Emission Monitoring Mobile Experiment (EMME): an overview and first results of the St. Petersburg megacity campaign-2019

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Abstract. Global climate change is one of the most important scientific, societal and economic contemporary challenges. Fundamental understanding of the major processes driving climate change is the key problem which is to be solved not only on a global but also on regional scales. The accuracy of regional climate modelling depends on a number of factors. One of these factors is the adequate and comprehensive information on the anthropogenic impact which is highest in industrial regions and areas with dense population – modern megacities. Megacities are not only "heat islands", but also significant sources of emissions of various substances into the atmosphere, including greenhouse and reactive gases. In 2019, the mobile experiment EMME (Emission Monitoring Mobile Experiment) was conducted within the St. Petersburg agglomeration (Russia) aiming to estimate the emission intensity of greenhouse (CO_2, CH_4) and reactive (CO, NO_x) gases for St. Petersburg which is the largest Northern megacity. St. Petersburg State University (Russia), Karlsruhe Institute of Technology (Germany) and the University of Bremen (Germany) jointly ran this experiment. The core instruments of the campaign were two portable FTIR spectrometers Bruker EM27/SUN 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 the opposite sides of the city. 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 OceanOptics HR4000 spectrometer using the DOAS technique. Simultaneously, air

30samples were collected in air bags for subsequent laboratory analysis. The air samples were taken at the locations of FTIR observations at the ground level and also at altitudes of about hundred meters when airbags were lifted by a kite (in case of suitable landscape and favourable wind conditions). The entire campaign consisted of 11 mostly cloudless days of measurements in March-April 2019. 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 35megacity area. The real-time corrections of the FTIR operation sites were performed depending on the actual evolution of the megacity NO_x plume as detected by the mobile DOAS observations. The data processing activities included the following steps: (1) the generation of calibrated spectra from raw interferograms; (2) the retrievals of the CO_2, CH_4, and CO column averaged abundances using the software tools provided by the COCCON (Collaborative Carbon Column Observing Network); (3) the retrieval of tropospheric NO_2 amount from DOAS measurements; (4) the laboratory analysis of air 40samples; (5) the numerical modelling of the plume movement based on the actual meteorological information. The estimates of the St. Petersburg emission intensities for the considered greenhouse and reactive gases were obtained by coupling a box model and the results of the EMME observational campaign using the mass balance approach. The CO_2 emission flux for St. Petersburg as an area source was estimated as 89 ± 28 kt km^{-2} yr^{-1} which is two times higher than the corresponding value in the EDGAR database. The experiment revealed the CH_4 emission flux of 135 ± 68 t km^{-2} yr^{-1} which is about one order of 45magnitude greater than the value reported by the official inventories of St. Petersburg emissions (~17 t km^{-2} yr^{-1} for 2017). At the same time, for the urban territory of St. Petersburg, both the EMME experiment and the official inventories for 2017 give similar results for the CO anthropogenic flux (251 ± 104 t km^{-2} yr^{-1} vs. 280 t km^{-2} yr^{-1}) and for the NO_x anthropogenic flux (66 ± 28 t km^{-2} yr^{-1} vs. 47 t km^{-2} yr^{-1}).

Keywords: ground-based remote sensing, portable spectrometers, FTIR spectroscopy, DOAS technique, mobile 50experiments, trace gas retrieval, greenhouse gases, reactive gases, anthropogenic emissions in megacities, transport modelling of air pollutants

1 Introduction

Global climate change is one of the most important scientific, societal and economic contemporary challenges. Fundamental understanding of the major processes driving climate change is the key problem which is to be solved not only on a global 55but also on regional scales (IPCC, 2013; WMO Greenhouse Gas Bulletin, 2018). The accuracy of regional climate modelling depends on a number of factors. One of these factors is the adequate and comprehensive information on the anthropogenic impact which is highest in industrial regions and areas with dense population - modern agglomerations and megacities. Agglomerations and megacities are not only "heat islands", but also significant sources of emissions of various substances

