Emission Monitoring Mobile Experiment (EMME): St. Petersburg megacity campaigns 2019 and 2020

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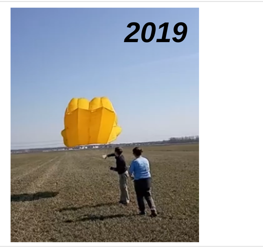
Motivation

In 2019 and 2020, the mobile experiments EMME (Emission Monitoring Mobile Experiment) were conducted within the St. Petersburg agglomeration (Russia) aiming to estimate the emission intensity of greenhouse (CO_2 , CH_4) and reactive (CO, NOx) gases for St. Petersburg, which is the largest northern megacity with a population of **~ 5.4 million** (7.5 million - unoficial info). SPbU, KIT and the UoB jointly organized and ran these field experiments.

EMME concept

EMME city campaigns were carried out:
- in March-April of 2019, totally 11 days of field measurements;
- in March-early May 2020, 6 days (3 days out of lockdown and 3 days during the COVID-19 lockdown).



The core instruments of the EMME-2019 were two portable Bruker EM27/SUN FTSs which were used for ground-based remote sensing measurements of the total column amount of CO_2, CH_4 and CO at upwind and downwind locations on opposite sides of the city. In comparison to 2019, all FTIR-measurements in 2020 were performed with one FTS which was moved between clean and polluted locations within one day.

During 2019 field campaign, the NO_2 tropospheric column amount was observed along a circular highway around the city by continuous mobile measurements of scattered solar visible radiation with an OceanOptics HR4000 spectrometer using the differential optical absorption spectroscopy (DOAS) technique. No DOAS observations were carried out in 2020.

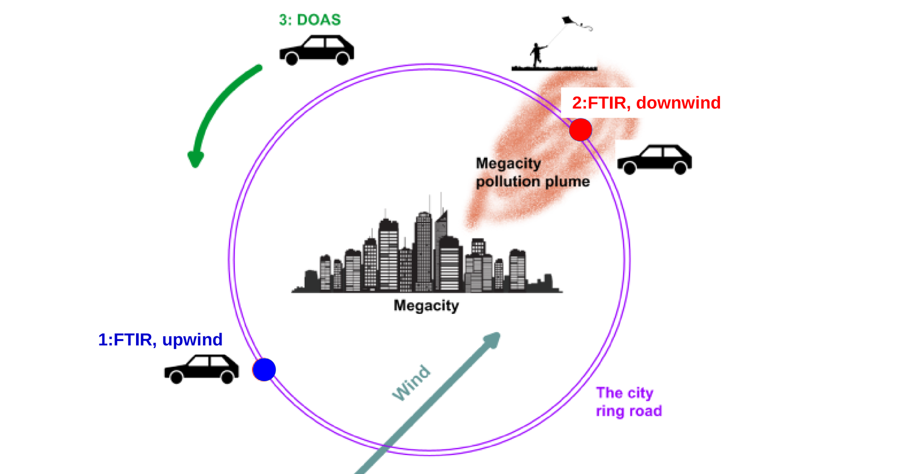
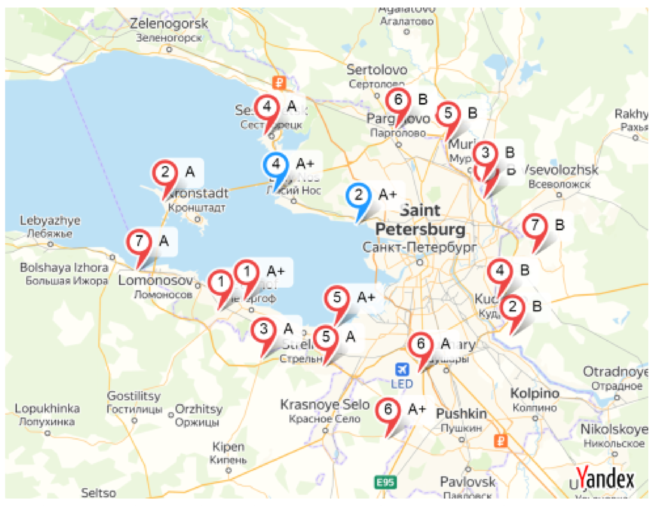
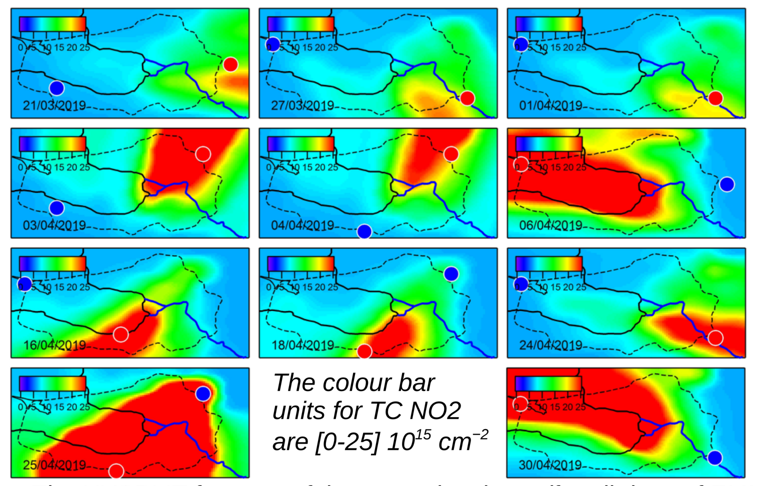


