QUANTIFYING URBAN, INDUSTRIAL, AND BACKGROUND CHANGES IN NO_2 DURING THE COVID-19 LOCKDOWN PERIOD BASED ON TROPOMI SATELLITE OBSERVATIONS

Vitali Fioletov[1], Chris A. McLinden[1], Debora Griffin[1], Nickolay Krotkov[2], Fei Liu[2], Henk Eskes[3]

[1]Air Quality Research Division, Environment and Climate Change Canada, Toronto, Canada
[2]Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[3]Environmental Sciences Group, Wageningen University, Wageningen, the Netherlands

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"Plume Hunters"

- Common approach: to "fit" satellite NO_2 data by functions of wind speed and direction, which describe dispersion of plume from known sources, and then to derive source emissions from the fit (*Beirle et al., Science, 2011; de Foy et al., Atmos. Environm., 2014; Fioletov et al, GRL, 2015; Liu et al., ACP, 2016)*
- The total NO_2 mass (m) of the plume is calculated from the fit and then emissions (E) are calculated as $E=m/\tau$, where τ is lifetime

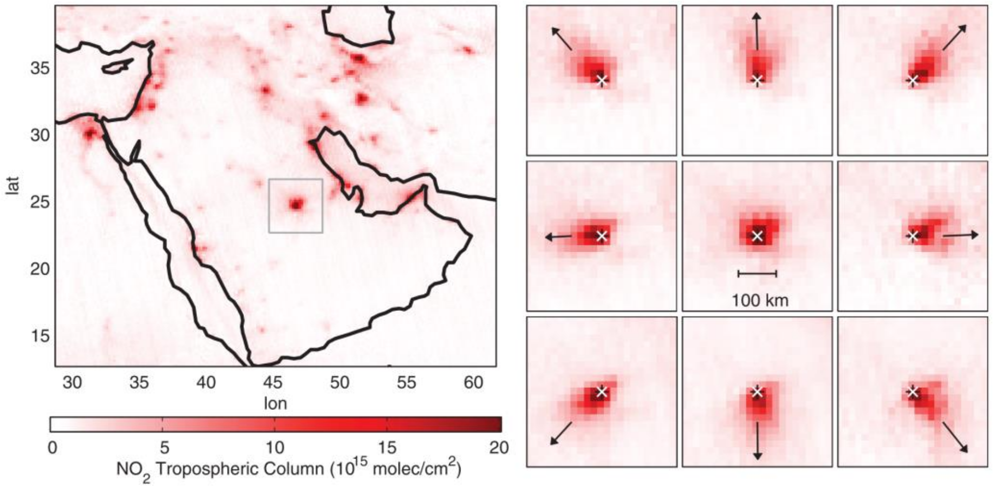


Fig. 1. Wind dependency of NO_2 column densities around Riyadh. (**Left**) Mean NO_2 tropospheric columns in the Middle East from OMI measurements during 2005 to 2009 for calm ($w < 2$ m/s) conditions with <30% cloud cover. The gray box indicates the area around Riyadh displayed in the enlarged plots on the right. (**Right**) Mean NO_2 column densities around Riyadh (white cross) for different wind conditions, i.e., calm (center panel) and eight main wind direction sectors (surrounding panels; arrows indicate the mean of the respective ECMWF winds).

From Beirle et al., Science, 2011

There are however several issues with this approach:

- Is a megacity really a point source?
- The algorithms remove a constant "background". What do we know about that "background? Is it really constant?
- What if there is uneven terrain around the source?
- What if we have more than one source in close proximity?

The developed algorithm addresses all these issues. We use the TROPOMI NO_2 data during the COVID-19 period to illustrate the algorithm.

Algorithm

- The approach is based on fitting satellite data by a statistical linear regression model with empirical plume dispersion functions driven by a meteorological reanalysis.
- For NO_2, it is based on the fit of TROPOMI data by a set of functions that represent three main components:
  - Large-scale background that depends on elevation
  - Plumes from industrial point sources (power plans, oil refineries, cement factories, etc.)
  - In case of multiple industrial point sources, the algorithm groups plumes from them into clusters using factor analysis. As a result, emissions are estimated not for individual sources, but for clusters.
  - Plumes from urban emissions that depend on population density grid
- Calculations were done for 3° by 4° areas around major cities assuming that emissions per capita are uniform within the area.
- Three months of TROPOMI data were fit by these functions multiplied by unknown coefficients. These coefficients are estimated using linear regression model. There are 4 coefficients related to the background, one coefficient related to urban plumes and one coefficient for each industrial source.
- The coefficients related to plumes essentially represent total mass that can converted to emissions ($E=m/\tau$).

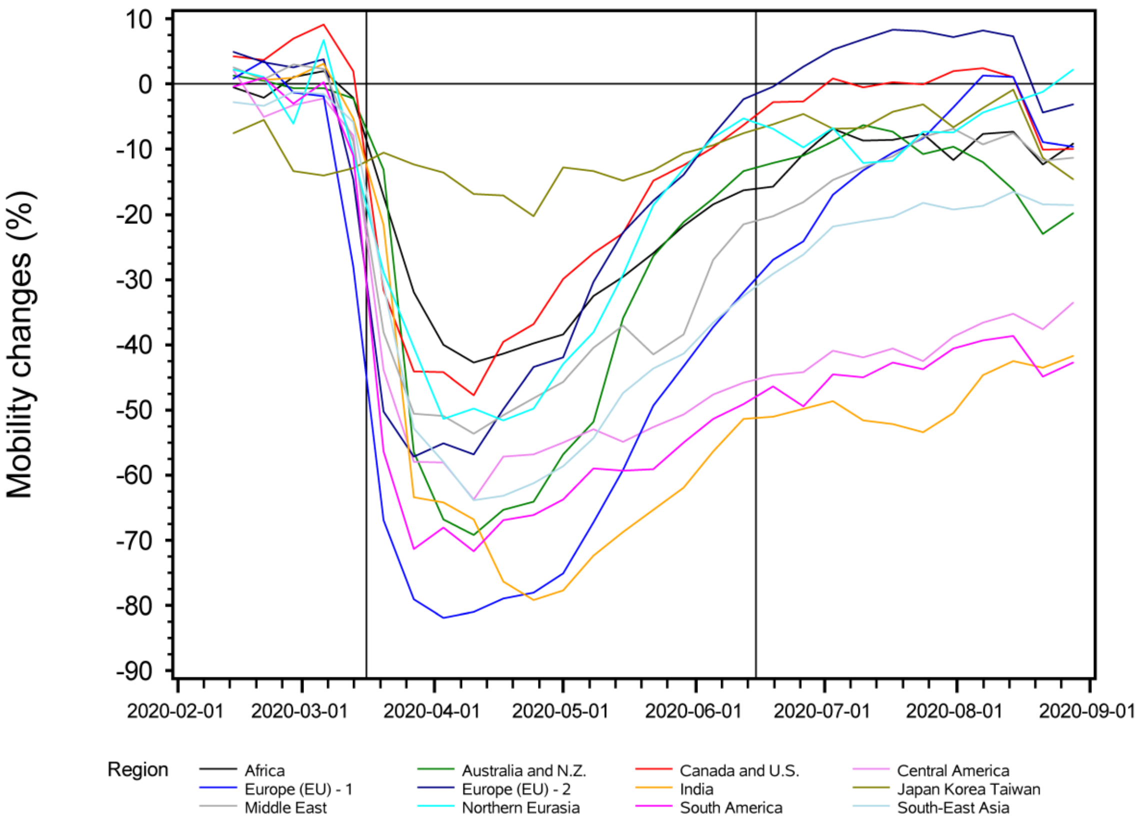
Contributions from all factors are estimated simultaneously by fitting TROPOMI data by a set of functions. When the fit coefficients are estimated, TROPOMI NO_2 can be represented as a sum of three individual components.

