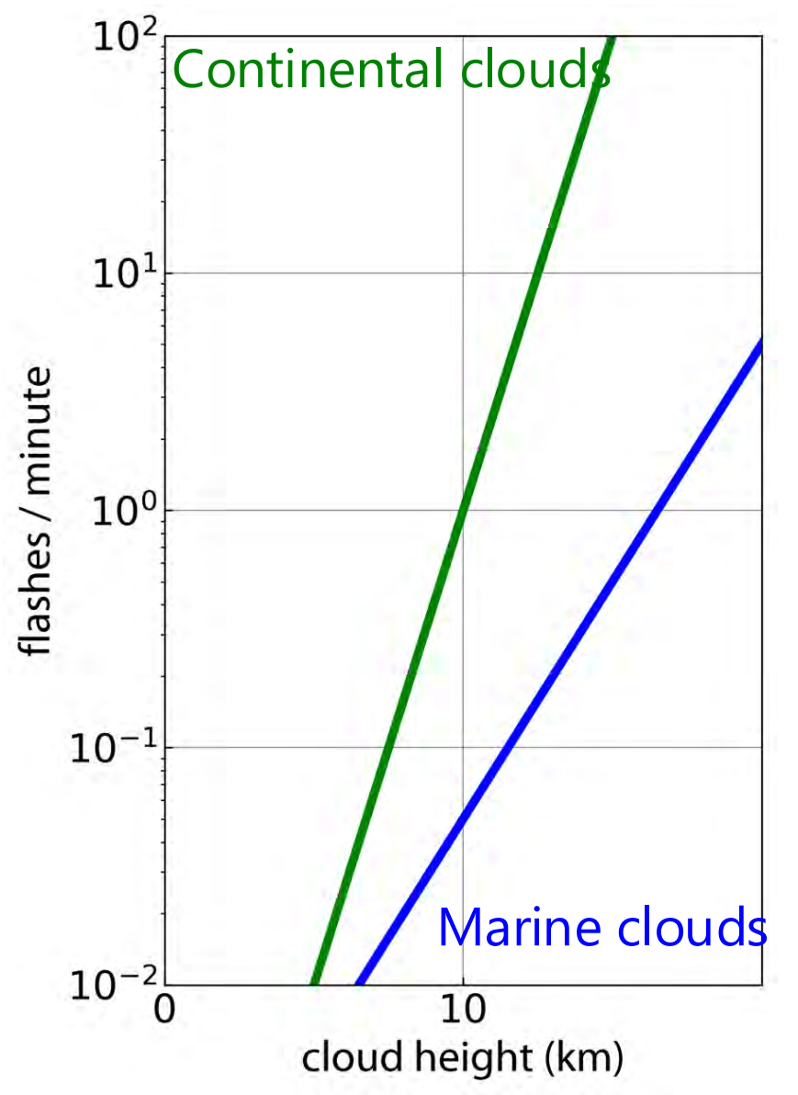


- NO_x initiates O_3 formation and drives radical cycles involving OH and HO_2, which influence the atmosphere's oxidation capacity.
- Compounds like PAN, PPN, and nighttime N_2O_5 act as temporary NO_x reservoirs, enabling redistribution across different regions before releasing NO_2 back into the atmosphere.

NO_x drives O_3 formation while reservoir compounds like PAN, PPN and N_2O_5 redistribute NO_x

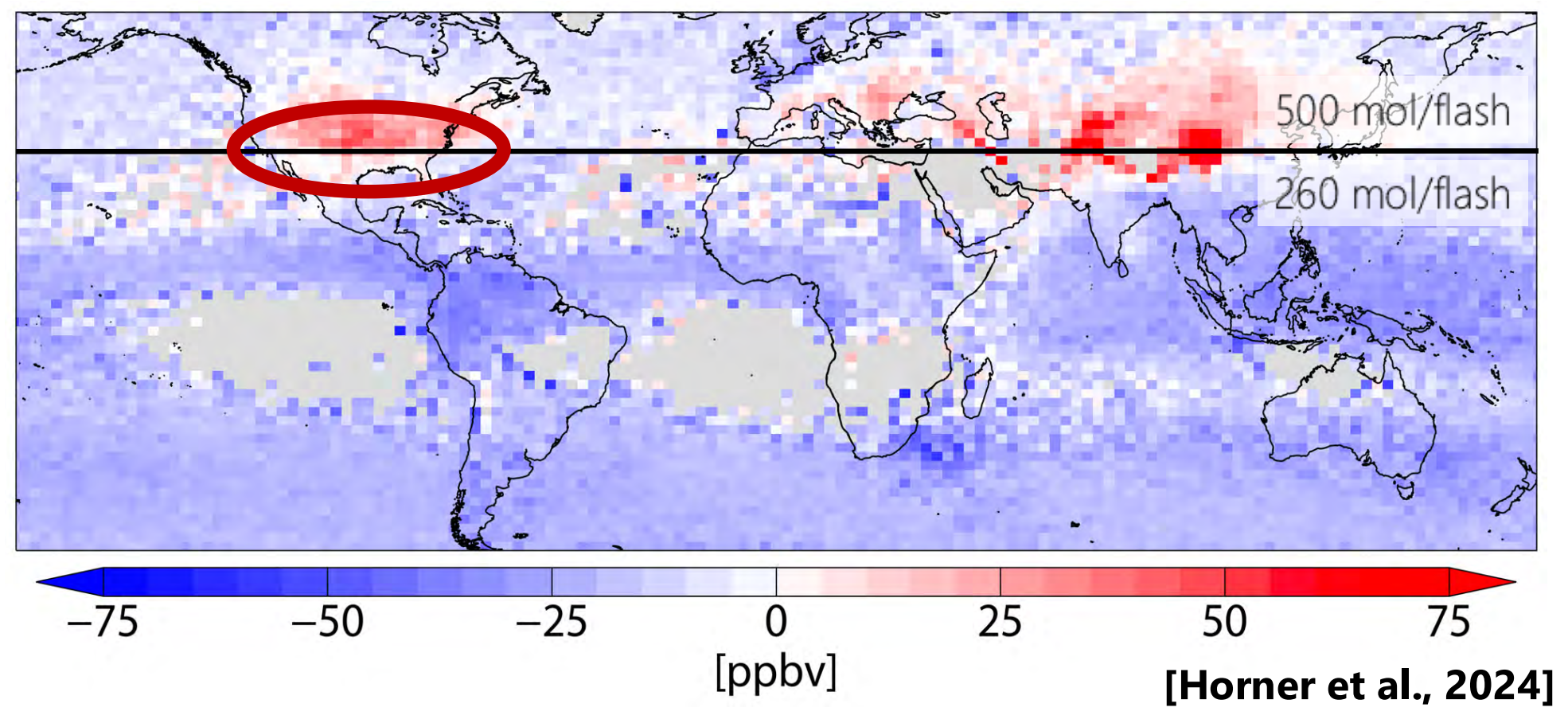
3 The current representation of lightning NO_x in atmospheric chemistry models