into the atmosphere, including greenhouse and reactive gases (Zinchenko et al., 2002; Wunch et al., 2009; Ammoura et al., 2014; Hase et al., 2015; Turner et al., 2015; Viatte et al., 2017). Estimating emission intensity for industrial areas and cities requires precise measurements of gas composition in the troposphere with a high horizontal resolution on a regional scale. Existing ground-based observational networks, in particular ESRL (ESRL, 2019), ICOS (ICOS, 2020), NDACC (NDACC, 2019) and TCCON (TCCON, 2019), are mainly focused on detecting the background concentrations of the greenhouse gases. Most of observational stations are sparsely distributed and located relatively far from industrial and highly populated areas. Portable Fourier Transform InfraRed (FTIR) spectrometers EM27/SUN (Gisi et al., 2012, Frey et al., 2015) are very promising instruments for the detection and quantification of the emissions of greenhouse gases from mesoscale area sources like cities or industrial areas (Hase et al., 2015). The data provided by these instruments are less affected by the vertical exchange processes than the data obtained from in situ measurements. Also, in contrast to current space-based sensors, the ground-based portable FTIR spectrometer data are essentially unaffected by the aerosol burden transported by the pollution plume.

The quantification of the gas fluxes from the sources located on the earth's surface can be carried out using various methods: the "forward" and "inverse" modelling (Maksyutov et al., 2013; Turner et al., 2015), the eddy covariance method (Helfter et al., 2011; Hiller et al., 2014a), the mass balance approach (Zimnoch et al., 2010; Strong et al., 2011, Hiller et al., 2014a), and the technique based on the radon measurements (Lopez et al., 2015). Depending on a method, the spatial coverage of investigated sources can vary from the local (for example, in the case of eddy covariance) to the meso- and the global scales (the assimilation of satellite data in atmospheric models). Each of these approaches has its own set of unique advantages and limitations depending on specific spatial and/or temporal scales. Therefore the efficacy and accuracy of many of these methods remain the subject of scientific debates (Cambaliza et al., 2014; Hiller et al., 2014a). Often, combinations of these methods can yield reduced uncertainty of target parameters, at the same time combining of different techniques often requires special field campaigns and comprehensive analysis (Hiller et al., 2014a; Hiller et al., 2014b).

Recently, several studies were performed with the goal to estimate the emissions of industrial regions and cities by means of ground-based mobile measurements of tropospheric gaseous composition using the FTIR technique. Hase et al. (2015) applied portable FTIR spectrometers for detecting greenhouse gas emissions of the major city Berlin. In this study, five portable EM27/SUN spectrometers were used for the accurate and precise observations of column-averaged abundances of CO_2 and CH_4 around the major city Berlin. It has been demonstrated that the CO_2 emissions of Berlin can be clearly identified in the observations. Luther et al. (2019) explored the feasibility of estimating CH_4 emissions for individual coal mine ventilation shafts and groups of shafts. They measured dry-air mole fractions of methane XCH_4 by the FTIR spectrometer Bruker EM27/SUN which was installed on a truck moving through the CH_4 plumes in the Upper Silesian Coal Basin while driving in stop-and-go patterns.

90   The motivation of the present study originated from the fact that the number of observational stations for greenhouse gas monitoring on the territory of Russia is very limited and there are considerable uncertainties of the greenhouse gas flux estimations for the natural and anthropogenic sources in Russia. St. Petersburg is the second largest megacity in Russia with the population of 5 million and, besides, it is the northernmost city in the world with the population of over one million people. The goal of the present study was to estimate the emissions of greenhouse (CO_2, CH_4) and reactive (CO, NO_x) gases

95 from St. Petersburg by means of mobile remote-sensing techniques and direct in situ measurements. The study was based on the observational campaign EMME-2019 (Emission Monitoring Mobile Experiment) which was performed in March-April 2019 on the territory of the St. Petersburg agglomeration. St. Petersburg State University (Russia), Karlsruhe Institute of Technology (Germany) and the University of Bremen (Germany) jointly ran this experiment in the frame of the International project VERIFY (VERIFY, 2019). The idea of EMME experiment was based mainly on the studies by Hase et al. (2015),

100 Ionov and Poberovskii (2015) and Viatte et al. (2017).

2 Concept of EMME, instruments and the experiment planning

The concept of EMME is based on remote measurements of the total column amount of CO_2, CH_4 and CO from two mobile platforms located inside and outside the city plume (usually at upwind and downwind locations on the opposite sides of the city of St. Petersburg) combined with the mobile circular measurements of tropospheric column amount of NO_2 from the

105 third mobile platform moving in a non-stop mode, the latter measurements are used for the real-time control of the megacity plume evolution. The simplified illustration of the concept is given in Fig. 1. The experiment requires clear-sky conditions since the instruments for remote sensing measure direct and scattered solar radiation. The ancillary measurements include control of the meteorological parameters and sampling of air portions at the locations inside and outside the city plume for subsequent laboratory analysis of concentrations of target gases. In order to assess the intensity of gas emissions by St.