COVID-19 study

- The new method of isolation of three components: background NO_2, NO_2 from urban sources, and from industrial point sources was applied.

- The TROPOMI tropospheric NO_2 VCD values over 261 (3° by 4°) urban areas from 12 regions in 2020 were compared with VCD values in 2018 and 2019.

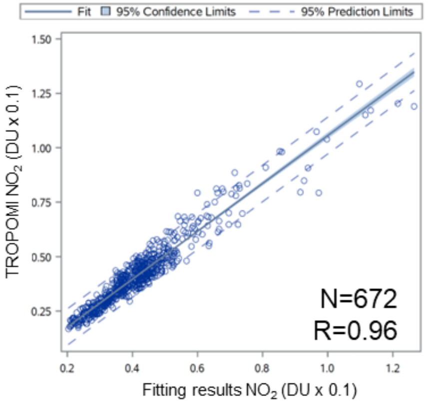
- The period for analysis (from March 16 to June 15, 2020) was chosen based on Google mobility data.



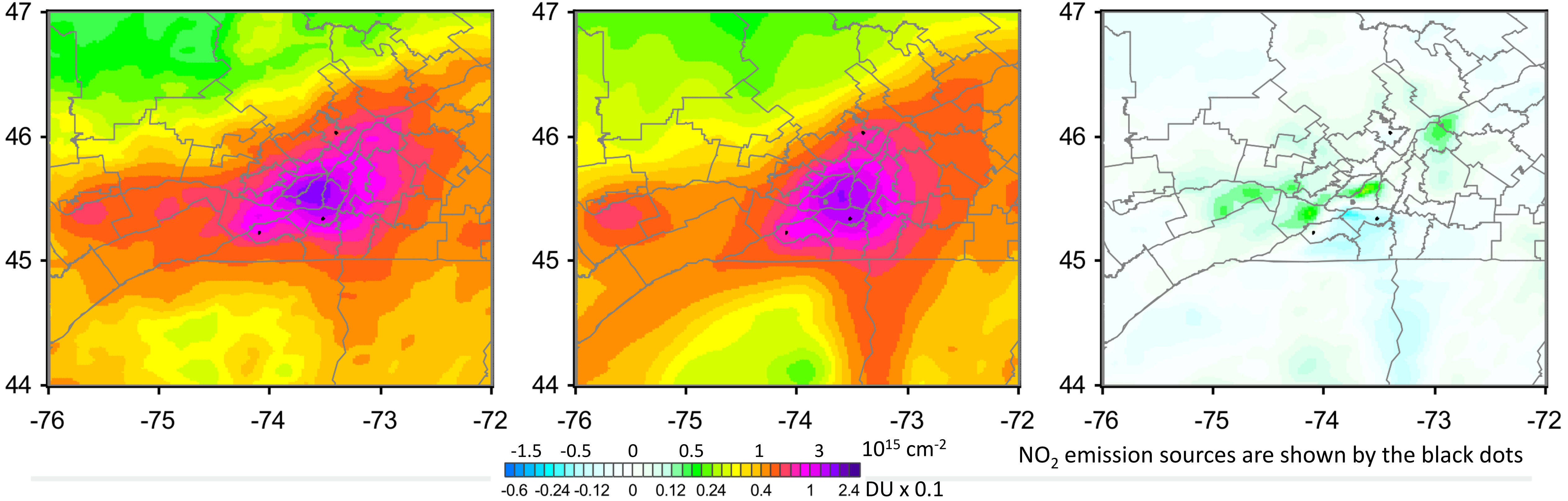
Changes in weekly **Google mobility data** (for "retail and recreation" category) relative to the baseline period (Jan 3 – Feb 6, 2020) for twelve regions analysed in this study. The black vertical lines represent the beginning and the end of the period analyzed in this study (March 16 – June 15).

The background, urban, and industrial components over 261 (3° by 4°) urban areas were analyzed separately to estimate any impact due to the COVID-19 lockdown on each of them.

Fitting TROPOMI tropospheric NO_2 VCD for March 16 – June 15, 2018-2019, over the Montreal area



Tropomi mean tropospheric NO_2 = Fitting results + Residuals



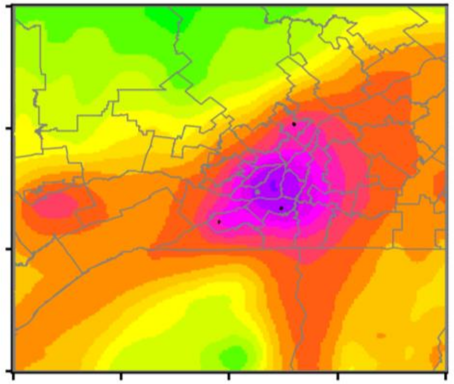
NO_2 emission sources are shown by the black dots

TROPOMI data represented as a sum of elevation-related "background" term, results of fitting by other factors and residuals

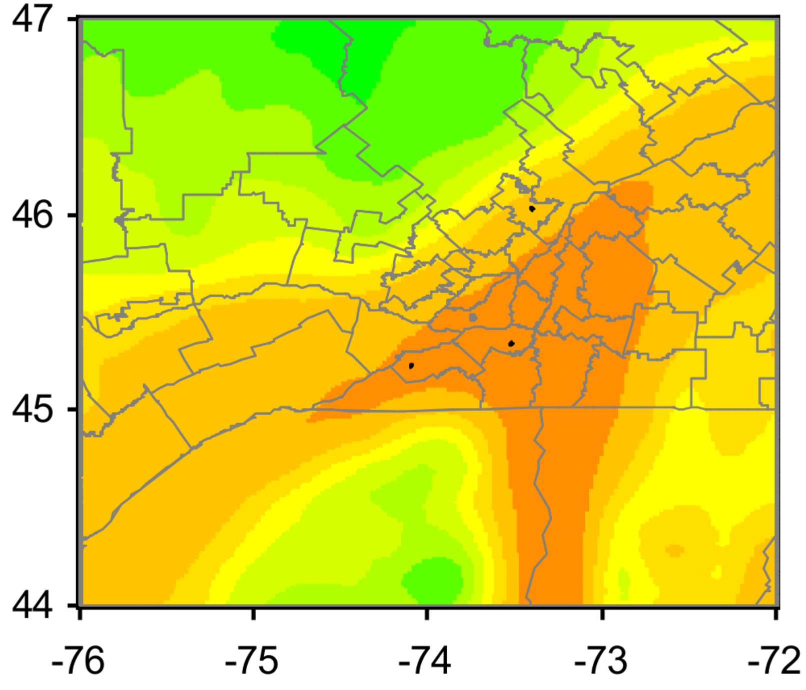
The plots are simplification. The actual fitting is done in 4D space with wind direction and speed taken into account

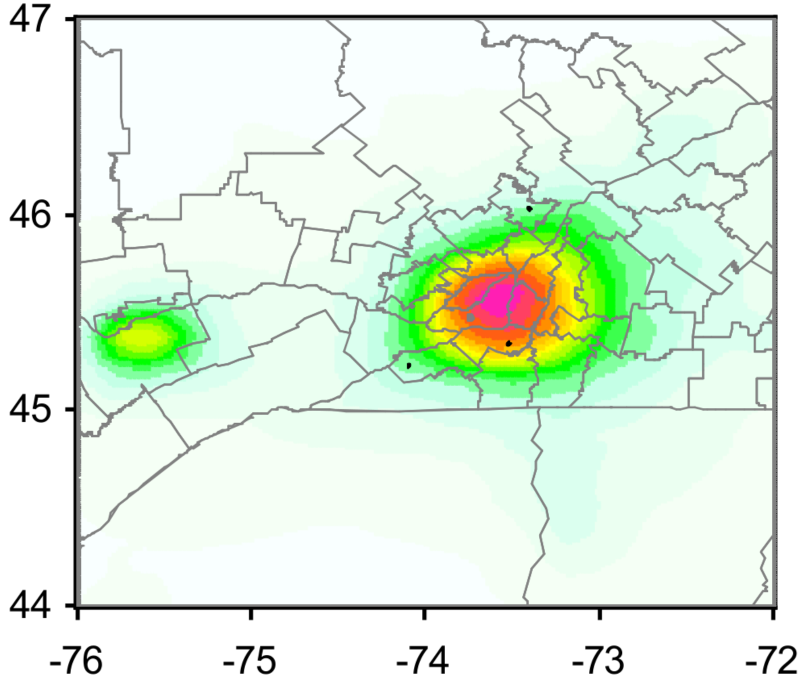
TROPOMI NO2 March 16 – June 15, 2018-2019, over Montreal area