- Lightning flash rates are calculated using the relationship with cloud-top height..
- Flash rates are adjusted with local scaling factors to match lightning flash climatologies from space-based detectors (Murray et al., 2012).
- NO_x emissions are calculated using static production rate of 500 mol/flash in the northern midlatitudes and 260 mol/flash everywhere else.



[Price & Rind, 1992]

GEOS-Chem minus satellite derived NO_2, 600-450 hPa



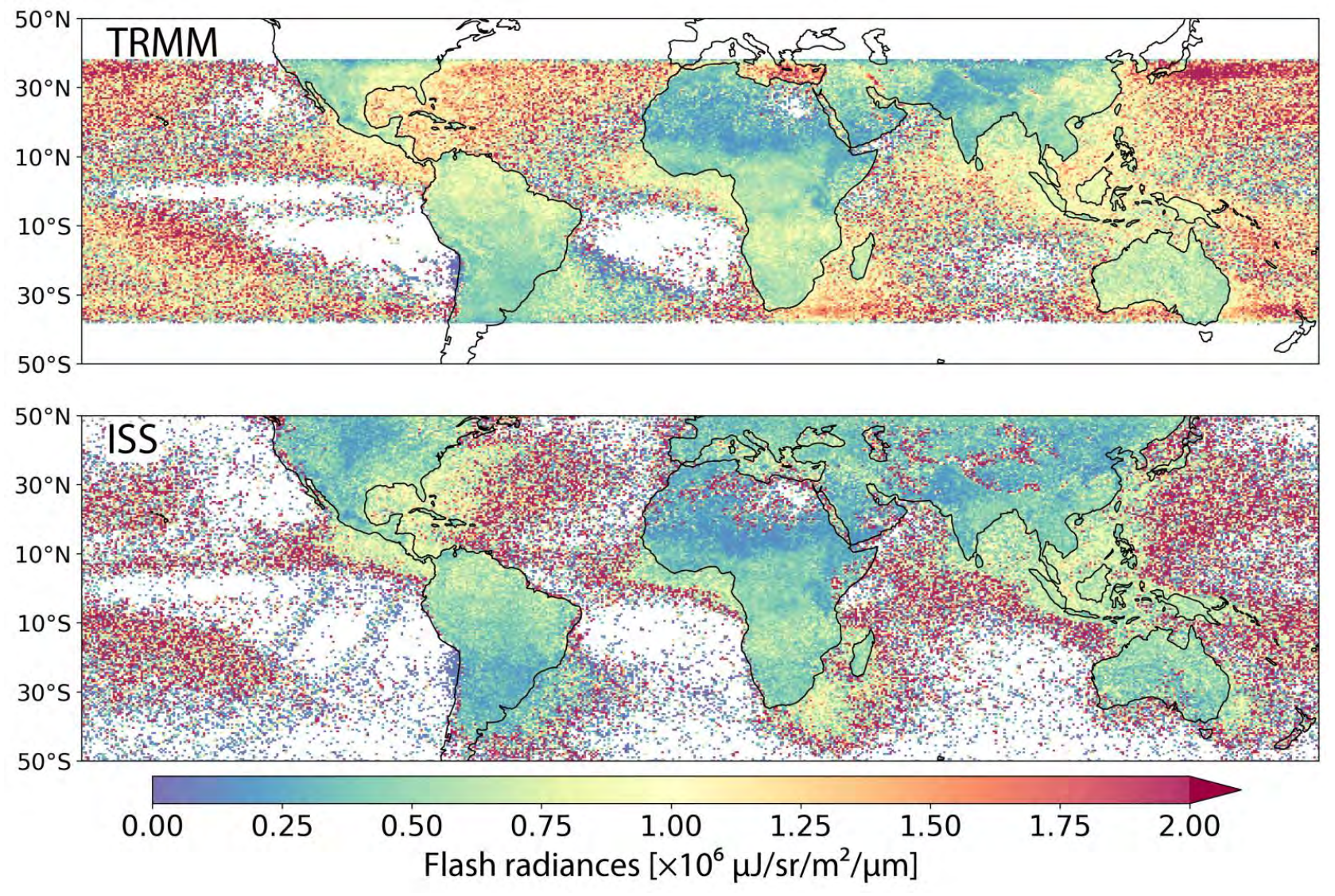
[Horner et al., 2024]

Highly parameterised lightning NO_x production rates lead to upper troposphere NO_x model biases in GEOS-Chem