110 Petersburg, the mass-balance approach is applied to the measurement data. The principal feature of EMME is its integrated character: several different instruments are used, and additionally, the planning of the field experiment and data processing are performed with the help of numerical modelling of the transport of the megacity pollution plume.

The core instruments of the campaign are two portable FTIR spectrometers Bruker EM27/SUN (Gisi et al., 2012; Frey et al., 2015) which are used for ground-based remote sensing measurements of total column amount of CO_2, CH_4 and

115 CO. The EM27/SUN instrument has a sun-tracking system and registers direct infrared solar radiation. The FTIR spectrometers are transported by cars to the measurement locations where they are unloaded and installed outside. The geographic coordinates are registered by the GNSS (Global Navigation Satellite System) sensor. A detached car battery with an inverter is used as a power supply which ensures about 3 h operation time. Under cold weather conditions, the instruments

are covered by electric heating blankets. The integration time for a single spectrum constitutes about 1 min. Within this
120 period, about 10 interferograms are registered and averaged, and then the corresponding spectrum is recorded.

The tropospheric NO_2 column is derived from measurements of the scattered solar radiation in the zenith direction by
the portable automatic spectrometer OceanOptics HR4000. This spectrometer is mounted on board of a car and connected to
a portable computer to ensure uninterruptible recording of spectra. Measurements are fully automatic while the car is
moving. The location of the car is controlled by the GNSS sensor and is routinely recorded by the onboard computer for
125 instant referencing of the results of measurements to the car route. The sampling period of time (time of exposure) for single
spectrum is calculated by the software tool accounting for illumination conditions and constitutes about 60 ms on average for
the observations at about noon. Recording of spectra is done every 1 min, all single spectra obtained within this period are
coadded. Thus, each final measurement is the mean of about 1000 instant spectra. The route includes the entire city ringway
(the highway around St. Petersburg), therefore the main emission sources are inside the route and the position of the
130 megacity plume can be detected with high accuracy. The described approach and the DOAS mobile experiment specific
design have been implemented previously and the results have been published by Ionov and Poberovskii (2012, 2015, 2017,
2019).

Air samples were collected at the locations of both FTIR spectrometers in two air bags: when FTIR measurements
started (the first bag) and before completion of FTIR measurements (the second bag). Each bag was a 25-liter Tedlar bag,
135 sampled for about 40 min. In case of suitable weather and landscape conditions at the location of one of the FTIR
spectrometers, sampling bags were lifted by a kite to an altitude of about 100 m. The laboratory analysis of the air samples
was performed with the help of gas analysers. Gas analyser Los Gatos Research GGA 24r-EP was used for measuring
volume mixing ratio (vmr) of CH_4, CO_2 and H_2O. Gas analyser Los Gatos Research CO 23r was used for measuring vmr of
CO and H_2O. The concentration of NO and NO_2 (NO_x) was measured by gas analyser ThermoScientific 42i-TL.

140 For the monitoring of meteorological parameters, two weather stations and the microwave radiometer RPG-HATPRO
were used. One portable weather station was operating either at upwind or at the downwind location of FTIR spectrometers.
The atmospheric pressure measurements were performed at both up- and downwind locations. The second stationary weather
station was operating on the roof of the building (56 m a.s.l.) of the Institute of Physics of St. Petersburg State University
(SPbU) located about 25 km west from the city centre. The RPG-HATPRO radiometer was operating also on the roof of this
145 building and delivered information on the temperature and humidity vertical profiles together with the information on the
cloud liquid water path (Kostsov, 2015; Kostsov et al., 2018).