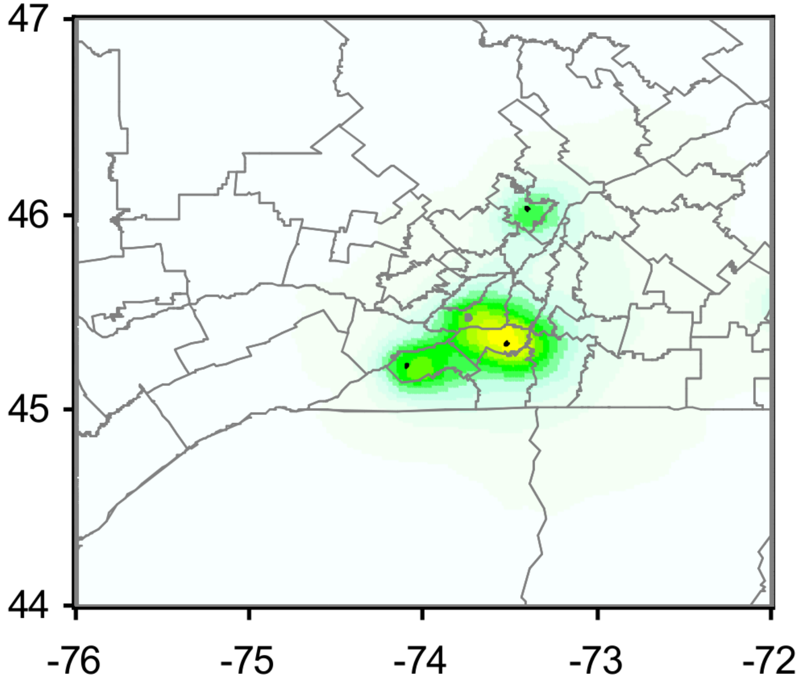
Fitting results
from the previous slide



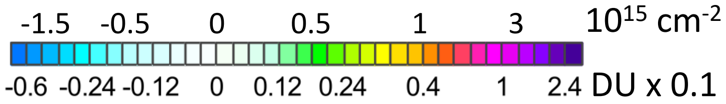
The fitting result is a <u>sum of three individual components</u>:





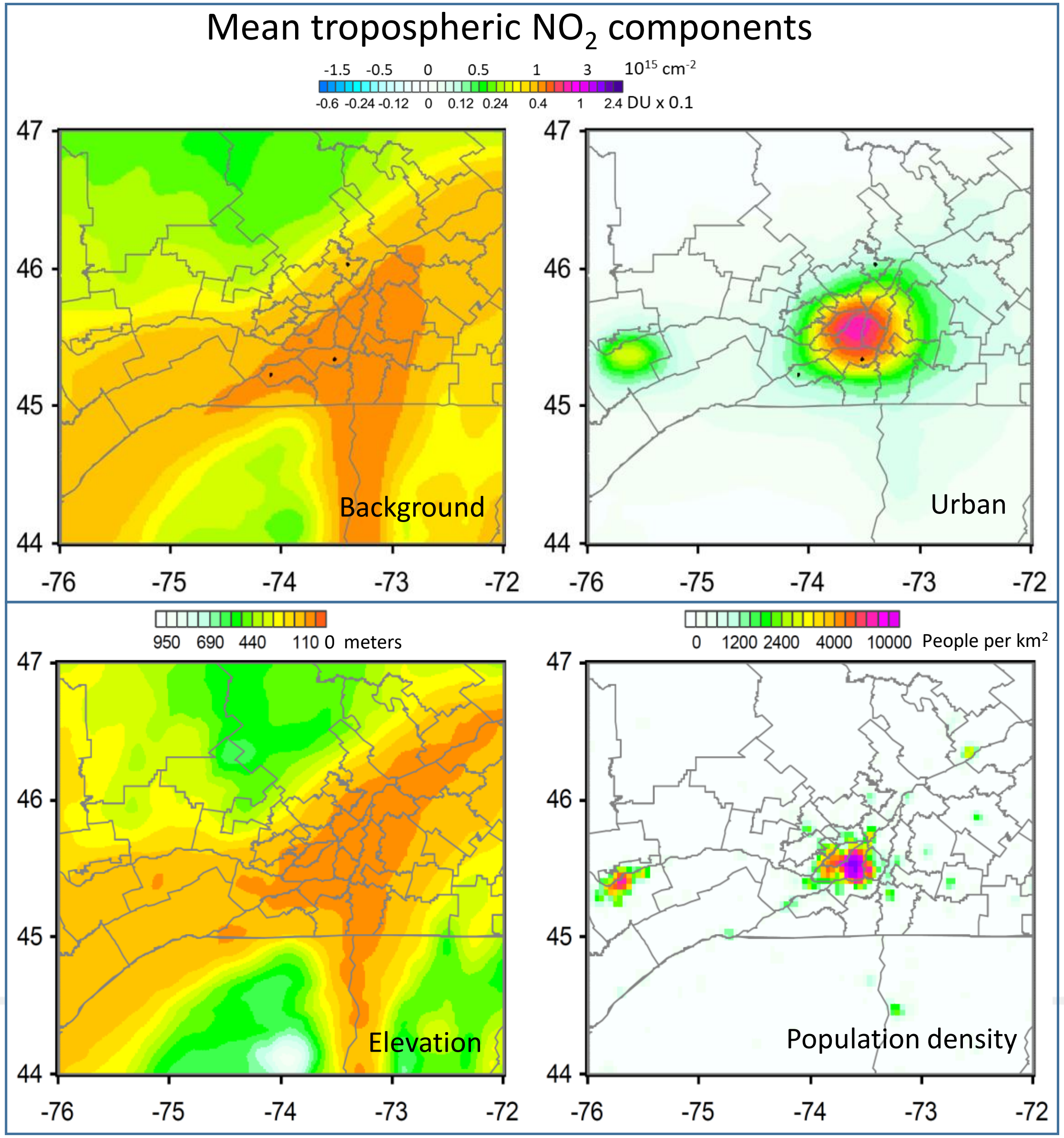


Background component, that depends on elevation + Population density-related (urban) + Industrial source-related



