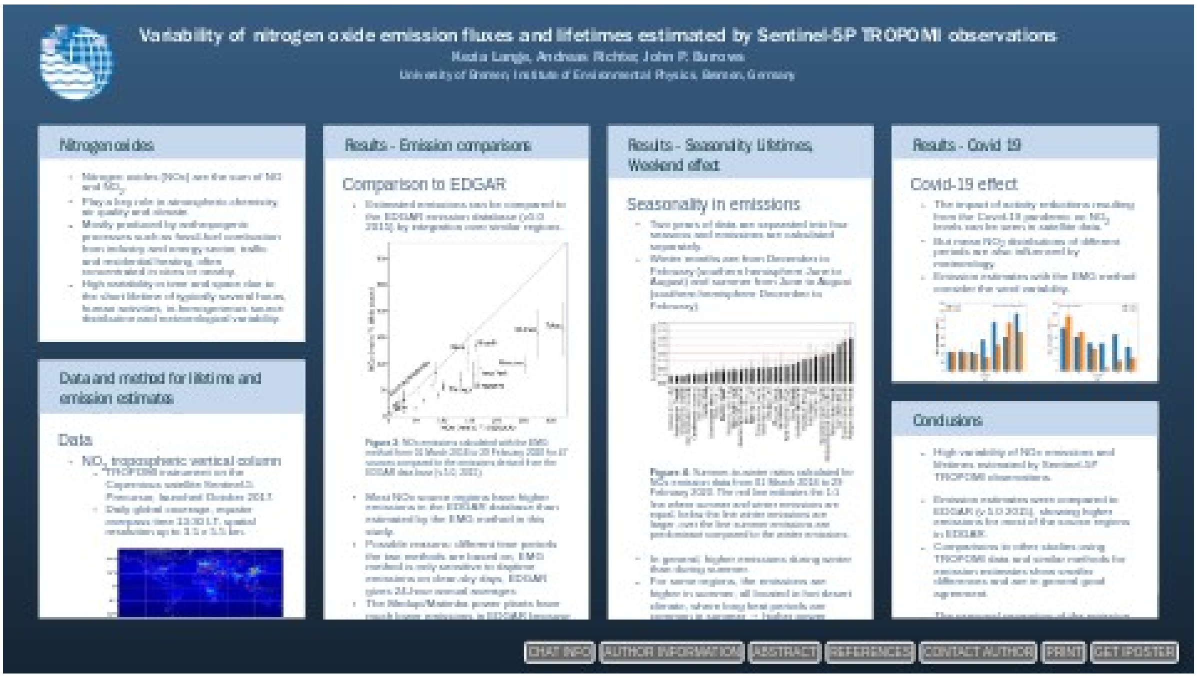
Variability of nitrogen oxide emission fluxes and lifetimes estimated by Sentinel-5P TROPOMI observations



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PRESENTED AT:

NITROGEN OXIDES

- Nitrogen oxides (NOx) are the sum of NO and NO_2.
- Play a key role in atmospheric chemistry, air quality and climate.
- Mostly produced by anthropogenic processes such as fossil-fuel combustion from industry and energy sector, traffic and residential heating, often concentrated in cities or nearby.
- High variability in time and space due to the short lifetime of typically several hours, human activities, in-homogeneous source distribution and meteorological variability.

DATA AND METHOD FOR LIFETIME AND EMISSION ESTIMATES

Data

- NO_2 tropospheric vertical column
  - TROPOMI instrument on the Copernicus satellite Sentinel-5 Precursor, launched October 2017.
  - Daily global coverage, equator overpass time 13:30 LT, spatial resolution up to 3.5 x 5.5 km.

