SPACEBORNE OBSERVATIONS OF LIGHTNING NO_2 IN THE ARCTIC

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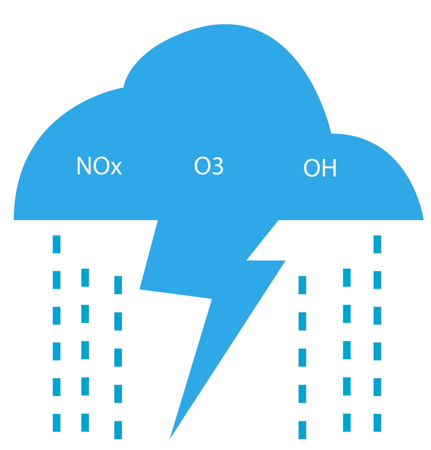
We have determined the Arctic lightning NO_2, its lifetime and production efficiency using consecutive TROPOMI observations.

Why Study Lightning NO_2 in the Arctic?

- The warming is four times faster in the Arctic than the average of the world.
- **More lightning in the Arctic** due to warming.
- Lightning NO_2 dominates the natural source of NO_2 in the upper troposphere.
- Lightning NO_2 affects **O_3, OH, CO, and CH_4**.
- Satellite measurements are a powerful tool to estimate lightning NO_2 directly.



Lightning NO_2 Selections

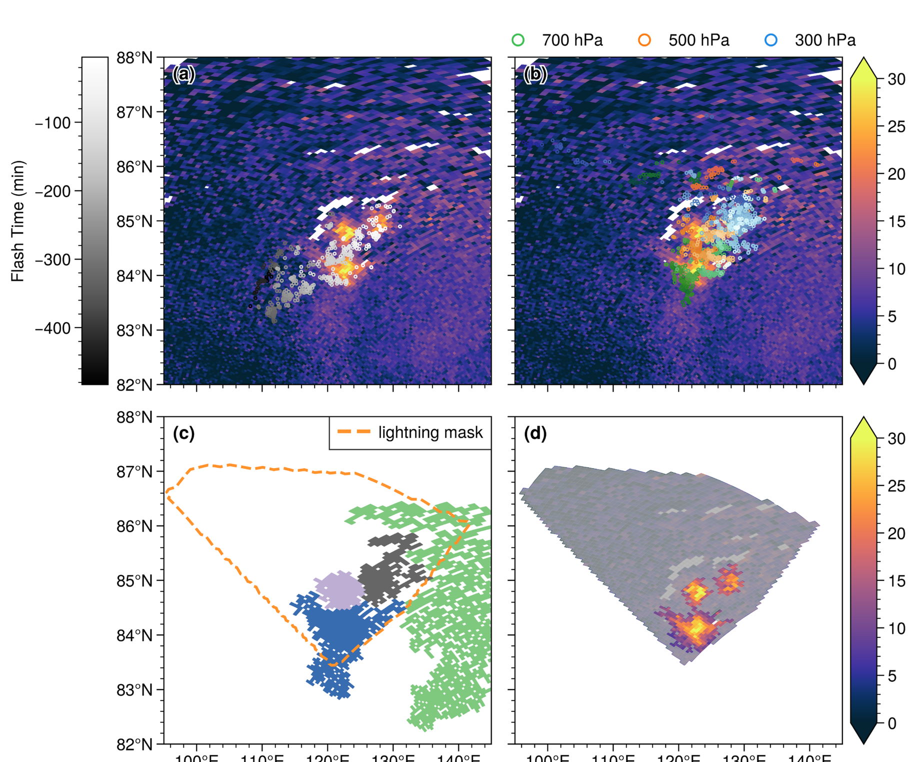


Figure 1. Schematic overview of selecting lightning NO_2 pixels. The TROPOMI-detected NO_2 tropospheric columns overlaid with (a) observed lightning strokes and (b) transported air parcels of lightning NO_2 at three pressure levels (300 hPa, 500 hPa, and 700 hPa). (c) Parcels are combined into one lightning mask (orange lines), which is overlapped with the high NO_2 selections (filled pixels). The different pixel colors stand for specific NO_2 selections. (d) Selection of lightning NO_2 in the mask by filtering out the low NO_2 (grey pixels).