NO_2 emission sources are shown by the black dots

TROPOMI NO_2 for March 16 – June 15, 2018-2019, over the Montreal area



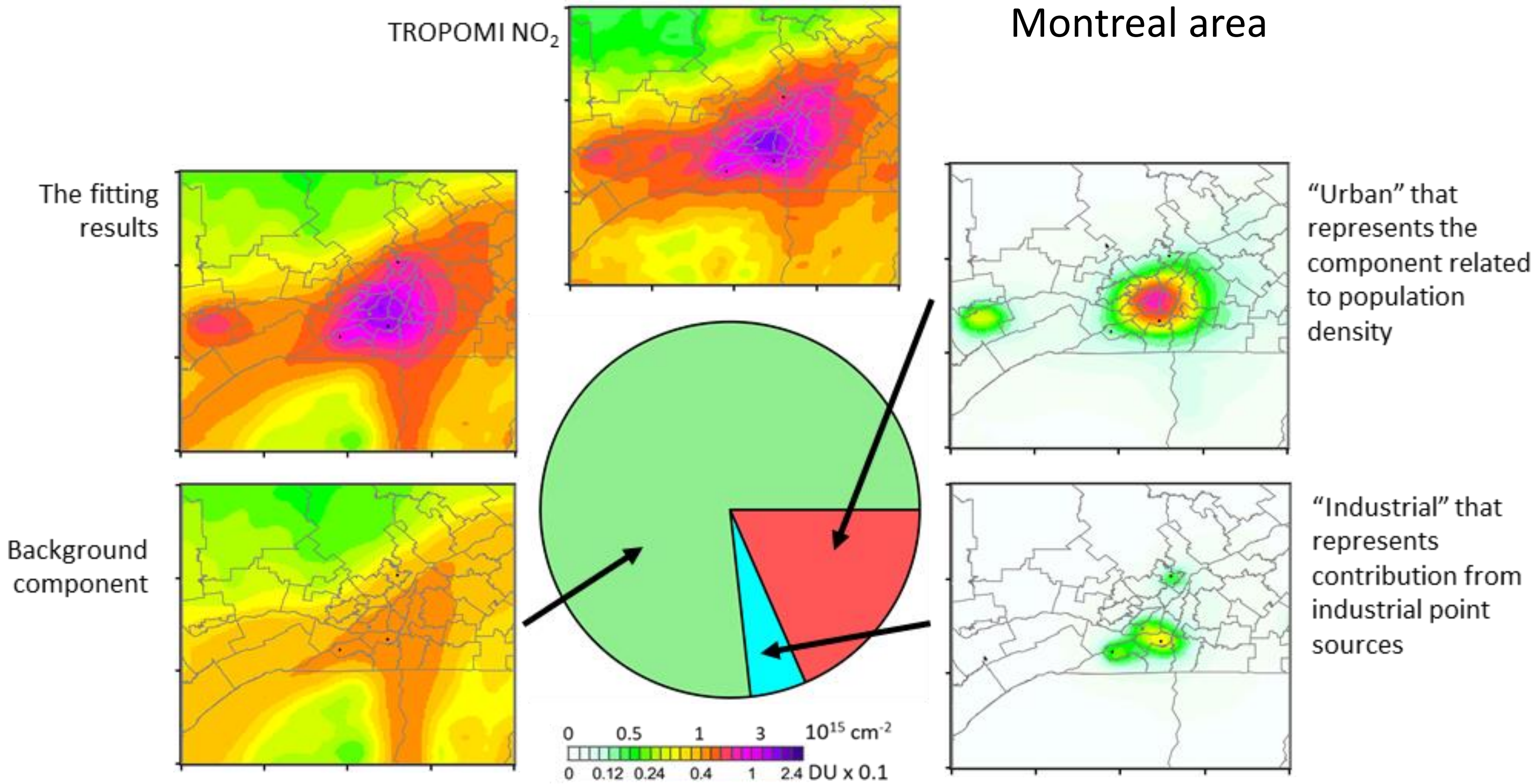
There is a clear link between background and urban components and underlying proxies:

- ***The background component follows the terrain***
- ***The urban component is population density convoluted with plume functions (or "smoothed")***