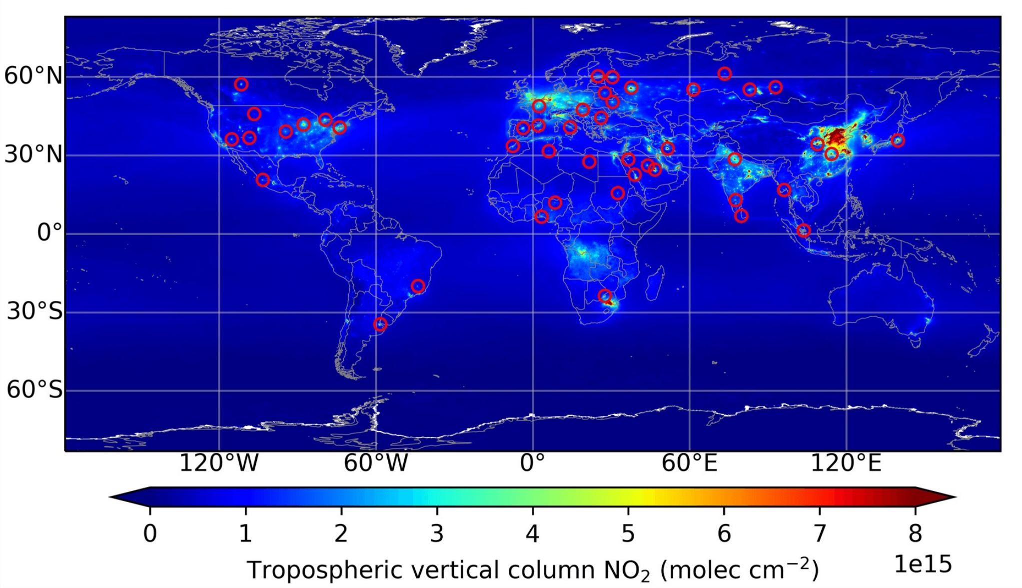

Figure 1: NO_2 tropospheric vertical column of the offline, level-2 Sentinel-5P TROPOMI product from 04 May 2018 - 31 December 2019. Red circles mark point sources used in this study.

  - We use data from March 2018 to July 2020 from the level-2 RPRO and OFFL tropospheric vertical column NO_2 product. Data from 30 April 2018 onwards is freely available on https://s5phub.copernicus.eu/ (https://s5phub.copernicus.eu/).
  - Data with a quality assurance value < 0.75 are filtered. This also excludes measurements with cloud radiance fractions > 50%.
  - Data is gridded to 0.01° x 0.01°.
- Wind data
  - Wind speed and direction at 100m from the ECMWF ERA5 reanalysis 3-hourly data with 0.25° x 0.25° resolution.
  - Interpolated to TROPOMI overpass time and re-gridded to the same resolution of 0.01° x 0.01°.
  - Wind data are merged with TROPOMI data → Only data with wind speeds > 2 m/s are used.
- Emission inventory
  - Bottom-up emission inventory EDGAR v5.0 of 2015.
  - NOx emission grid maps with 0.1° x 0.1° resolution.

Method

- Exponentially modified Gaussian (EMG) method by Beirle et al. (2011) and refined by later studies.
- Two years of TROPOMI NO_2 tropospheric vertical column data from 01 March 2018 to 29 February 2020.
- First the source region has to be selected → 47 isolated point sources, distributed over the world to analyze the influence of seasons, climatic conditions, latitudinal dependence and behavioral patterns on lifetimes and emissions.
- Next step is a rotation of the satellite data around the source with the corresponding wind data to a common wind direction resulting in an upwind-downwind pattern.
- In the last step, we apply a line density fit to the NO_2 column measurements with an exponentially modified Gaussian (EMG) function to calculate the NOx emission and lifetime.