Illustration of the concept of EMME: two FTSs at the upwind (1) and downwind (2) locations on opposite sides of the city and moving DOAS spectrometer (3).



The set of FTS locations around St. Petersburg.



The HYSPLIT forecast of the megacity plume (for all days of EMME-2019, 10:00 UTC) used for planning the field campaign.

Planning of measurements for each day included the determination of optimal location for FTIR spectrometers based on weather forecasts, combined with the numerical modelling of the pollution transport in the megacity area. The real-time corrections of the FTIR operation sites were performed depending on the actual evolution of the megacity NOx plume as detected by the mobile DOAS observations.

Results of EMME 2019 and 2020

Evaluation of the CO_2, CH_4, CO and NOx area fluxes (https://doi.org/10.5194/amt-14-1047-2021)

The evaluation of the St. Petersburg area fluxes (*F*) for CO_2, CH_4, CO, and NOx was performed by coupling a mass balance approach in the form of one-box model and the differences in gases TCs recorded at down and upwind locations. Calculation of air parcel path length (*L*) was based on the HYSPLIT backward trajectories and the landuse classification specially developed for the territory of St.Petersburg and its nearest suburbs.

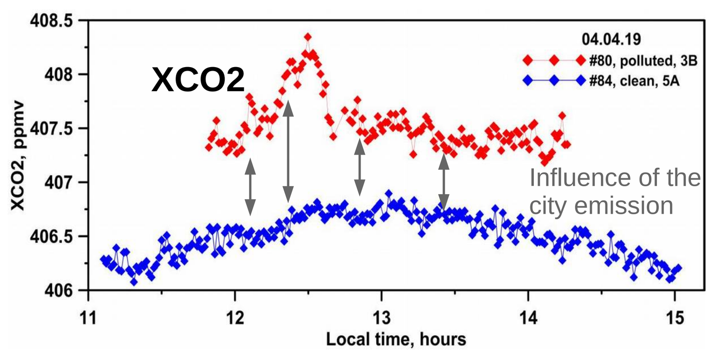
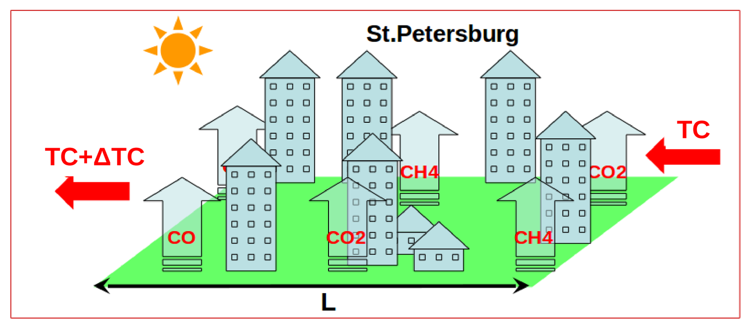
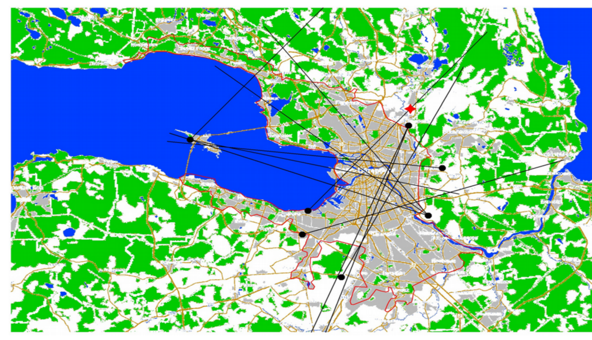