- Air parcels affected by lightning NO_2 are defined at three pressure levels (300 hPa, 500 hPa, and 700 hPa) based on the time and location of detected strokes (Figure 1a).
- To determine the location of the air parcels at the TROPOMI overpass time, we used the hourly ERA5 wind data (Figure 1b).
- The final air parcel locations are combined into one lightning mask (orange lines in Figure 1c).
- The final LNO_2 area (bright pixels in Figure 1d) is the high tropospheric NO_2 slant column in the lightning mask.

Lightning NO_2 Estimations

$$V_{LNO2} = \frac{S_{NO2} - S_{BG}}{AMF_{LNO2}} \leftarrow \frac{\text{a priori } S_{LNO2}}{\text{a priori } V_{LNO2}}$$

V: vertical column density; S: slant column density; AMF: air mass factor
BG: background NO_2; LNO_2: lightning NO_2

The a priori LNO_2 profile is presented by a modified Gaussian distribution.

The peak width of Gaussian distribution is set as 60 hPa.

The peak level is the highest TROPOMI cloud pressure in the lightning mask.

For two consecutive orbits, the relationship between V_{LNO2} (mol m^{-2}) at two timestamps can be defined as

$$V_{\mathrm{LNO_2}T_2} A_{T2} = V_{\mathrm{LNO_2}T_1} A_{T1} e^{\frac{-(T_2 - T_1)}{\tau}} + PE \sum_{N} e^{\frac{-(t_i - T_1)}{\tau}}$$

T : TROPOMI overpass time; t: lightning occurring time; τ: near-field LNO_2 lifetime
A: area (m²) of each pixel; PE : LNO_2 production efficiency (mol stroke⁻¹)
N: total number of strokes during the interval between consecutive orbits
The exponential component considers the chemical loss of NO_2.

Note that if there is no lightning between two consecutive orbits, the equation can be simplified and the **lifetime τ is estimated as 6 hours**.

$$V_{\mathrm{LNO_2}T_2} A_{T2} = V_{\mathrm{LNO_2}T_1} A_{T1} e^{\frac{-(T_2 - T_1)}{\tau}}$$