NO_2 emission sources are shown by the black dots

Total NO_2 mass can be represented as a sum of three components

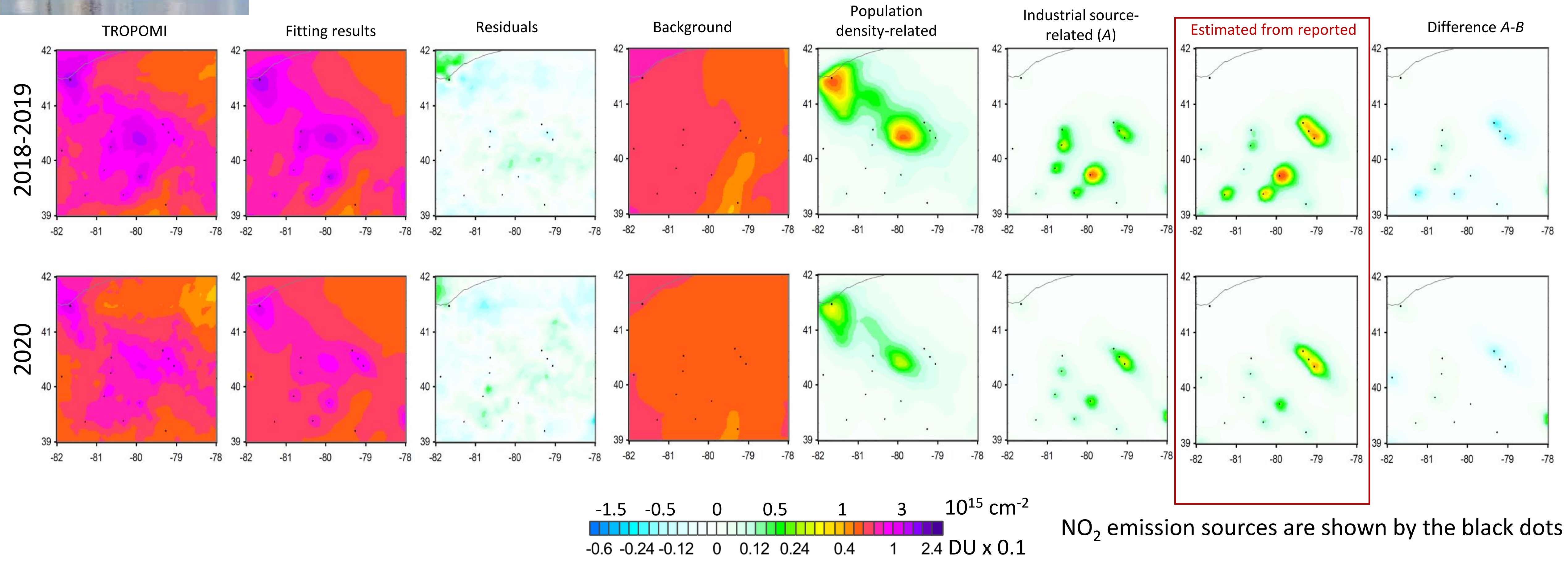
Montreal area



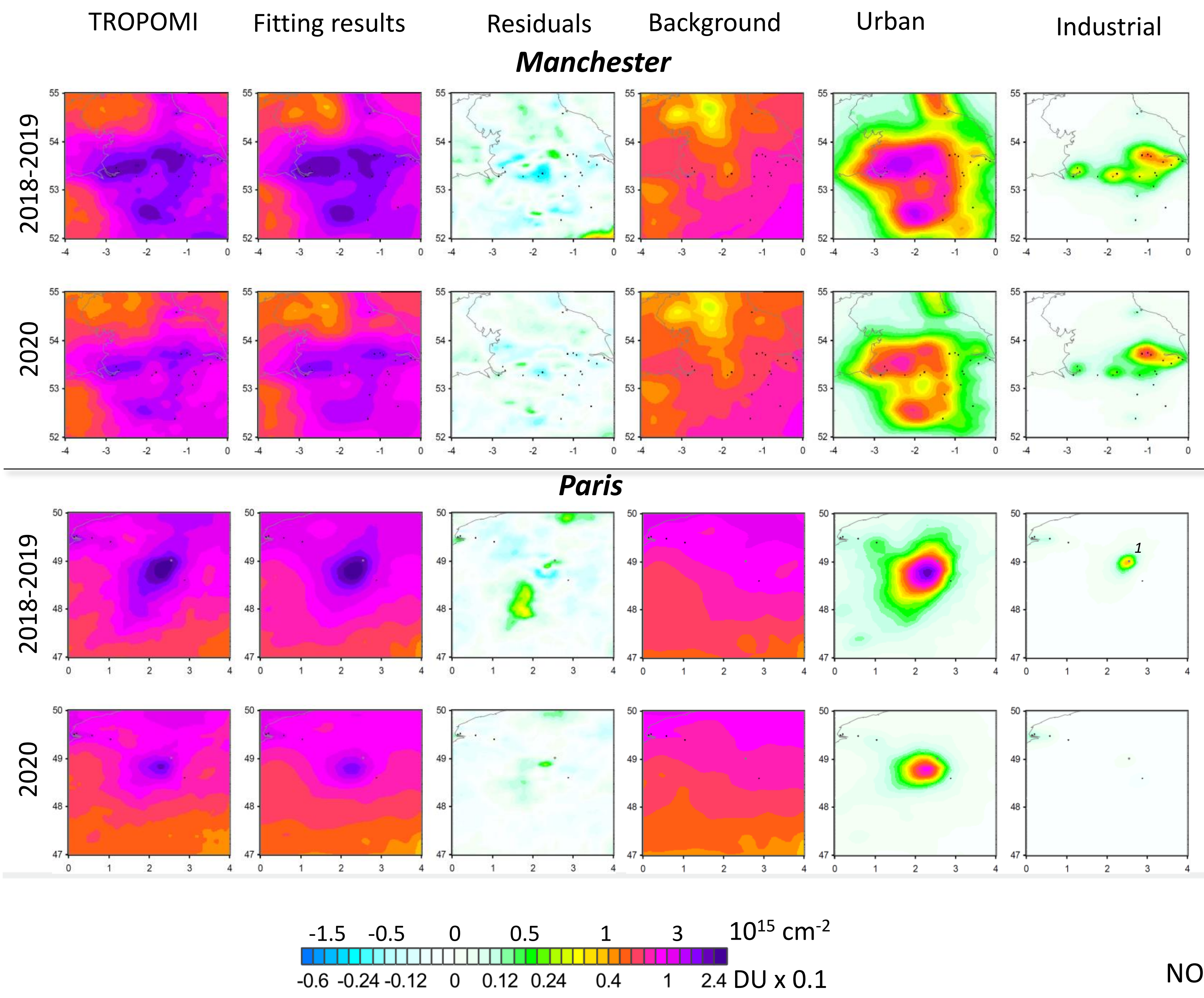
Relative contribution of individual components to the total NO_2 mass over the analyzed area

It appears that "plumes" from industrial sources and cities are responsible for a just fraction of total NO_2 mass.

Pittsburgh area: multiple industrial sources and high industrial emissions



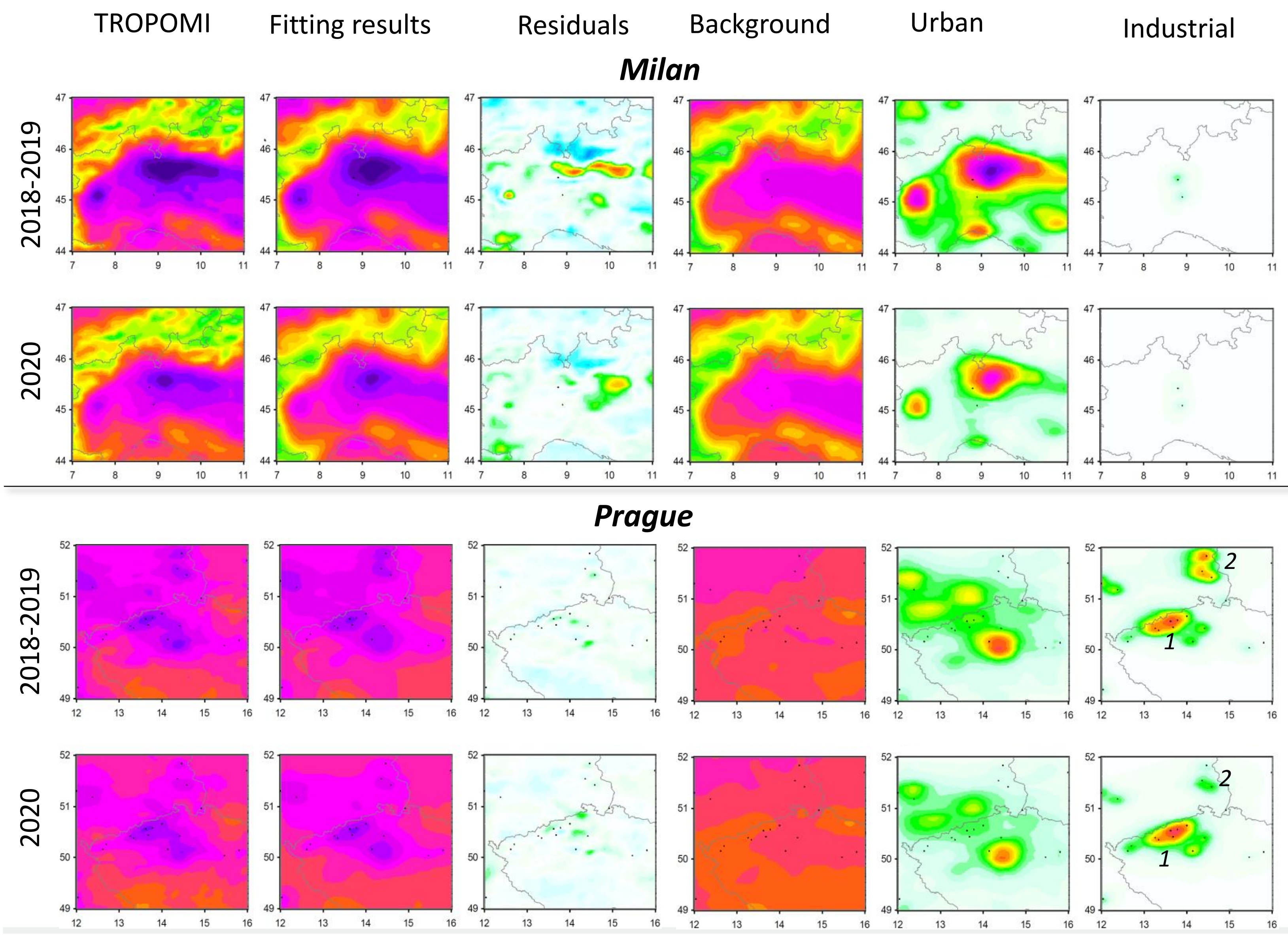
How can we validate the results? We can compare our estimated industrial emissions with reported ones. Or we can take sources with known emissions and calculate what NO_2 VCDs from their emissions would be seen by TROPOMI.

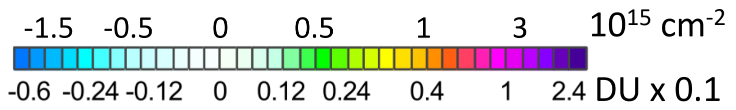


- The analysis shows a -40%±1.4% and -18%±5.6% decline for the urban and industrial components respectively
- Reported decline in traffic and industrial emissions is -35% to -50% and -20% respectively
- There is practically no change in the background component

- The decline the background component is about -10%±0.5%, while the decline in the urban component is about -57%±1.5%
- Estimated decline in emissions from Charles de Gaulle Airport (1) is about 90%. Reported decline in traffic is 95%