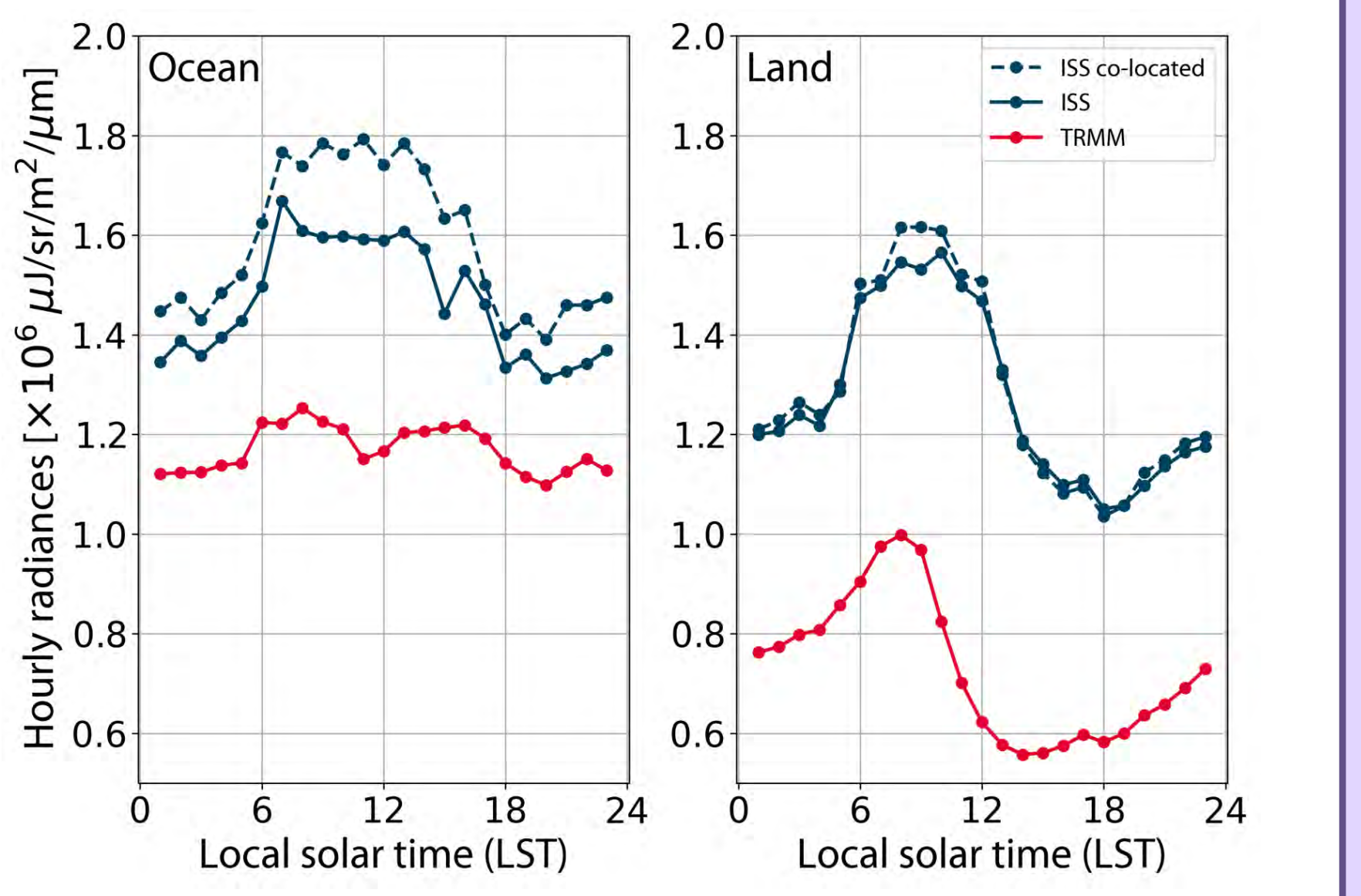
4 Lightning flash energies from the Lightning Imaging Sensor

- Lightning Imaging Sensors (LIS) onboard the TRMM satellite and the International Space Station measures lightning flash energies that can constraint NO_x production.
- Flash radiances are ~60% greater over oceans than land, driven by oceanic conductivity, larger storms, and cloud microphysics. ISS-LIS (International Space Station) radiances are 31% greater than TRMM-LIS (Tropical Rainfall Measuring Mission), with a greater difference between ocean and land.
- Flash radiances over land peak at 7-10 LST due to overnight charge build-up, while ocean radiance stays elevated from 5-18 LST due temperatures.

LIS lightning flash radiances



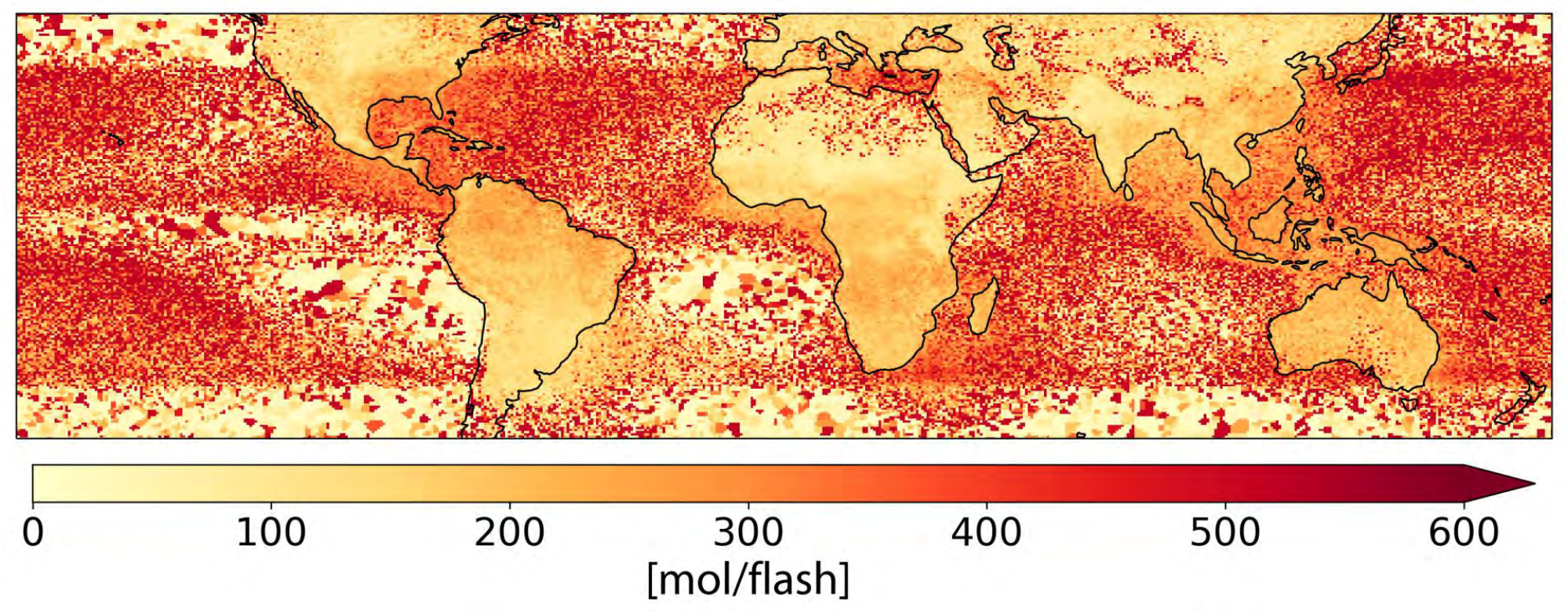
Diurnal variation in LIS lightning flash radiances