Illustration of downwind (red) and upwind (blue) XCO2 values measured on 04.04.2019



*Box model (mass balance approach): F~ΔTC*V/L, where V - wind speed, L – air parcel path lengh*



The major land use classes: blue - water bodies, grey - residential buildings/industrial areas and green - parks and forests. Linear backward paths - black lines; black dots - downwind FTS locations.

Area fluxes for CO_2 (kt km^{-2} yr^{-1}), CH_4 (t km^{-2} yr^{-1}), CO (t km^{-2} yr^{-1}) and NO_x (t km^{-2} yr^{-1}) obtained during EMME-2019 and EMME-2020 (including 3 days of COVID-19 lockdown) and the flux estimates for St. Petersburg based on in situ measurements. The values previously reported in literature are also presented.

Area flux	EMME		In situ measurements (St.Petersburg)	Literature sources	
	2019	2020			
	9 days	6 days		St. Petersburg	The world's cities
CO_2, kt km^{-2} yr^{-1}	89 ± 28	72 ± 24	40 ± 30	31 (Serebritsky, 2018) 46 (EDGAR database, 2018) 6 (suburbs, Makarova, 2018)	29 (London, O'Shea, 2014) 12.8 (Mexico City,Velasco, 2005) 12.3 (Tokyo, Moriwaki & Kanda, 2004) 28.3 (Berlin, Hase, 2015)
CH_4, t km^{-2} yr^{-1}	135 ± 68	198 ± 152	120 ± 80	25 (Serebritsky, 2018, 2019) 110 (Makarova, 2006) 44 (suburbs, Makarova, 2018) 32 (suburbs, Zinchenko, 2002)	66 (London, O'Shea, 2014) 7 – 28 (Krakow, Zimnoch, 2010)
CO, t km^{-2} yr^{-1}	251± 104	220± 117	90 ± 50	410 (Serebritsky, 2018, 2019) 390 (Makarova, 2011) 90 (suburbs, Makarova, 2018)	106 (London, O'Shea, 2014) 1520 (Mexico City, Stremme, 2013)
NO_x, t km^{-2} yr^{-1}	66 ± 28	-	-	69 (Serebritsky, 2018, 2019)	63-252 (London, Lee, 2015) 13- 300 (Norfolk, Marr, 2013)

The most important findings based on the analysis of EMME-2019 and EMME-2020 are:

- the average value of CO2 area flux for St. Petersburg was estimated to be 89 ± 28 (kt km^{-2} yr^{-1}) for 2019 and 72 ± 24 (kt km^{-2} yr^{-1}) for 2020 (including 3 days of COVID-19 lockdown). These values are 2-3 times higher than the official inventory number reported for St. Petersburg (~31 kt km^{-2} yr^{-1} for 2017);

- CH4 area flux is of 135 ± 68 (t km^{-2} yr^{-1}) for 2019 and 198 ± 152 (t km^{-2} yr^{-1}) for 2020 which are about 1 order of magnitude greater than the value reported by the official inventories of St. Petersburg emissions (~25 t km^{-2} yr^{-1} for 2017);

- for the urban territory of St. Petersburg, both the EMME-2019 experiment and the official inventories for 2017 give similar results for the NOx anthropogenic flux: 66 ± 28 (t km^{-2} yr^{-1}) vs. 69 (t km^{-2} yr^{-1});

- CO anthropogenic fluxes estimated during EMME-2019 (251 ± 104 t km^{-2} yr^{-1}) and EMME-2020 (220 ± 117 t km^{-2} yr^{-1}) are lower than official inventory number (~ 410 t km^{-2} yr^{-1} for 2017);

- CO2 and CO area fluxes obtained as a result of EMME-2020 are of 20% and 10% lower than the corresponding values of fluxes for EMME-2019.