NO_2 emission sources are shown by the black dots



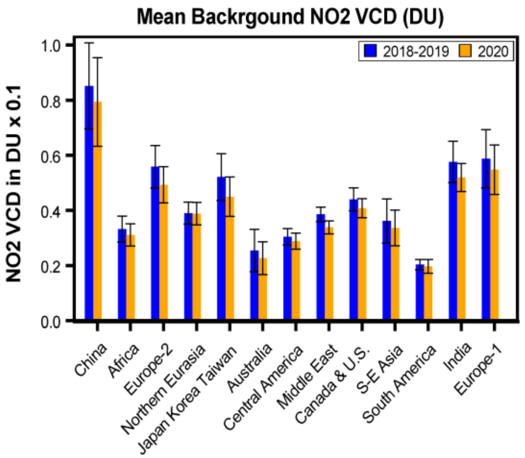


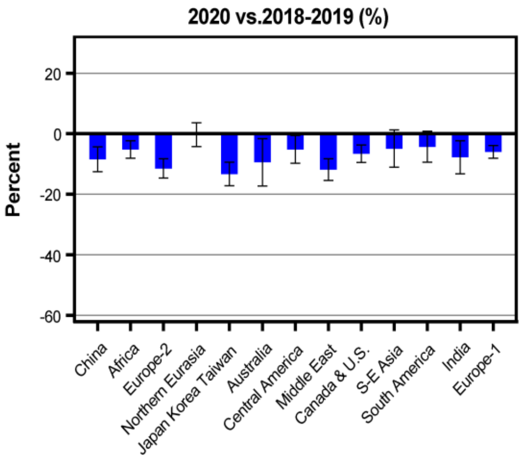
- The analysis shows a -53%±1.5% decline for the urban component
- There is practically no change in the background component

- The decline in the urban component is about -16%±3%
- Power plants in Czech Republic (1) show practically no decline in emissions, while power plants in Germany (2) show a 60% decline

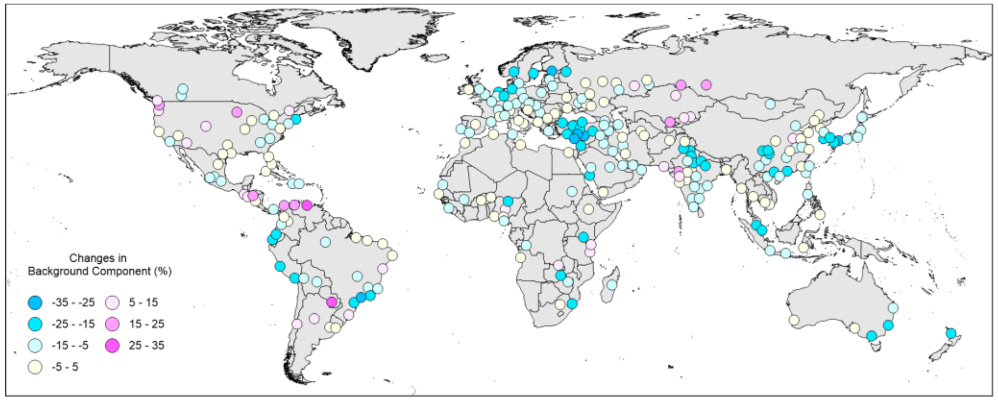
NO_2 emission sources are shown by the black dots

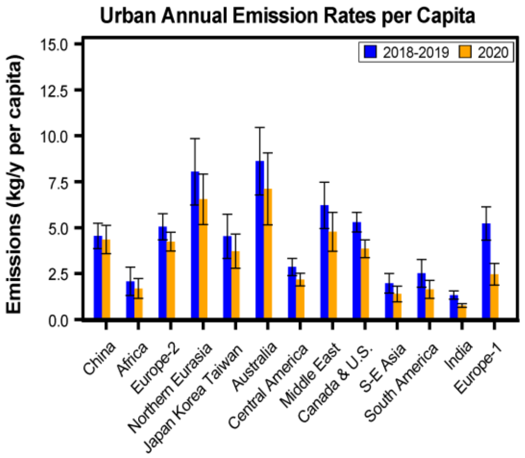
Changes in 2020 vs. 2018-2019 for background and urban components