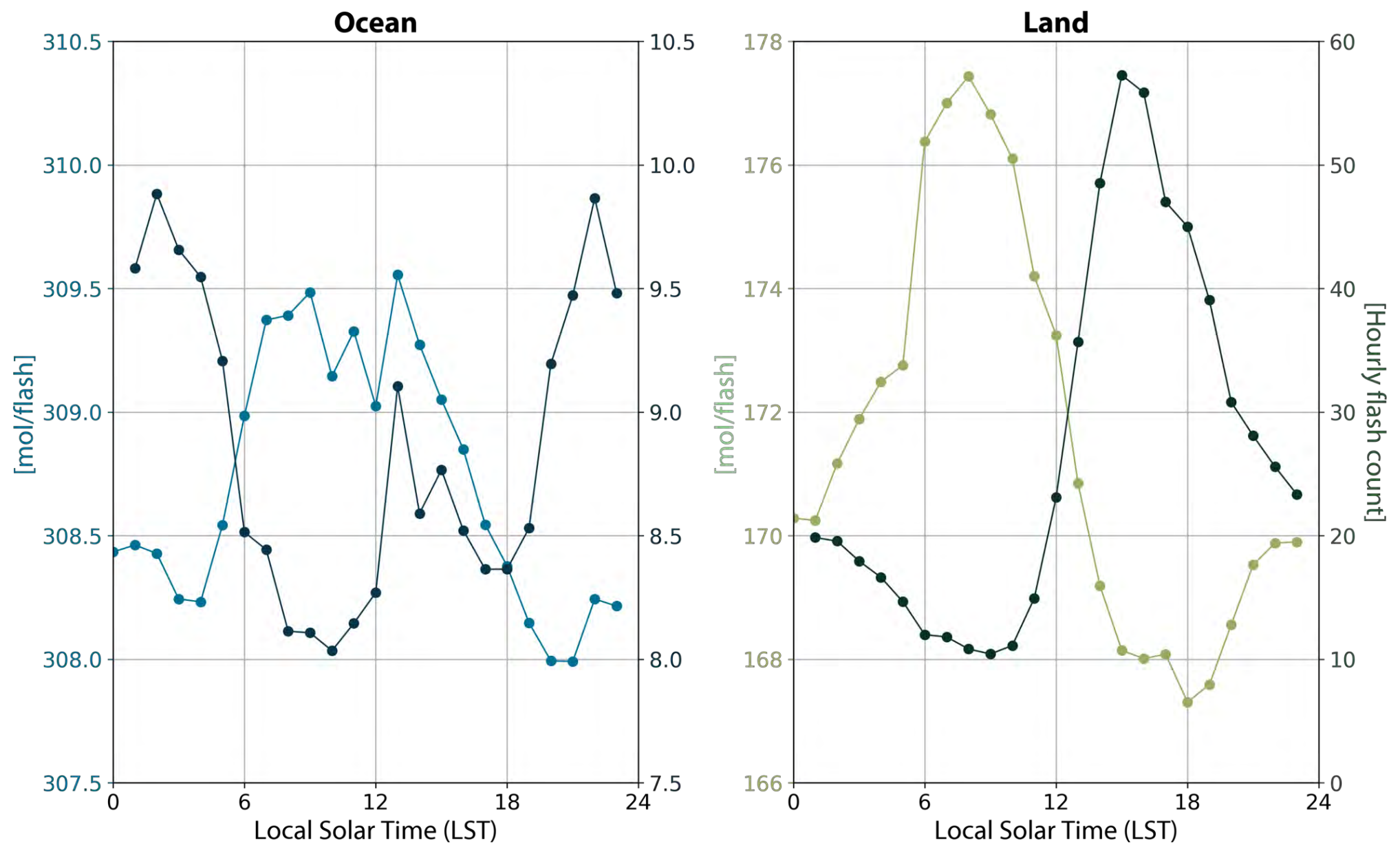
LIS flash radiances are higher over oceans than land, with ISS-LIS exceeding TRMM-LIS