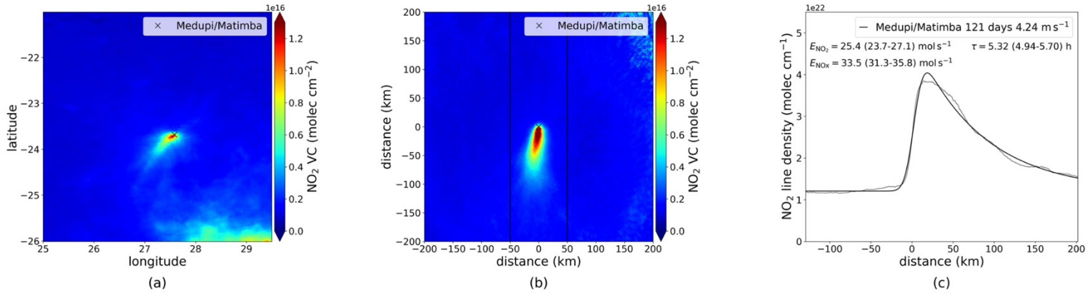

Figure 2: (a) NO2 tropospheric vertical column from 01 March 2018 to 29 February 2020 in the region of the Medupi/Matimba power plants in South Africa. (b) Upwind-downwind pattern after rotation. Black lines indicate a sector of 100 km around the source. (c) Line density calculated for the 100 km sector as function of distance to the source. Fit results with estimated emission and lifetime.

RESULTS - EMISSION COMPARISONS

Comparison to EDGAR

- Estimated emissions can be compared to the EDGAR emission database (v5.0 2015) by integration over similar regions.