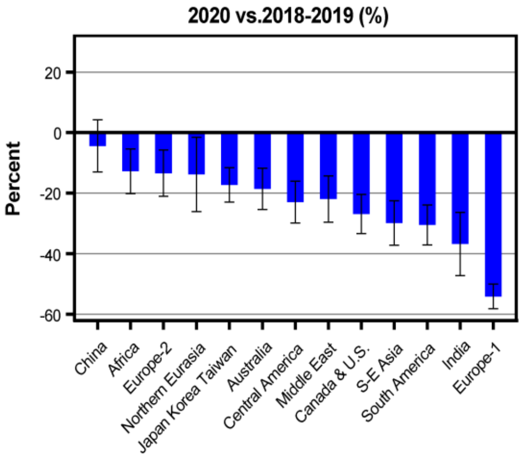




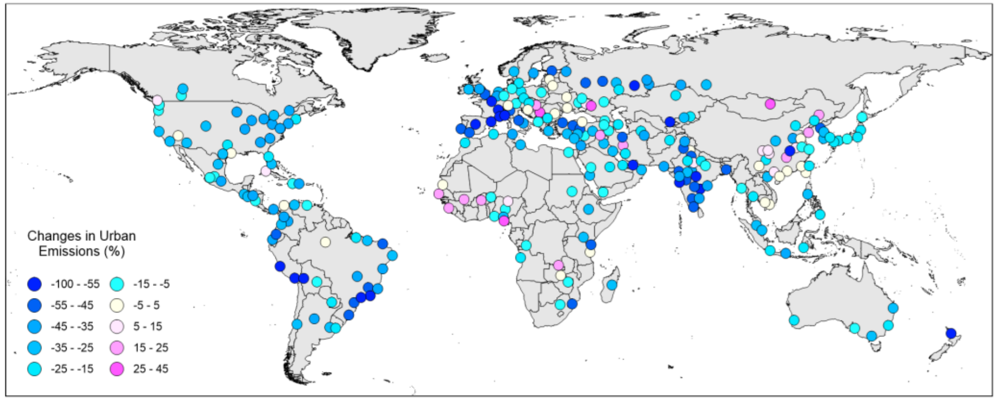
Background component







Urban component

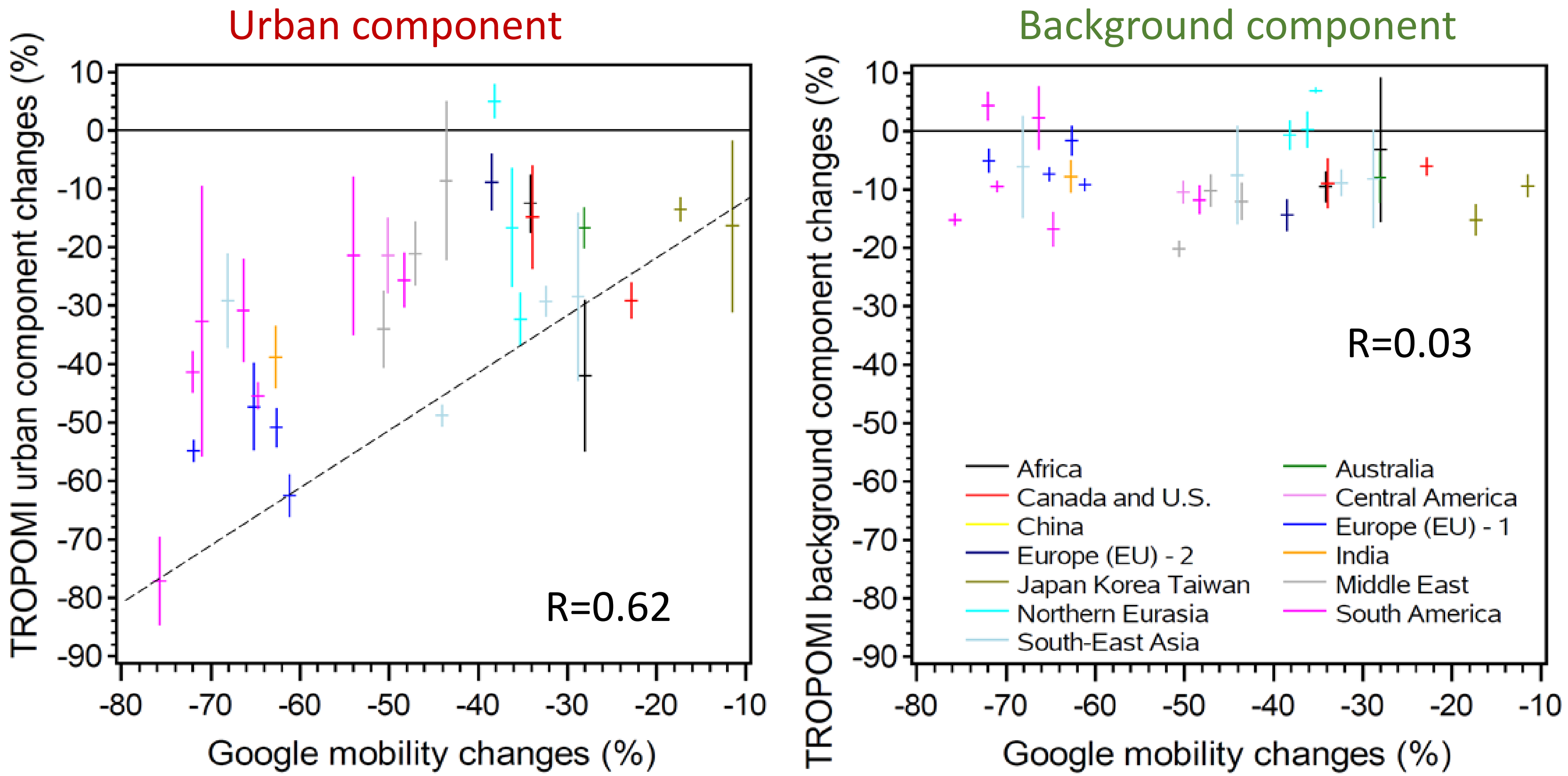


The mean values (left) and decline in 2020 from the mean 2018-2019 values in percent (right). Europe-1 includes Italy, Spain, U.K., Portugal, Ireland. Europe-2 includes most of the other European countries

The map of NO_2 changes between 2018-2019 and 2020 for March 16 – June 15 estimated from TROPOMI for (top) background component and (bottom) urban emissions. The analysis was done for large cities (> 1 million).

The change in the background component was typically small, under 10%, while changes in the urban component were typically between 15% and 28%. South America, India, and a part of Europe demonstrated >30% decline.

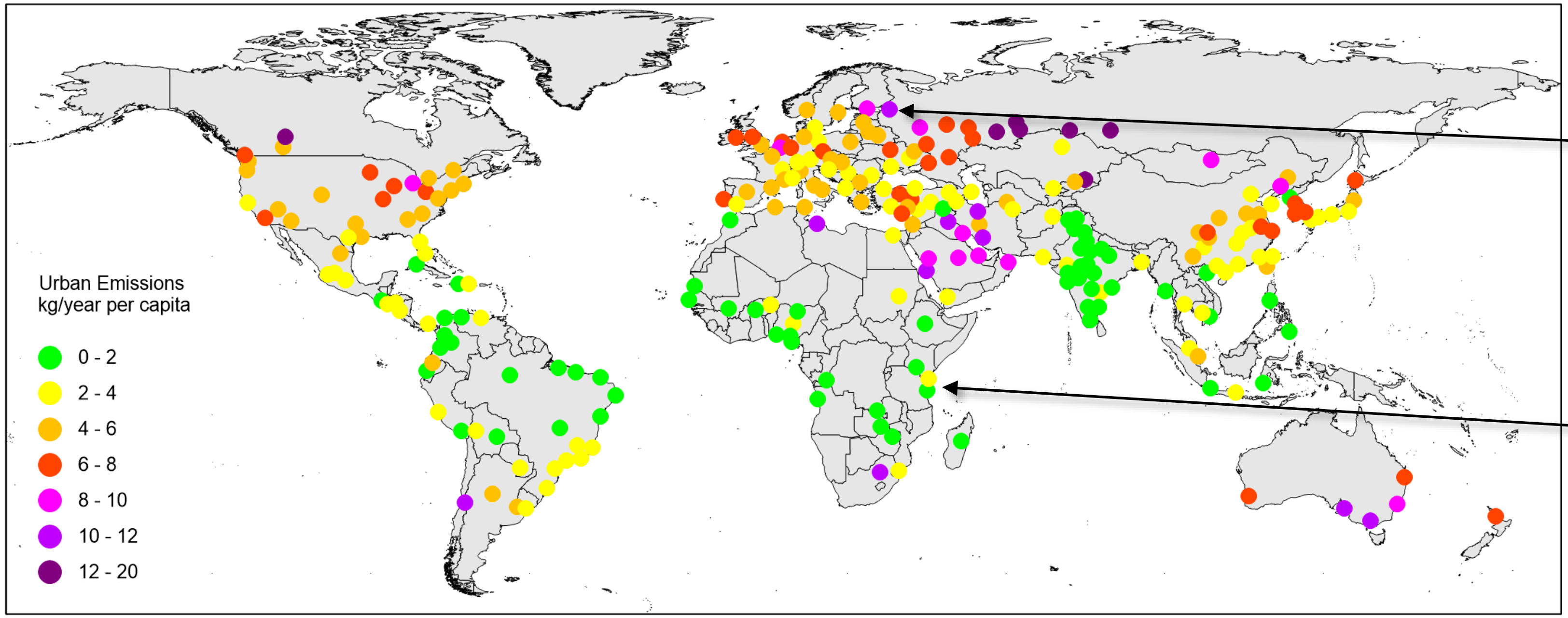
Changes in urban and background components vs. changes in Google mobility data

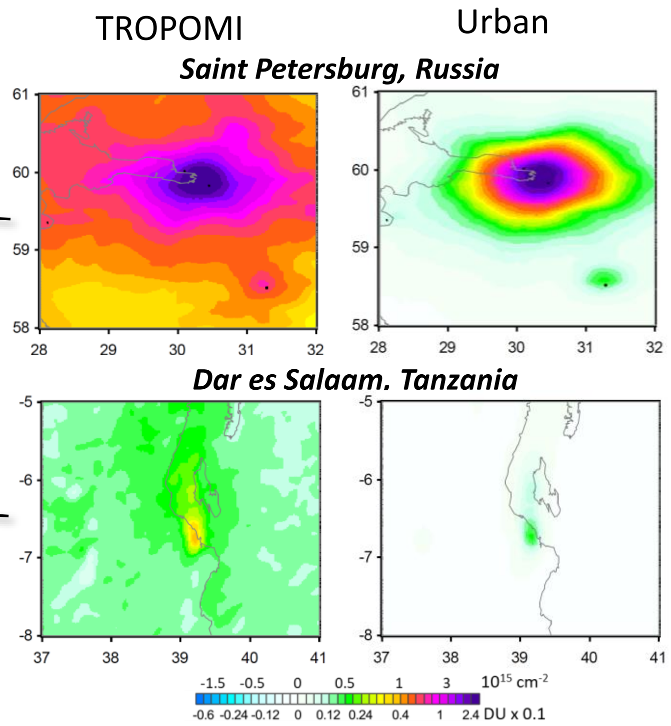


A scatter plot of Google mobility statistic (for “retail and recreation” sites) changes vs. TROPOMI NO2 VCD changes for the urban (population density-related) component during the period from March 16 to June 15. The Google mobility statistic changes show the difference with the pre-lockdown period in percent. For TROPOMI, the difference is between the 2020 values and the average for the 2018-2019 period. Each dot represents one country, the dot colour demonstrates the region as shown in the legend.

Changes in mobility and urban components are correlated but there is no statistically significant correlation between the background NO_2 and mobility data.