5 Calculating lightning NO_x production rates from flash radiances

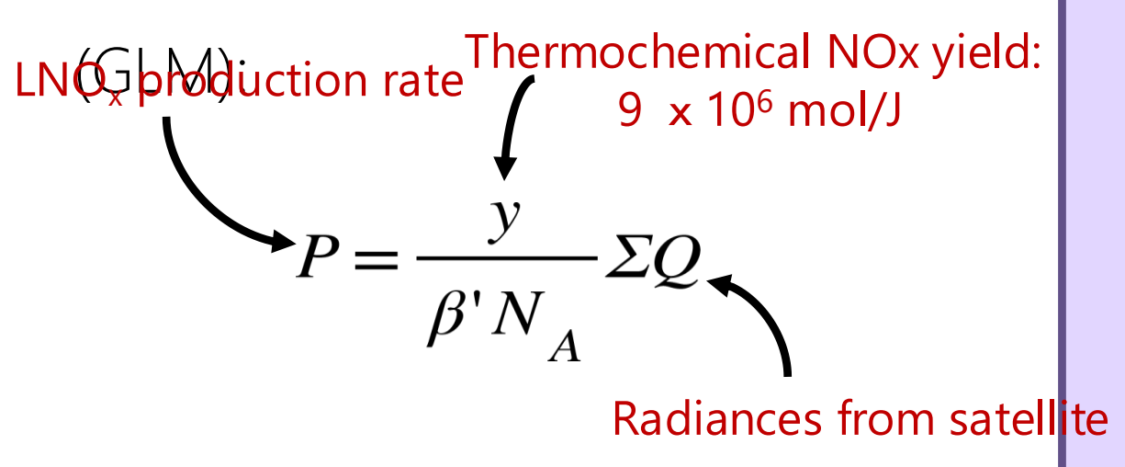
New LIS derived lightning NO_x production rates



Diurnal variation in lightning NO_x production rates and flash counts



- Wu et al. (2023) estimated lightning NO_x production rates using satellite-based lightning optical energy from the Geostationary Lightning Mapper (GLM).



$$P = \frac{y}{\beta' N_A} \Sigma Q$$

- We adapt this so-called β-method (Koshak et al., 2017) to use LIS flash radiances (μJ/sr/m²/μm) instead of optical energies (J), assuming a proportional relationship between lightning optical energy and NO_x production:

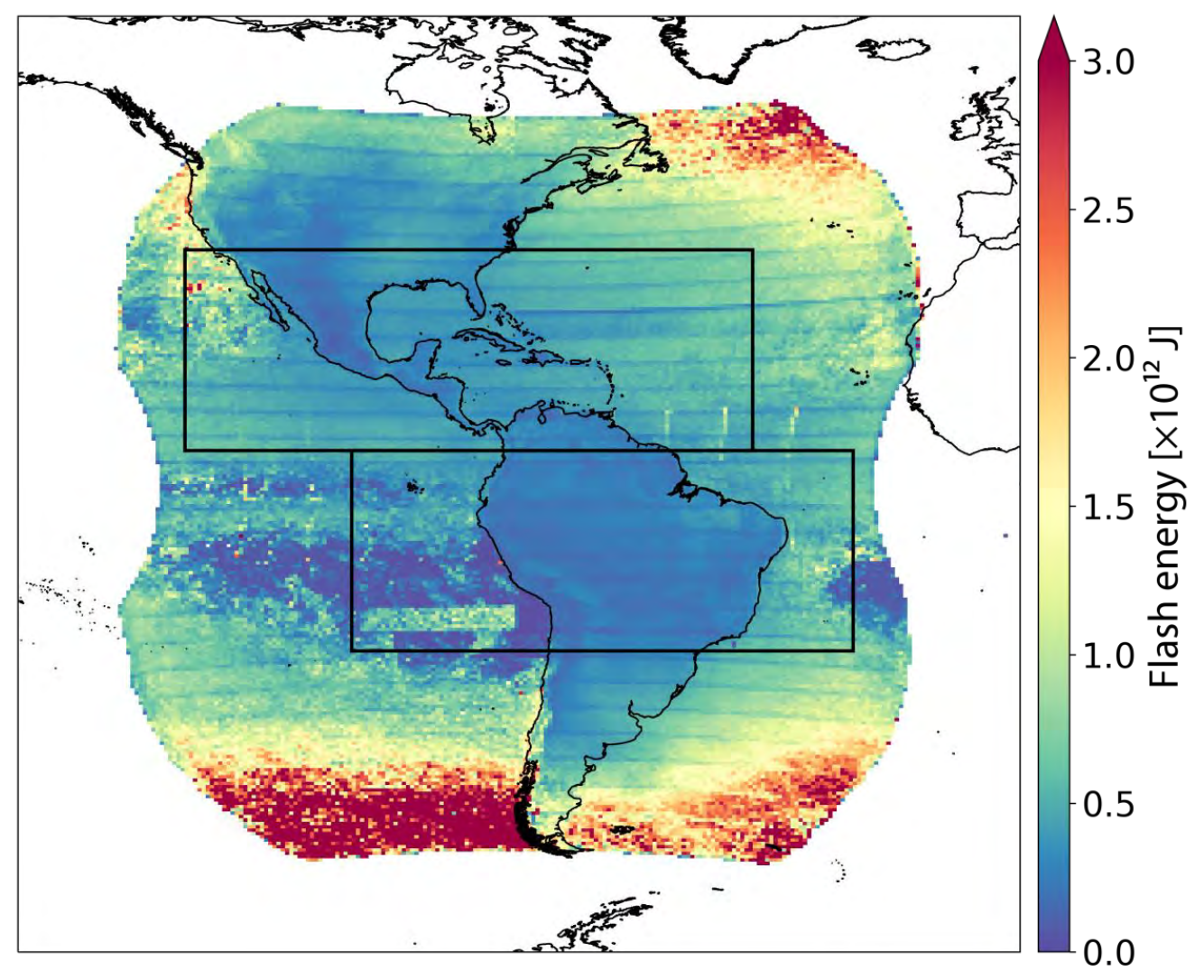
$$\beta' = \frac{y}{N_A}\left(\frac{\overline{Q}}{\overline{P}}\right)$$

The β-method is adapted to estimate lightning NOx production rates using LIS flash radiant energy