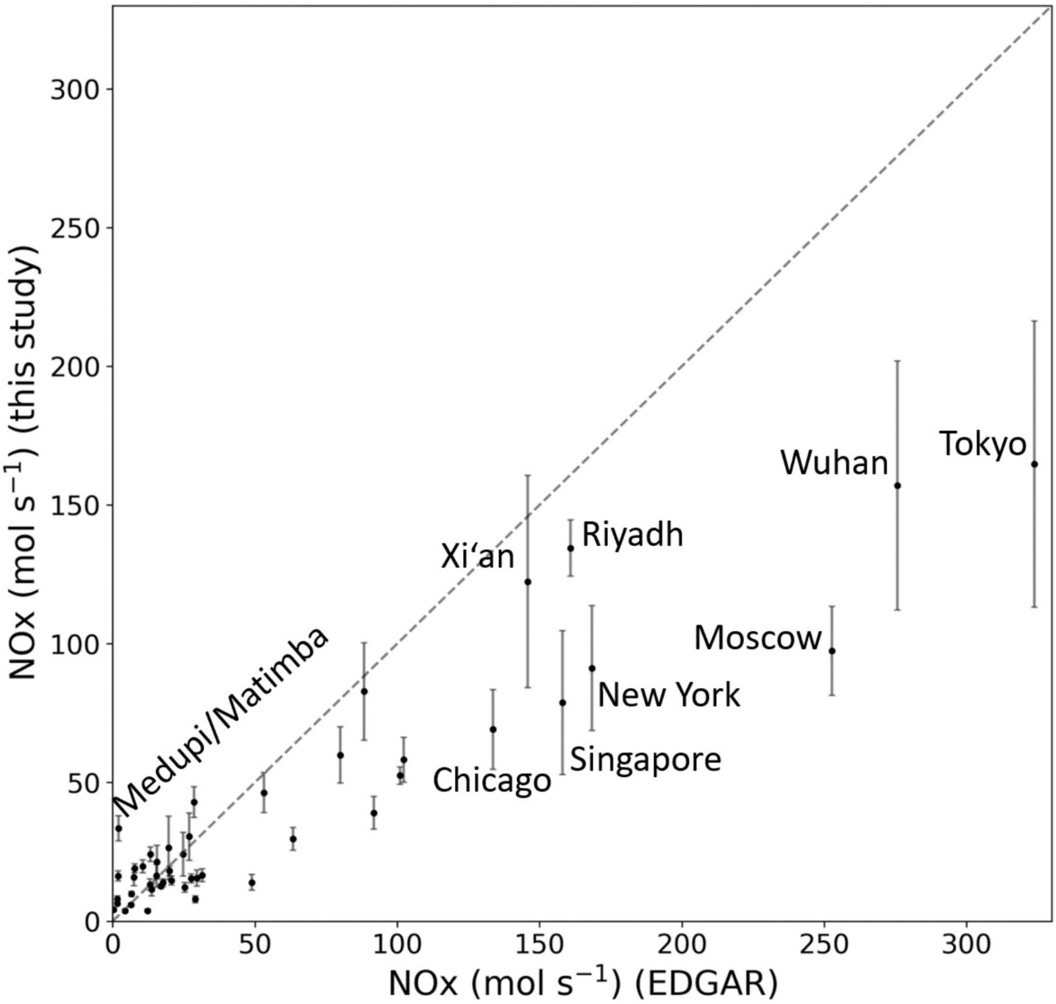

Figure 3: NOx emissions calculated with the EMG method from 01 March 2018 to 29 February 2020 for 47 sources compared to the emissions derived from the EDGAR data base (v.5.0, 2015).

- Most NOx source regions have higher emissions in the EDGAR database than estimated by the EMG method in this study.
- Possible reasons: different time periods the two methods are based on, EMG method is only sensitive to daytime emissions on clear-sky days, EDGAR gives 24-hour annual averages
- The Medupi/Matimba power plants have much lower emissions in EDGAR because Medupi was put in operation only in 2015.

Comparison to recent studies

- Determined emissions can also be compared to recent studies.

Source region	NOx emissions ($mol\,s^{-1}$)			
	This study	Beirle et al. (2019)	Goldberg et al. (2019)	Lorente et al. (2019)
Riyadh	136.2 ± 4	144.7	—	—
Medupi/Matimba	33.4 ± 2	37.2	—	—
Chicago	72 ± 7	—	73	—
New York	$75{,}1 \pm 10$	—	57.4	—
Toronto	41.4 ± 3	—	51.9	—
Colstrip	3.8 ± 0.2	—	5.3	—
Four Corners	12.2 ± 1.3	—	5.4	—
Paris	45.1 ± 3	—	—	53

Table 1: NOx emissions compared to emissions derived by recent emission studies, also based on TROPOMI data.

- All studies used TROPOMI data but different time periods and slightly different methods.
- Differences are expected but in general the emissions are in good agreement.

RESULTS - SEASONALITY, LIFETIMES, WEEKEND EFFECT

Seasonality in emissions

- Two years of data are separated into four seasons and emissions are calculated separately.
- Winter months are from December to February (southern hemisphere June to August) and summer from June to August (southern hemisphere December to February).