Results

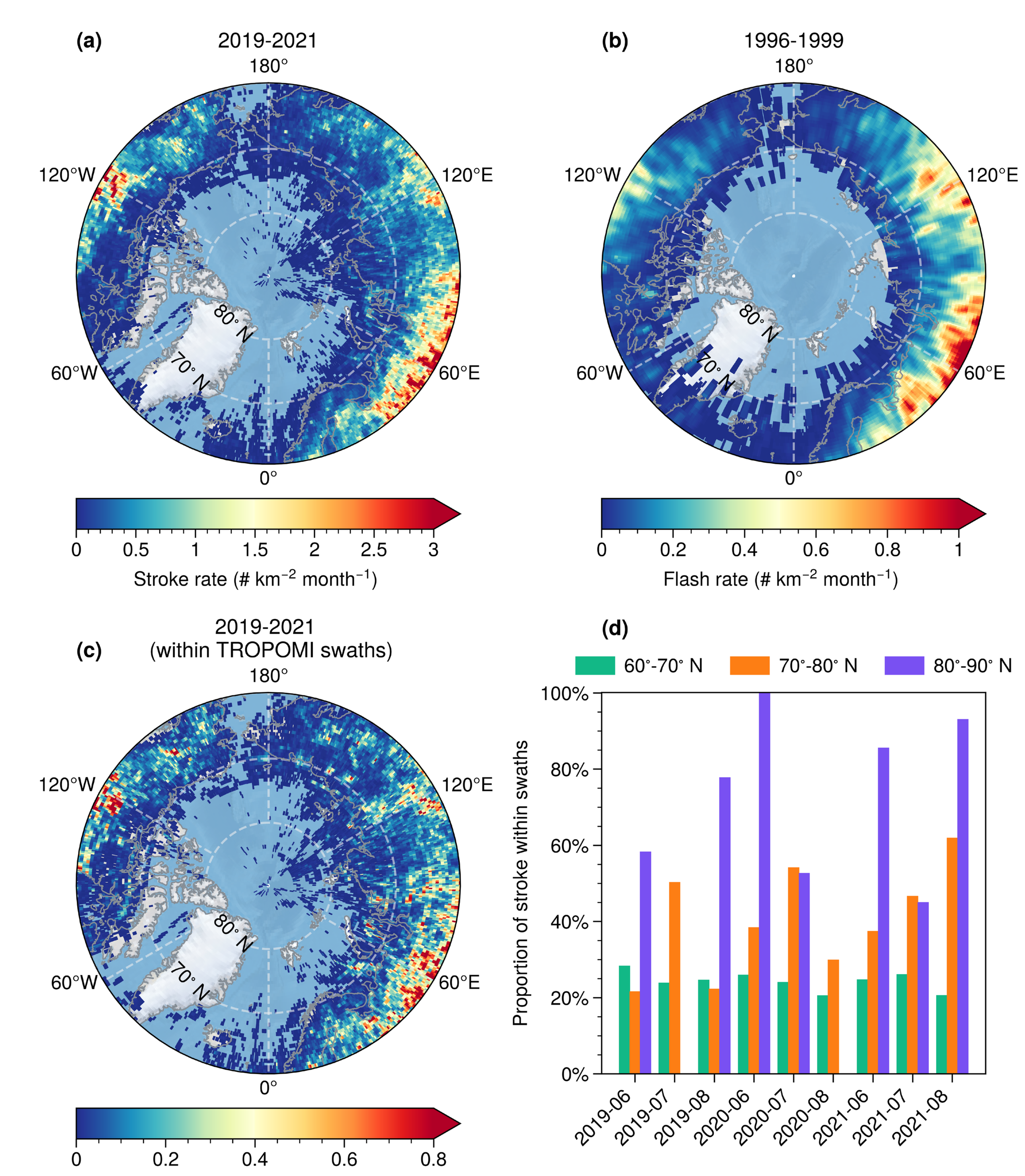


Figure 2: (a) Mean GLD360 lightning stroke rate over June–August of 2019–2021; (b) Mean OTD lightning flash rate over June–August of 1996–1999; (c) Same as (b) but only counting the lightning inside the TROPOMI swaths during the 6 hour period before the TROPOMI overpass time. Grids with no lightning are set as transparent in (a)–(c) panels. (d) The monthly ratio of (c) to (b).

- The Optical Transient Detector (OTD) instrument only observed lightning south of 75° N while the ground stroke data are from the Vaisala Global Lightning Dataset 360 (GLD360, 2019–2021).
- Both datasets show higher lightning rates over the **Siberia** and **Alaska permafrost** (60°–65° N, Figure 2a and b), which is the main **Arctic fire regime**.
- The stroke counts within the TROPOMI swaths (Figure 2c) are about 26% of the total counts and they share the same geographical pattern (Figure 2a).
- The proportion of within-swath lightning strokes increases with latitude from < 30% (60°–70° N) to 22%–62% (70°–80° N) and 45%–100% (80°–90° N, Figure 2d) due to **more overlapping swaths at higher latitudes.**