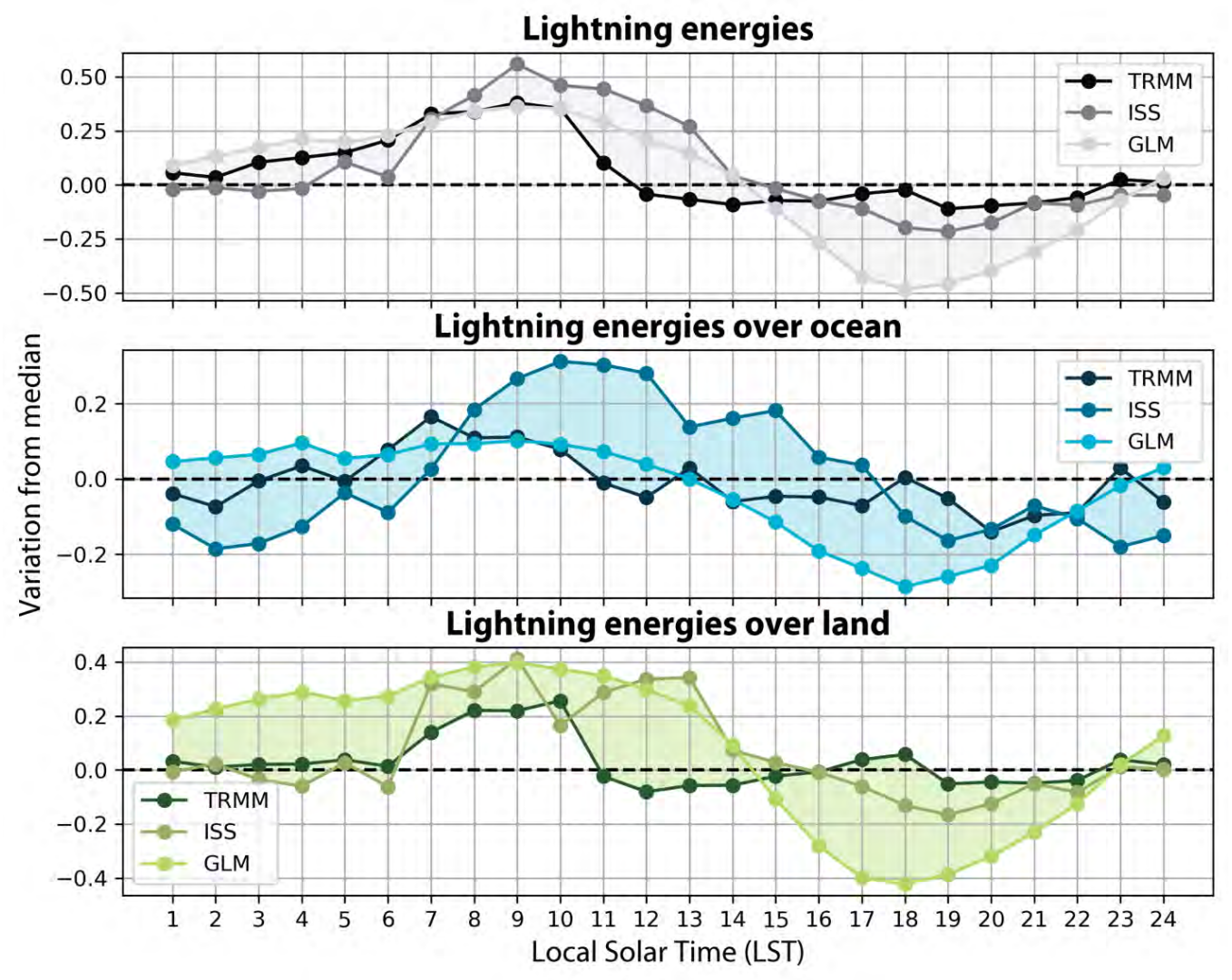
6 Evaluation using the Geostationary Lightning Mapper

- Normalising GLM, TRMM, and ISS lightning energy data enables direct comparison, revealing a similar morning peak (9:00 LST) in over land, 10-55% higher than average.
- GLM peaks earlier over oceans (4:00 LST) than land (9:00 LST) due to its continuous geostationary coverage, while ISS consistently peaks between 9:00-10:00 LST over both land and ocean and TRMM peaks at 7:00 LST over ocean and 10:00 LST over land.
- These morning peaks align with increased convection driven by solar heating, which destabilises the lower atmosphere, enhances updrafts, and intensifies thunderstorms, leading to higher