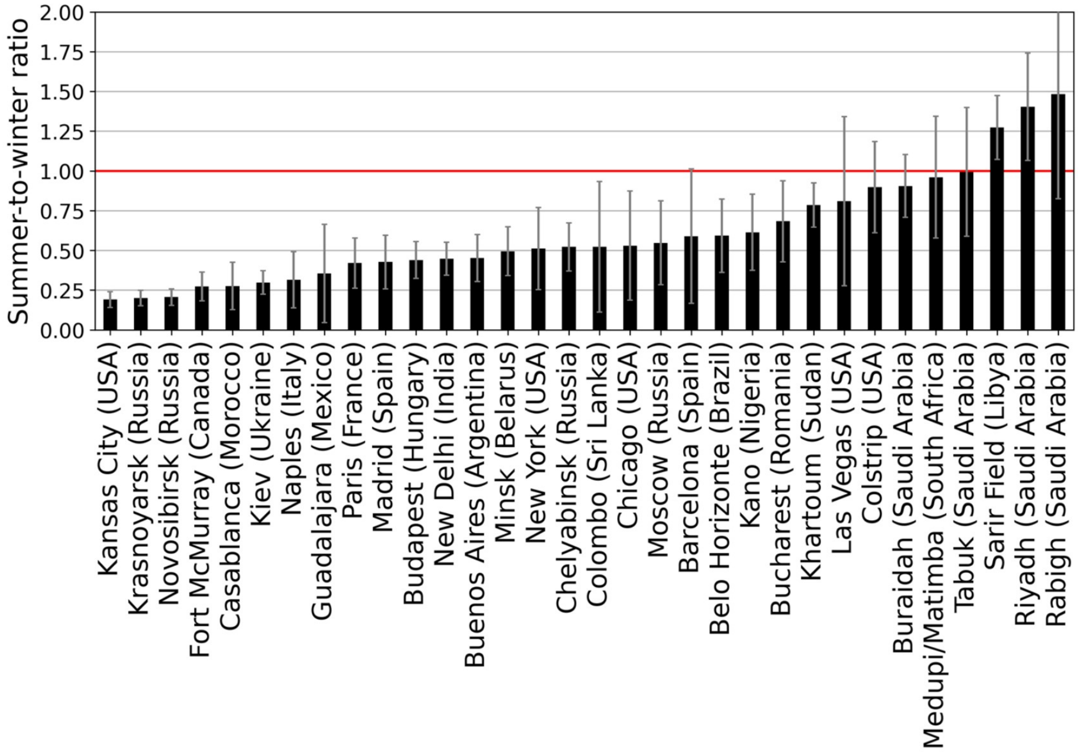

Figure 4: Summer-to-winter ratios calculated for NOx emission data from 01 March 2018 to 29 February 2020. The red line indicates the 1:1 line where summer and winter emissions are equal, below the line winter emissions are larger, over the line summer emissions are predominant compared to the winter emissions.

- In general, higher emissions during winter than during summer.
- For some regions, the emissions are higher in summer, all located in hot desert climate, where long heat periods are common in summer → higher power consumption caused by air conditioning.

Latitudinal and seasonal dependence of lifetimes

- Another result of the EMG method is the mean effective lifetime of NOx.
- The NOx lifetime depends on several factors like chemical composition, meteorology and actinic flux → dependence on latitude and season expected.

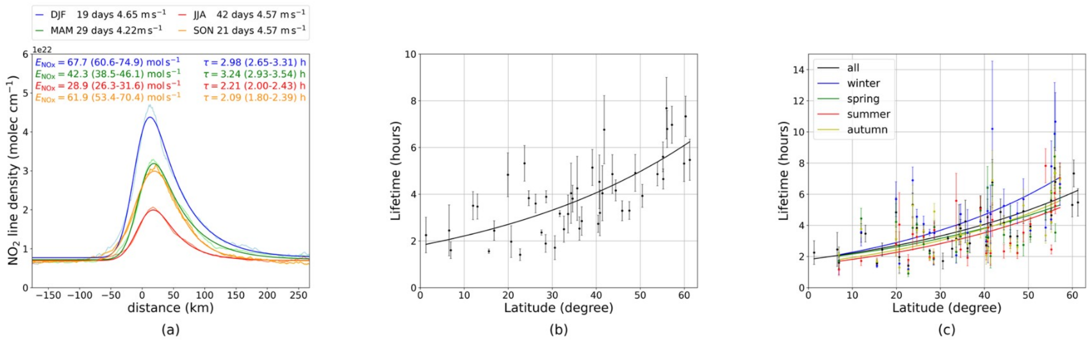

Figure 5: (a) NO_2 line densities for the city Madrid separated into seasons. (b) Estimated lifetimes for 47 source regions as function of latitude. (c) Lifetimes in dependence of latitude (black), separated into winter (blue), spring (green), summer (red) and autumn (yellow). Sources from southern hemisphere are mirrored in latitude and season.

- Lifetimes are increasing from approximately two hours for source regions at low latitudes near the equator to about six hours for source regions at high latitudes of around 60 degrees.
- A seasonal dependence is visible with the shortest lifetimes in summer and longer lifetimes in winter but in general seasonal differences are small.