Results of EMME 2019 and 2020 (continuation)

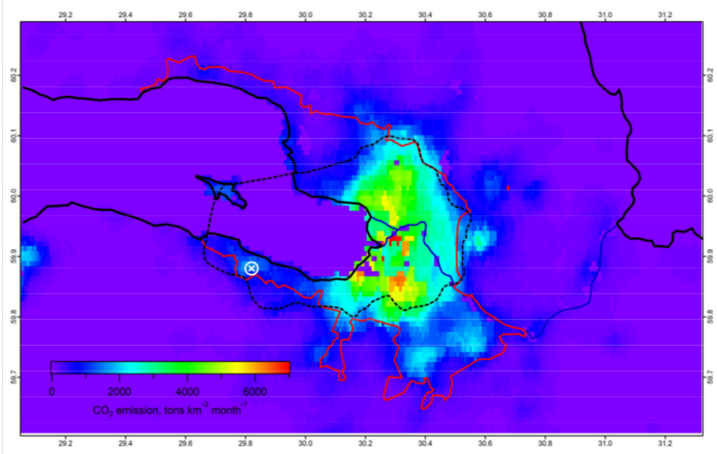
Evaluation of the CO2 integral emission of St.Petersburg (https://doi.org/10.5194/acp-2020-1174)

The derivation of the integral CO2 emission from St. Petersburg was performed by coupling the results of the EMME observational campaigns of 2019 and 2020 and the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectories) model. The ODIAC (Open-source Data Inventory for Anthropogenic CO2) database is used as the source of the a priori information on the CO2 emissions for the territory of St. Petersburg.

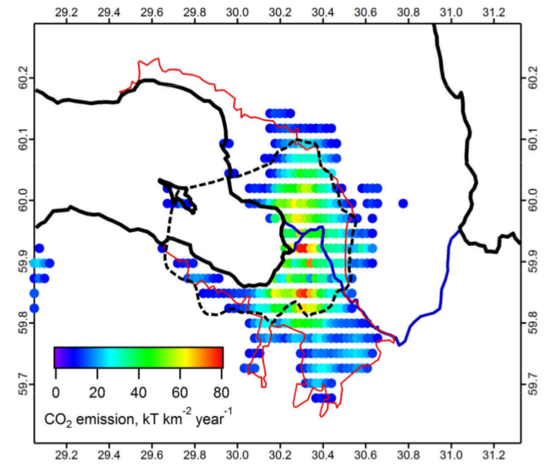
Evaluation of the integral CO2 emission by St. Petersburg megacity consists of the following four basic steps:

1. We use mobile FTIR measurements to obtain CO2 column enhancements (ΔXCO2) related to urban anthropogenic emissions. A number of studies (Pillai et al., 2016; Broquet et al. 2018; Kuhlmann et al., 2019; Babenhauserheide et al., 2020) have shown that emissions from large CO2 sources (cities, thermal power plants) can be characterized by the difference between the results of measurements of the CO2 concentration in the dry atmospheric column inside and outside of the pollution plume (ΔXCO2). The results of measurement campaigns in 2019 and 2020 have shown that for **St.Petersburg** in a set of mobile experiments the values of **ΔXCO2** averaged over the duration of FTIR observations were in the range of **0.05-4.46 ppmv**. For comparison, similar studies revealed the following values of ΔXCO2 : 0.16-1.03 ppmv for Berlin, Germany (Kuhlmann et al., 2019), 0.80-1.35 ppmv for Paris, France (Pillai et al., 2016; Broquet et al. 2018), and 0-2 ppmv for Tokyo, Japan (Babenhauserheide et al., 2020).

2. We adapt the ODIAC database (Oda and Maksyutov, 2011) to construct a priori information on the spatio-temporal distribution of anthropogenic CO2 emissions on the territory of St. Petersburg.