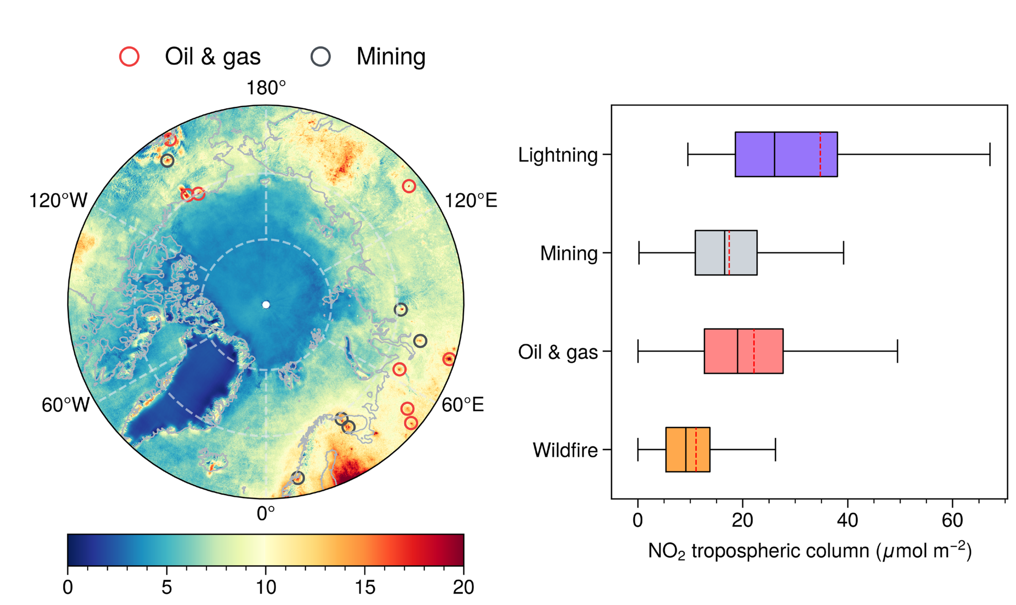


Figure 3: (a) Mean 4 km × 4 km TROPOMI tropospheric NO_2 column density in the local afternoon during June–August of 2019–2021. The mining and oil & gas stations are gray and red circles shown in panel (a), respectively. The wildfire girds are located mainly in East Siberia by more than 300 fire detections of VIIRS (not shown). (b) Comparisons of NO_2 among four sources: lightning, mining, oil & gas, and wildfire. The bar of lightning represents the maximum NO_2 values over pixels of each lightning case. The wildfire, mining, and oil & gas bars are the daily maximum NO_2 values over typical locations.

- While the averaged LNO_2 is disappearing into the background, the NO_2 enhancements can still be observed over urban, industrial, and wildfire regions (Figure 3a).
- **The LNO_2 concentration is comparable** to anthropogenic NO_2 although the time scale of emission is in the order of hours (Figure 3b).

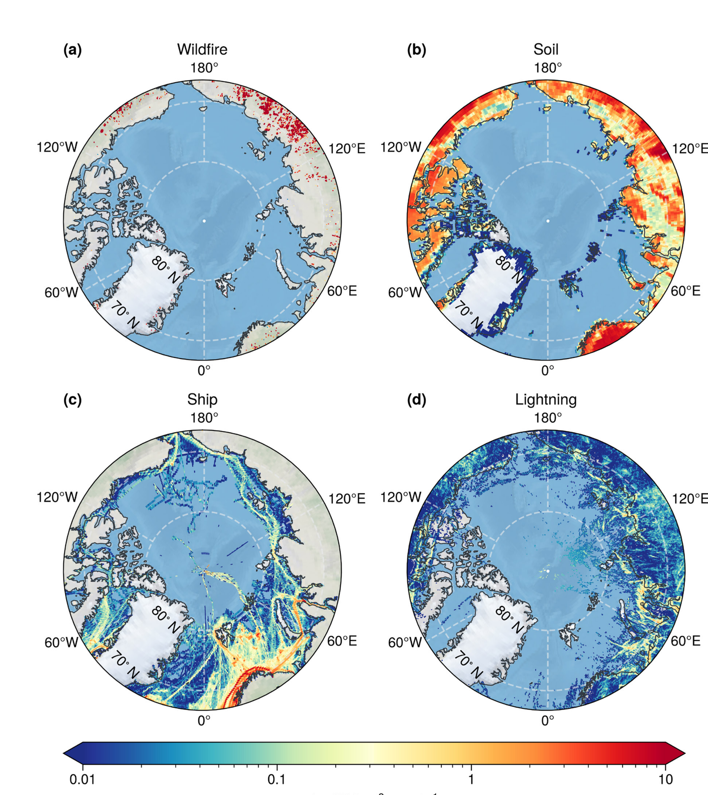


Figure 4: The monthly NO_x emissions from June to August in the Arctic from (a) wildfire, (b) soil, (c) ships, and (d) lightning. The lightning NO_x emission is the mean values from 2019 to 2021. Other emissions are from the Copernicus Atmosphere Monitoring Service (CAMS) 2018 global emission inventories.

- Although the wildfire is mostly located in Siberia and Alaska, it dominates the NO_x over the Arctic land, while the soil emission is the second highest source.
- The ship emission is the main NO_x source over the Arctic ocean, but the **LNO_x contributes to 78% of NO_x over the northeast of Arctic ocean.**

Chen, Y. et al. (2021), Future Increases in Arctic Lightning and Fire Risk for Permafrost Carbon. Nat. Clim. Chang., 11, 404–410.
Holzworth, R. H. et al. (2021), Lightning in the Arctic. Geophys. Res. Lett., 48, e2020GL091366.
Zhang, X. et al. (2022), Spaceborne observations of lightning NO_2 in the Arctic (in preparation).

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