GLM lightning flash energies



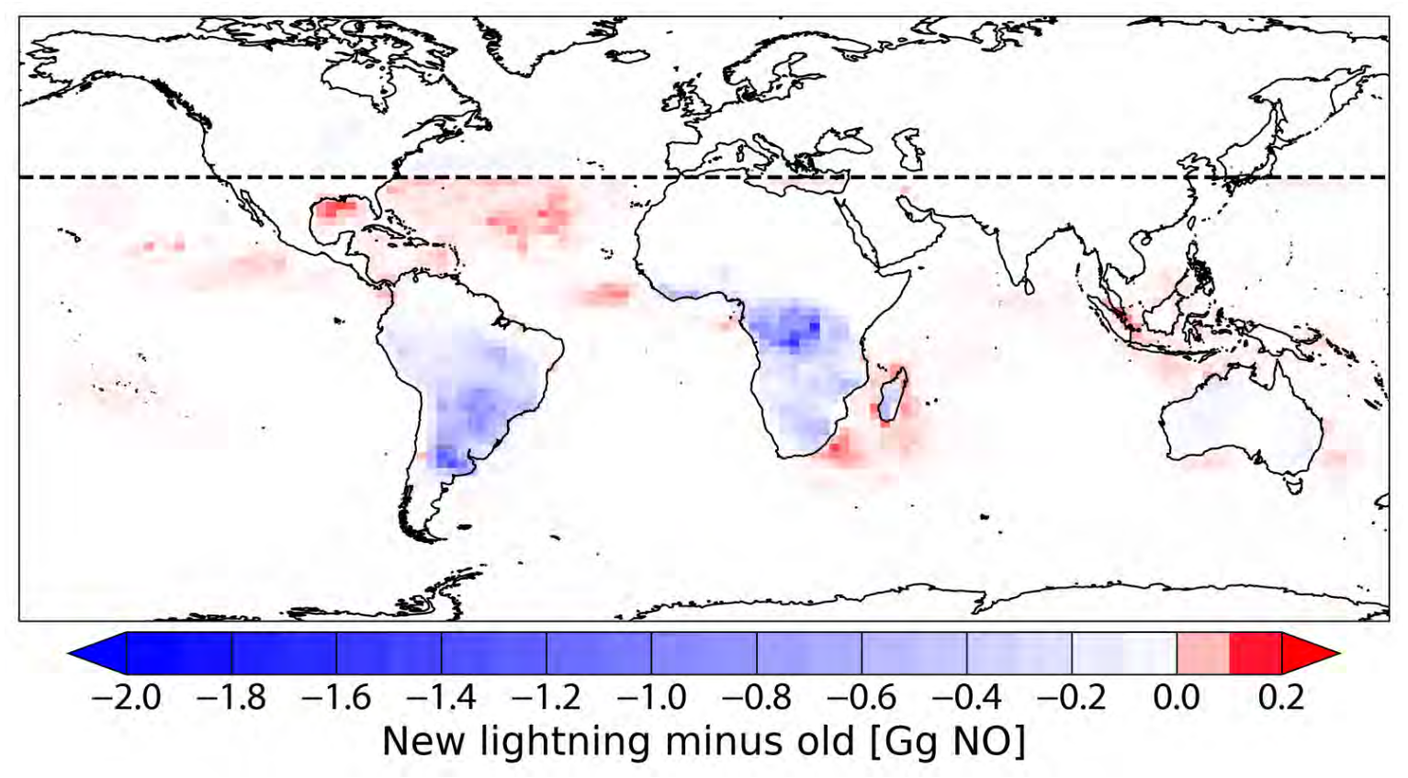
Diurnal variation in flash energies



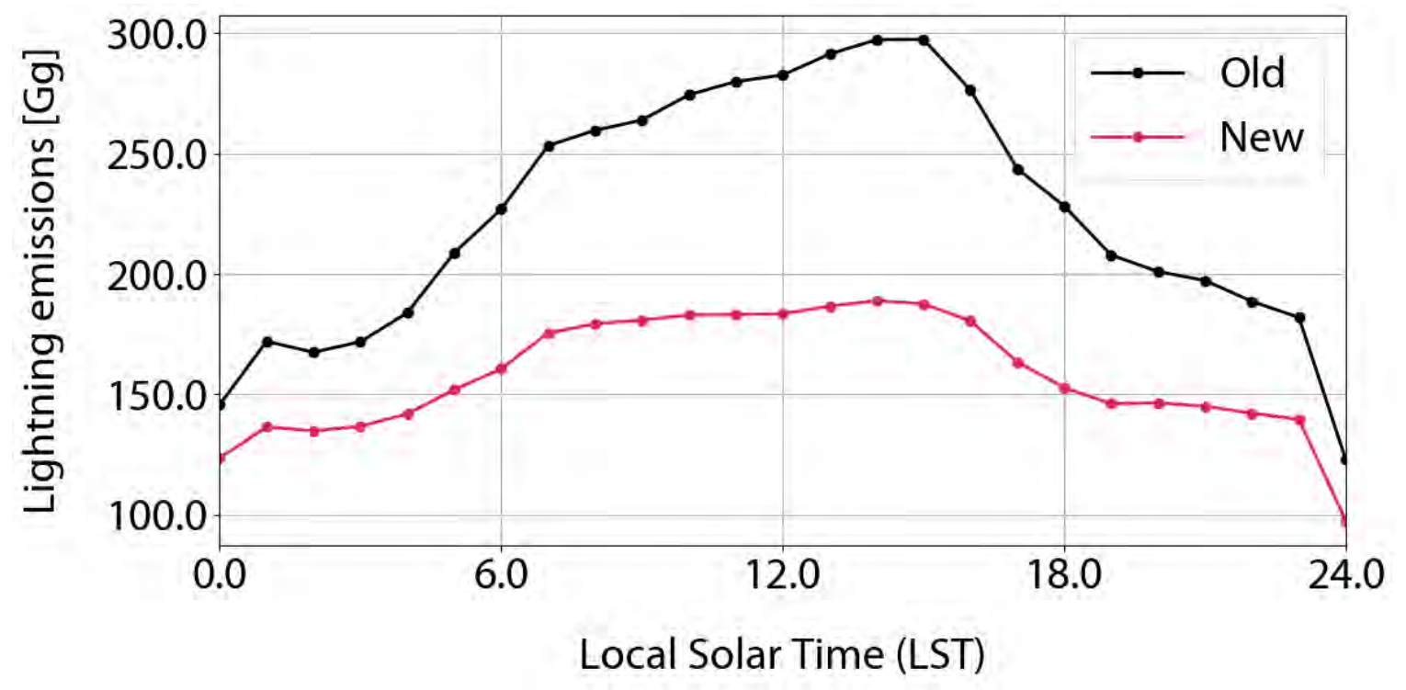
Data show morning peaks, driven by solar heating and atmospheric convection