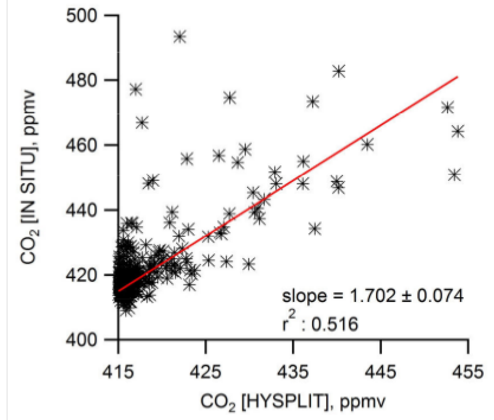


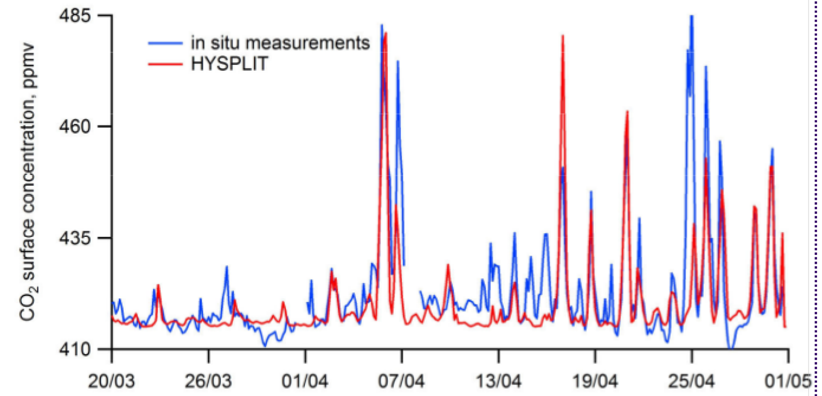
Original data (CO2 FF fluxes) of ODIAC2019 on the territory of the St. Petersburg. The red line is the administrative border of the city; the black dotted line is the city ring road. A white circle is the location atmospheric monitoring station of SPbU (in Peterhof).



The resulting set of 376 pixels of CO2 FF fluxes which was used as the input for HYSPLIT simulations. This set of larger pixels (~3.6 km2) was generated using ODIAC2019.

3. We initialize the HYSPLIT dispersion model (Draxler and Hess, 1998) with the ODIAC emissions to simulate CO2 3D field over the city of St. Petersburg, and evaluate the performance of our HYSPLIT model setup by calculating the surface CO2 concentration and comparing them with the routine in-situ measurement results (Foka et al., 2019).



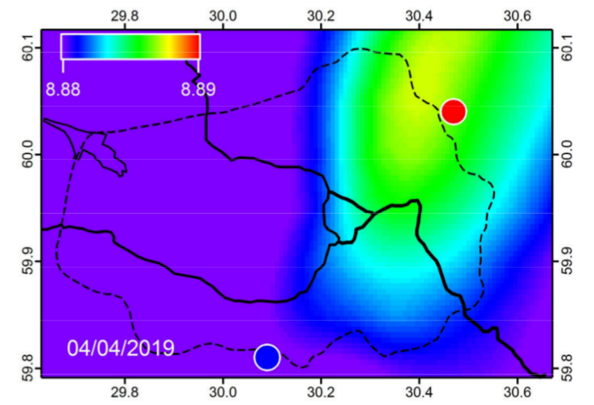


Comparison of the HYSPLIT simulations and the in situ measurements of surface CO2 concentration in Peterhof (59.88°N, 29.82° E) in March-April 2019.

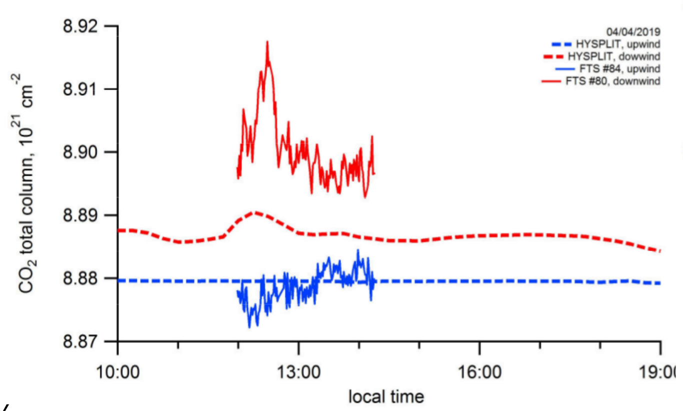
Left panel: The values of surface CO2 compared with the HYSPLIT simulations without scaling of the ODIAC emissions data.