Weekend effect

- The two years of data are separated into week and weekend days and emissions and lifetimes are calculated separately.

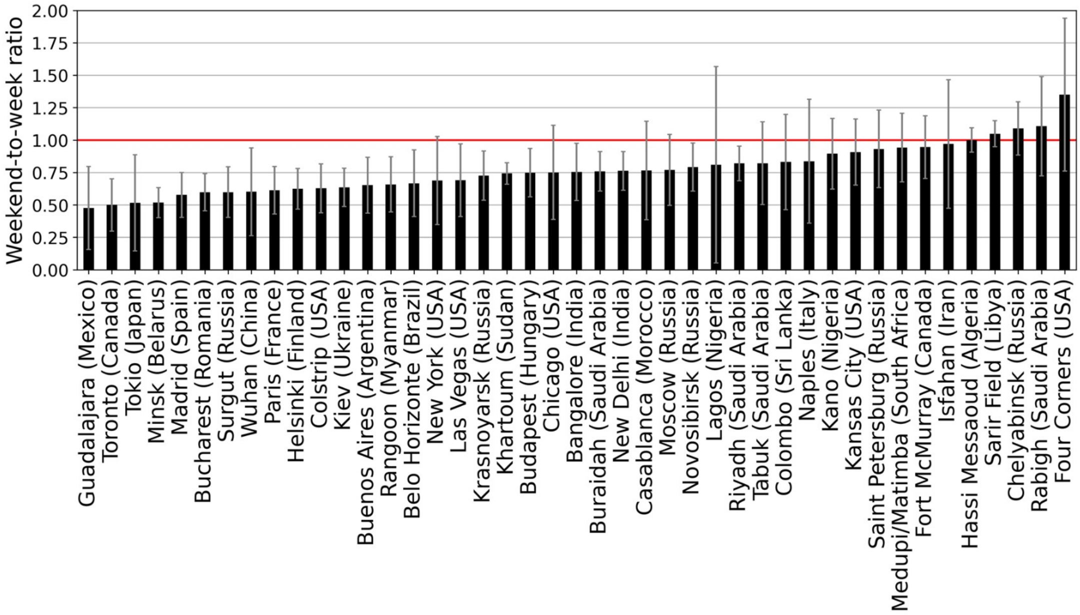

Figure 6: Weekend-to-weekday ratio for two years of NOx emission data. Weekend can be one or two days and days and can also differ according to religious tradition, which is considered. The red line indicates the 1:1 line where weekend and week emissions are equal, below the line week emissions are predominant and above the line weekend emissions are higher.

- For most NOx source regions, emissions are higher during weekdays than on the weekend albeit with rather high variability.
- Source regions not showing any reductions on the weekend are mostly dominated by power plants.
- The separately calculated lifetimes do not show a clear tendency to longer lifetimes on weekends.

RESULTS - COVID 19

Covid-19 effect

- The impact of activity reductions resulting from the Covid-19 pandemic on NO_2 levels can be seen in satellite data.
- But mean NO_2 distributions of different periods are also influenced by meteorology.
- Emission estimates with the EMG method consider the wind variability.