7 Impact on simulated lightning NO_x emissions

Annual change in lightning NO_x emissions



Diurnal variation in lightning NO_x emissions



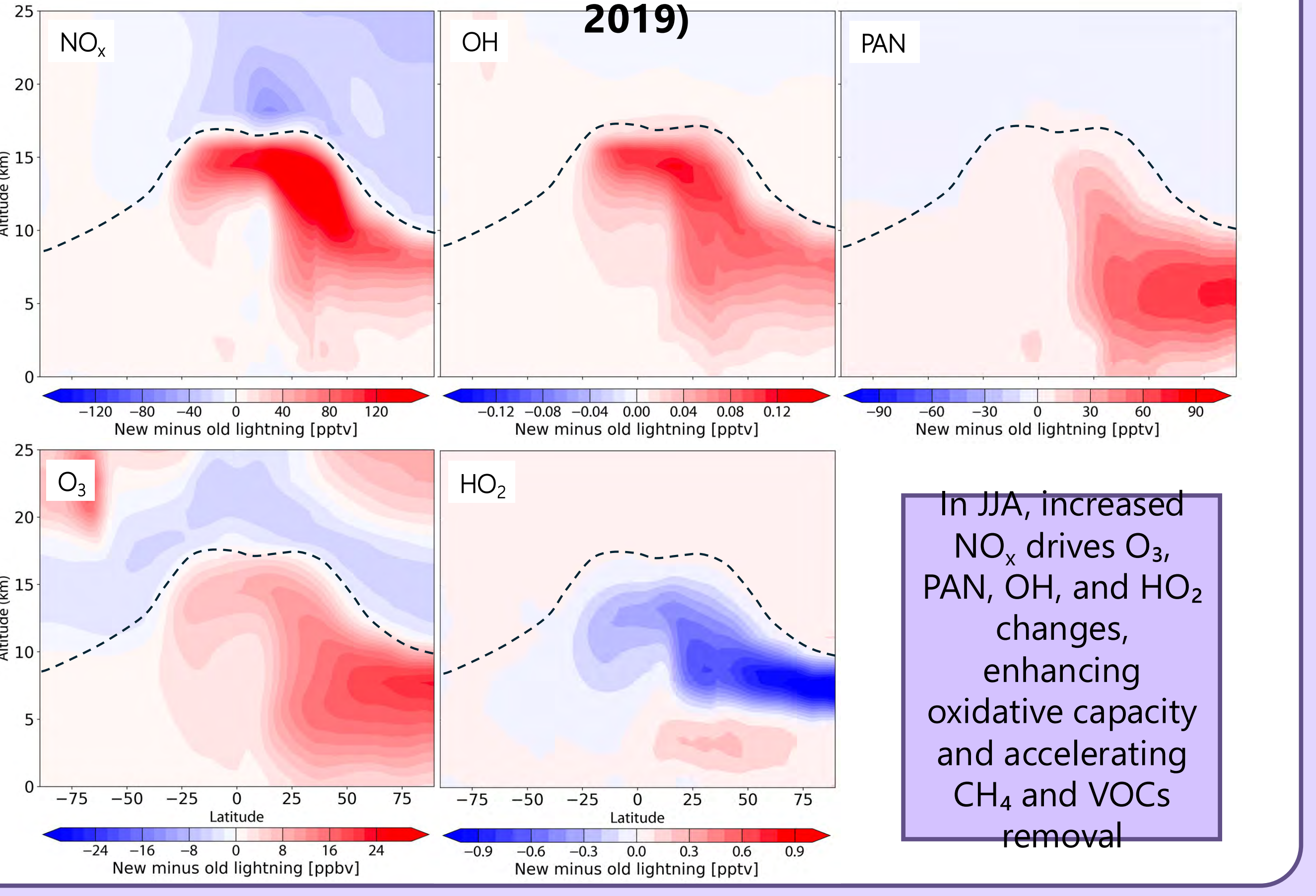
- Updated lightning NO_x production rates decrease global lightning NO_x emissions from 5.5 ± 0.2 Tg N yr^{-1} to 3.6 ± 0.1 Tg N yr^{-1} between 2015-2019. Global lightning NO_x emissions peak in JJA (1.14 ± 0.04 Tg N yr^{-1}) and a minimum in DJF (0.65 ± 0.03 Tg N yr^{-1}).
- NO_x emissions increase in tropical/subtropical areas (e.g., Central America, Gulf of Mexico, South Africa) due to higher energy marine lightning flashes, while parts of the tropics (Central Africa, South America) show significant decreases due to updated lower lightning NO_x production rates (decrease from 260 mol/flash to 220 & 180 mol/flash respectively).
- NO_x emissions peak between 13-16 LST but the variability is dampened because the previous parameterisation has no diurnal variability in lightning NO_x production rates.

Updated lightning NO_x production rates reduce global lightning NO_x emissions from 5.5 TgN yr^{-1} to 3.6 TgN yr^{-1}

8 Impact of updated lightning NO_x on tropospheric composition

- In June-August (JJA) NO_x increases up to 190 pptv despite the global decline in lightning NO_x emissions because of convective uplift of localised increases that occur in the subtropics.
- This drives northern hemisphere O_3 increases of 25 ppbv due to O_3's longer lifetime and poleward transport. PAN enhancements (>65 pptv) occur across 20-90°N. OH increases up to 0.13 pptv, driven by enhanced O_3 photolysis and HO_2 decreases by up to 0.95 pptv due to enhanced OH cycling with NO, maintaining oxidative balance.
- The same spatial changes are seen in other seasons of the year though the magnitude is smaller because of the reduced convective uplift.

Changes in atmospheric composition from updated lightning (JJA 2019)



In JJA, increased NO_x drives O_3, PAN, OH, and HO_2 changes, enhancing oxidative capacity and accelerating CH_4 and VOCs removal

Key References

Price, C. & D. Rind (1992), Journal of Geophysical Research, 97(D9), **Murray** et al. (2012), Journal of Geophysical Research: Atmospheres, 117(D20), **Horner** et al. (2024), Atmospheric Chemistry & Physics, 24(11), **Wu** et al. (2023), Journal of Geophysical Research: Atmospheres, 128(4), **Koshak** et al. (2017), 16th Annual CMAS Conference.

Acknowledgements

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