Right panel: HYSPLIT data obtained using scaled ODIAC emissions compared with observed surface CO2.

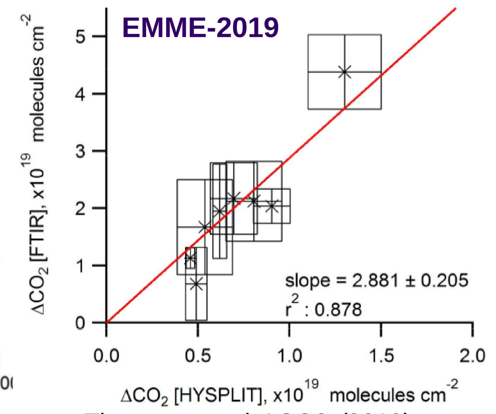
4. We scale the emission input data for the HYSPLIT model simulations in order to reproduce the observed ΔCO2 and, finally, from the scaled emission a priori data we get the estimate of integral CO2 emission by St.Petersburg.



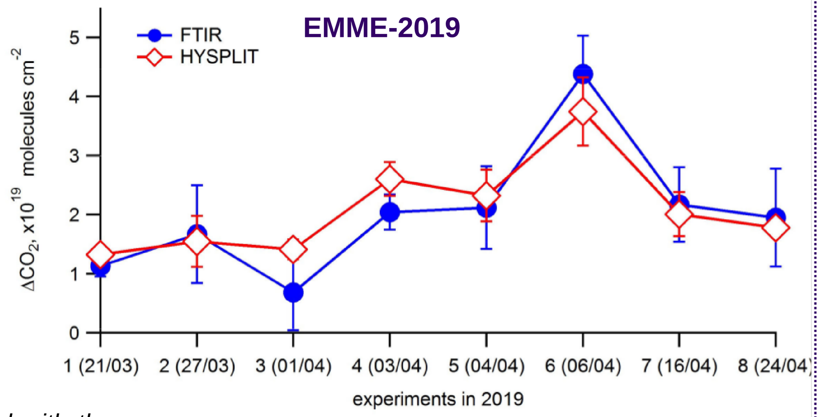
*St. Petersburg pollution plume simulated by HYSPLIT (April 4, 2019, 10:00 UTC). The colour bar designates the CO2 total column in units 10**21 cm-2. The blue and red circles indicate the locations of upwind and downwind FTSs, respectively.*



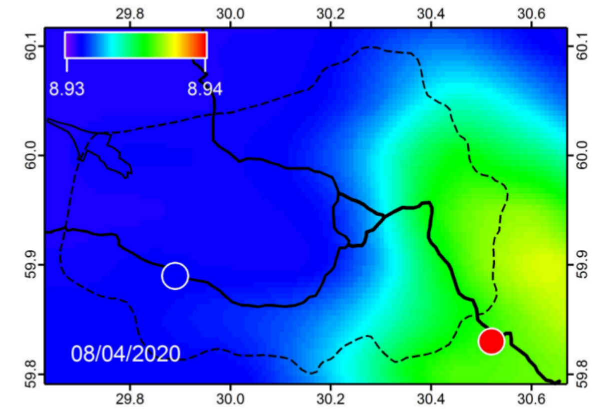
Time series of measured (FTS) and simulated (HYSPLIT, without scaling of the ODIAC emissions data) CO2 total column at the upwind (blue lines) and downwind (red lines) locations for April 4, 2019.



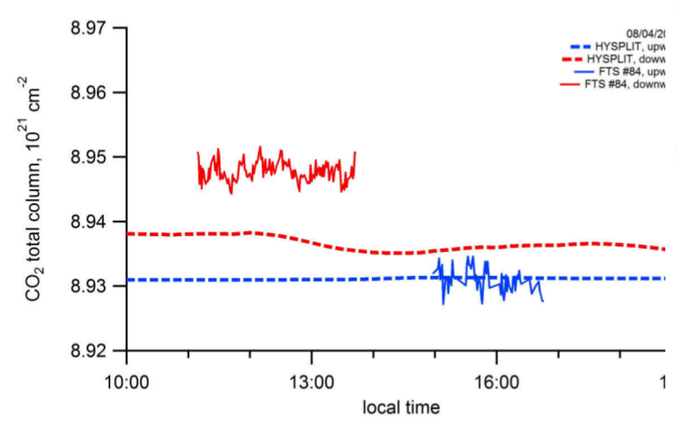
The measured ΔCO2 (2019) compared with the results of HYSPLIT simulations without scaling of the ODIAC data. Measurement and simulation data are averaged over time intervals of FTIR measurements.