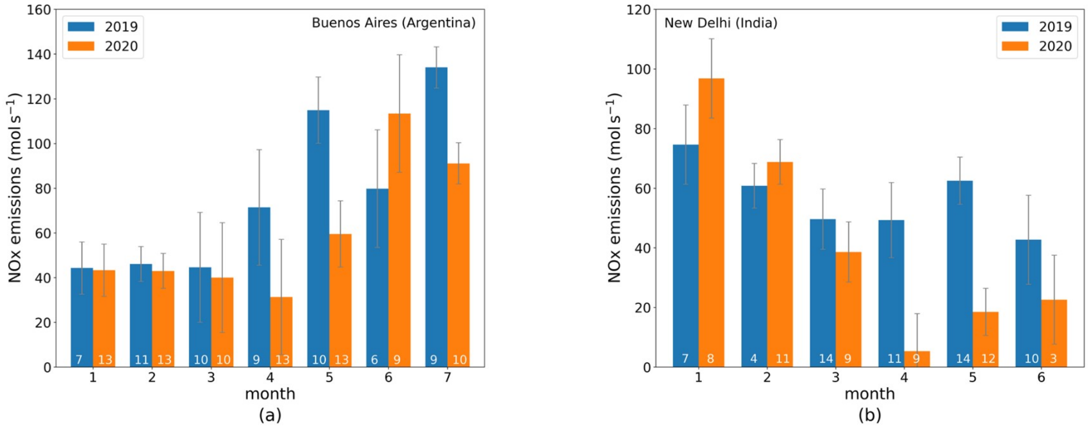

Figure 7: Monthly NOx emissions calculated with the EMG method for 2019 and 2020 for (a) January to July for Buenos Aires and (b) January to June for New Delhi. The numbers in the bars represent the number of available days for the monthly mean.

- NOx emission reductions in April 2020 compared to 2019 are -56% for Buenos Aires and -89% for New Delhi, estimated from the TROPOMI data using the EMG method.

CONCLUSIONS

- High variability of NOx emissions and lifetimes estimated by Sentinel-5P TROPOMI observations.

- Emission estimates were compared to EDGAR (v.5.0 2015), showing higher emissions for most of the source regions in EDGAR.
- Comparisons to other studies using TROPOMI data and similar methods for emission estimates show smaller differences and are in general good agreement.

- The seasonal separation of the emission estimates shows in general the highest emissions during winter, except for cities in hot desert climate.
- The investigation of latitudinal and seasonal dependence of the NOx lifetime shows an increase in lifetime (2 to 6 hours) in correlation to an increase in latitude but only a weak seasonal dependence.
- For most NOx sources, emissions are higher during weekdays than on the weekend, with weekend-to-week ratios with high variability.

- Short term reduction in emissions due to the Covid-19 measures was found comparing NOx emissions from April 2019 to April 2020 for Buenos Aires (-56%) and New Delhi (-89%).

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ABSTRACT

Observations of the instrument TROPOMI on the Sentinel-5 Precursor satellite provide measurements of nitrogen dioxide (NO2) at city level and allow quantifying variability of nitrogen oxide (NOx) emissions and lifetimes on a seasonal and daily basis.

To quantify nitrogen oxide emissions and lifetimes with their high variability in space and time, satellite data is especially suited as it provides daily global coverage and a large number of measurements. In this study two years of Sentinel-5P TROPOMI NO2 data with a spatial resolution of up to 3.5 km x 5.5 km together with ECMWF ERA5 wind data is analyzed. The NO2 satellite data around the source are linked to the ERA5 wind data and rotated to a uniform wind direction to get clear NO2 plumes. Out of these two-dimensional maps of the mean NO2 distribution, one dimensional line densities are calculated by integration across wind direction. Lifetimes and emission fluxes are calculated for up to 45 different NOx sources represented by cities and power plants distributed over the world.

Calculated emissions compared to bottom-up emission inventories show significantly lower values but are in good agreement with other studies which analyzed emissions using TROPOMI data. Separation into seasons shows a seasonal dependence of emissions with in general the highest emissions during winter, except for cities in Saudi Arabia. The investigation of the latitudinal dependence of the NOx lifetime shows an increase in lifetime in correlation to an increase in latitude but only a weak seasonal dependence for separation into seasons. Weekday variability of emissions is found with weekend-to-weekday ratios of up to 0.5 but with a high variability for the different source regions. Emission comparisons of pre Covid-19 times and the lockdown period during Covid-19 show strong reductions in NOx emissions during the lockdown.

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