Annual per capita urban NO_2 emissions





The map of annual per capita urban NO_2 emissions in 2018-2019 for the period March 16 – June 15. The analysis was done using estimates for cities with population greater than 6 million in China and 1 million for the rest of the world.

(left)The map of TROPOMI mean tropospheric NO_2 (right) and the urban component in 2018-2019 for the period March 16 – June 15 for Saint Petersburg, and Dar es Salaam, cities with similar population of about 6 million people, but very different NO_2 "footprint"

Bonus: with this approach, we can compare emissions per capita in different parts of the world. For example, the total mass of NO_2 per capita related to the urban component for Saint Petersburg is 40 times larger than for Dar es Salaam.

Summary

- A new method of isolation of three components: background NO_2, NO_2 from urban sources, and from industrial point sources is suggested.
- The urban and industrial components are representing plumes from cities and industrial point sources, respectively. Population density data can be used as a proxy of urban emissions.
- The background component is influenced by the terrain and likely related to much longer (than in the plumes) lifetimes of NO_2 under relatively clean conditions plus NO_2 emissions from other (area?) sources.
- The method was applied to estimate the impact of the COVID-19 lockdown on each of three components.
- On the global scale, the urban NO_2 declined almost everywhere, and the decline was correlated to changes in mobility. The decline in the background component was much smaller than for the urban component and has no correlation with mobility.

Thank you!

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Vitali Fioletov[1], Chris A. McLinden[1], Debora Griffin[1], Nickolay Krotkov[2], Fei Liu[2], and Henk Eskes[3]

[1]Air Quality Research Division, Environment and Climate Change Canada, Toronto, Canada
[2]Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[3]Royal Netherlands Meteorological Institute, De Bilt, the Netherlands

Correspondence: Vitali Fioletov (vitali.fioletov@outlook.com, vitali.fioletov@ec.gc.ca)

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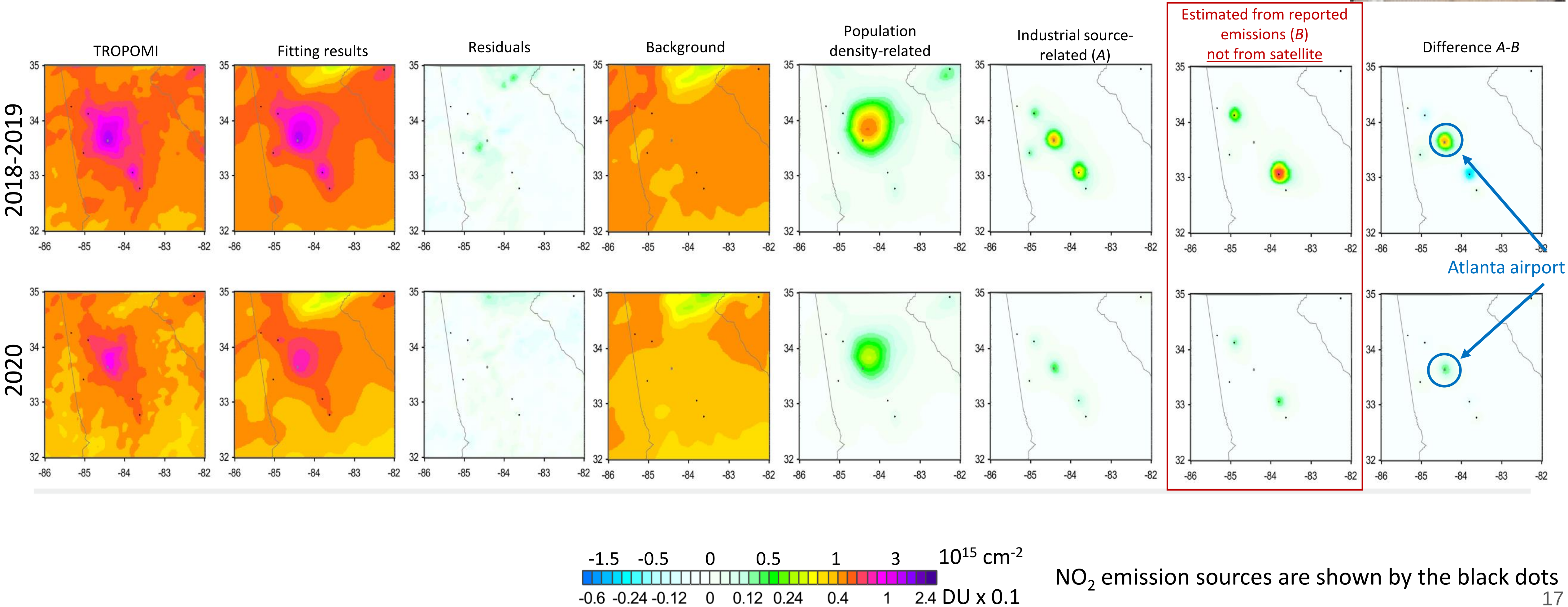
Atlanta area: Hartsfield-Jackson International, the world's busiest airport

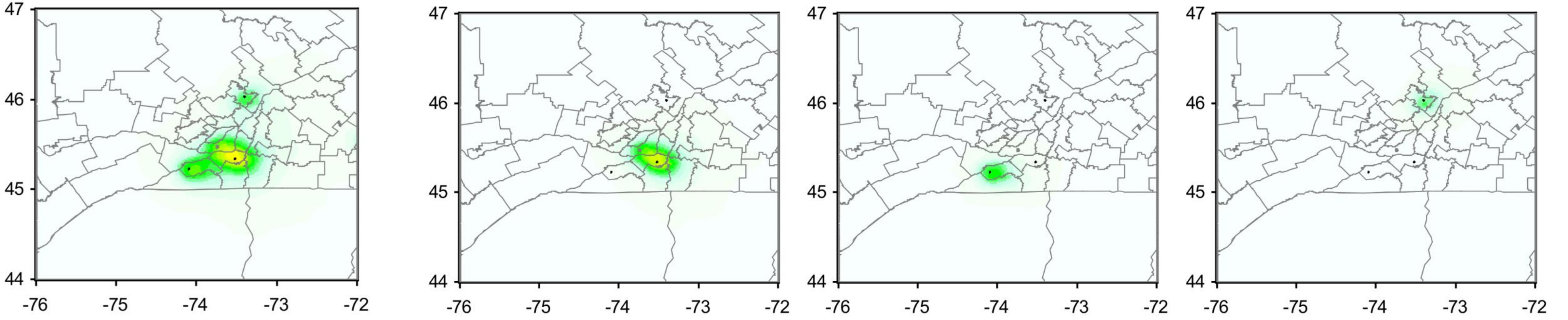
Atlanta airport signal can be easily isolated since the airport is located far away from industrial sources and at a distance from city of Atlanta's most populated area. Estimated emissions from industrial sources are in line with estimates based on actual emissions and the airport is the only remaining hotspot when emission-based signal is subtracted from estimated industrial-source-related component in TROPOMI NO_2 data.



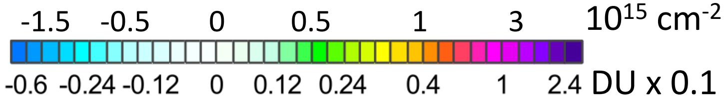
NO_2 emission sources are shown by the black dots

Montreal area TROPOMI NO_2, Industrial component, 2018-2019

The industrial sources-related component is calculated as a sum of $\alpha_i\Omega_i$ where α_i are the coefficients estimated from the regression and Ω_i are the source plume functions. Unlike the original algorithm from Fioletov et al., (2017), where Ω_i were plume functions of the individual sources, Ω_i here are plume functions for clusters of sources determined by factor analysis.



Industrial sources-related component = Contribution from factor #1 (2 sources) + Contribution from factor #2 (1 source) + Contribution from factor #3 (1)



NO_2 emission sources are shown by the black dots