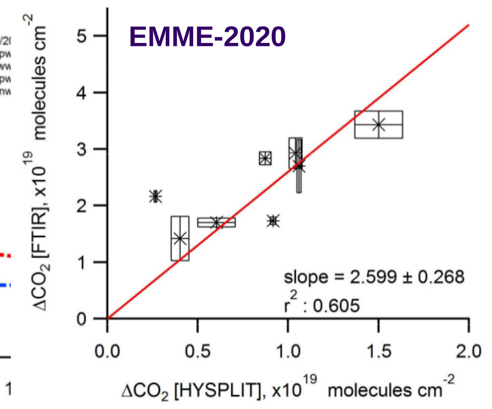
HYSPLIT data obtained using scaled ODIAC CO2 FF emissions compared with observed ΔCO2 (2019) .



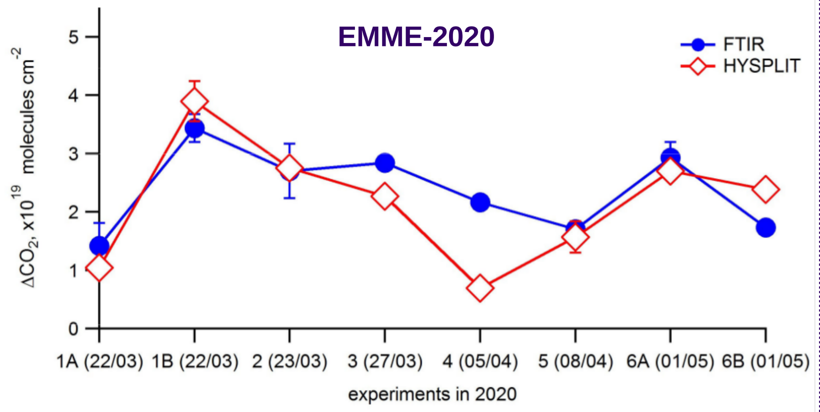
*St. Petersburg pollution plume simulated by HYSPLIT (April 8, 2020, 10:00 UTC). The colour bar designates the CO2 total column in units 10**21 cm-2. The blue and red circles indicate the locations of upwind and downwind FTSs, respectively.*



Time series of measured (FTS) and simulated (HYSPLIT, without scaling of the ODIAC emissions data) CO2 total column at the upwind (blue lines) and downwind (red lines) locations for April 8, 2020.



The measured ΔCO2 (2020) compared with the results of HYSPLIT simulations without scaling of the ODIAC data. Measurement and simulation data are averaged over time intervals of FTIR measurements.



HYSPLIT data obtained using scaled ODIAC CO2 FF emissions compared with observed ΔCO2 (2020) .

The most important findings based on the analysis of EMME-2019 and EMME-2020 are (continuation):

- a significantly higher CO2 emission from the megacity of St. Petersburg as compared to the official inventory data: ~75800±5400 kt yr−1 for 2019, ~68400±7100 kt yr−1 for 2020 versus ~30000 kt yr−1 reported by official inventory;

- the decrease in CO2 emission of 8 % or 5800 kt yr−1 obtained during the COVID-19 lockdown in 2020 in comparison with the results obtained during the same period of 2019.

For further details and references, please see:

Makarova et al.: Emission Monitoring Mobile Experiment (EMME): an overview and first results of the St. Petersburg megacity campaign 2019, Atmos. Meas. Tech., 14, 1047–1073, https://doi.org/10.5194/amt-14-1047-2021, 2021.

Ionov et al.: The CO2 integral emission by the megacity of St. Petersburg as quantified from ground-based FTIR measurements combined with dispersion modelling, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2020-1174, in review, 2021.

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