The essential part of EMME was the preparatory stage which lasted for three months before the start of the campaign.
During this stage the optimal set of FTIR measurement locations in the close vicinity of the St. Petersburg ringway was

determined accounting for several criteria. First, this set of locations should have had sufficient spatial density to ensure the
150 possibility to perform up- and down-wind FTIR measurements for practically any wind directions. Second, every location
should have been convenient for car parking in the ringway proximity, and for installation of the instruments. We tried to
choose the locations at a certain distance from the highway and roads with intensive traffic in order to avoid contamination
of air by local sources. The set of FTIR measurement locations around the St. Petersburg agglomeration which was chosen
during the preparatory stage is shown in Fig.2. It should be emphasized that during the preparatory stage a kind of rehearsal
155 was carried out. This rehearsal has helped to reveal how time consuming the following processes are: loading the equipment
on cars at the Institute of Physics, unloading the equipment at a measurement location, setting up and tuning the instruments
for data acquisition. This information is critical for understanding whether it is possible to reach the desired up- and down-
wind locations in proper time by different crews and to start simultaneous FTIR measurements.

Special attention was paid to planning of the experiment a day before. We analysed the weather forecasts presented by
160 different sources with special attention to cloud cover and wind direction. Mainly, we used the cloud maps from
https://www.msn.com (last access 12 November 2019). In order to determine FTIR measurement locations for specific day,
we made a forecast of the megacity plume using the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectories)
model (Draxler and Hess, 1998; Stein et al., 2015). In addition, in the morning of a measurement day we monitored the cloud
cover using web cameras which operated nearby the planned measurement locations. As an example, in Fig. 3 we present a
165 nice picture – the screenshot made from the web camera installed on top of the Lakhta Centre which is the highest building
in St. Petersburg (462 m). The field of view allowed getting information on a large sector which comprised eastern and
south-eastern parts of the St. Petersburg megacity.

3 Overview of the 2019 campaign

3.1 Field observations, weather conditions and auxiliary data

170 The EMME field campaign in 2019 consisted of 11 days of measurements in March-April. For all days of the field
campaign, Table 1 presents information on the location of FTIR spectrometers, FTIR spectrometer identifier, number of bags
of air samples, flight of a kite and air sampling altitude. The last column of Table 1 includes information on the experiment
setup (up-and downwind or cross sectional setup) and FTIR spectrometer operator's notes about meteorological phenomena,
changes in cloud cover, and local air pollution events observed during FTIR field measurements. Below, we refer to the two
175 Fourier Transform Spectrometers (FTS) as FTS#80 and FTS#84.

During the EMME-2019 we implemented two types of field experiment setup regarding the position of FTIR
spectrometers relative to the dominant air flow (wind) direction:

- for most of the days of observations (ten of the eleven), FTIR spectrometers were installed along the wind direction line - in up- and downwind locations on the opposite sides of the city of St. Petersburg (Fig.1, locations #1 and #2);

180 - for 16 April – the cross sectional setup was implemented. FTIR spectrometers were located on the line which is nearly perpendicular to the dominant wind direction line (not shown in Fig.1).

In Table 2 we collect the main characteristics of weather conditions for each measurement day. The weather information is provided for local noon from the observational data of the meteorological station located in the centre of St. Petersburg (index no. 26063, 59.97°N, 30.28°E). The daytime surface air temperature was varying from ~0 °C on 185 March 27 to +21 °C on April 25; relative humidity – varying from 84% on March 21 to 21% in April 6. Generally, surface wind speed throughout the campaign was moderate in the range of 2-3 m s^{-1}, except on April 24 and 25, when light surface winds were registered (1 m s^{-1}). Prevailing wind direction for St. Petersburg is southwest, and surface winds blowing from southwest and west-southwest were registered during most days of the campaign; however, other wind directions were registered, too (see Table 2). The satellite images of cloud cover detected by the MODIS satellite instrument in the vicinity of 190 St. Petersburg are presented in Fig. 4. They confirm daytime clear sky conditions for the duration of the campaign, except the day of April 30, when the altocumulus translucidus clouds started to develop. Besides, Fig. 4 gives an impression of rapid sea ice and snow melting as the daytime air temperature rises from ~0 °C in March to ~20 °C in April.

In order to forecast the spatial distribution of urban air pollution on each day of campaign observations, we used the HYSPLIT model. Following our previous experience of simulating the dispersion of urban contamination from 195 St. Petersburg, the NO_2 content in the lower troposphere was set as a tracer of the polluted air mass distribution (Ionov and Poberovskii, 2019). This numerical modelling was done by means of the dispersion module within the offline version of HYSPLIT. It allowed performing the 3D simulation of the generation and dispersion of NO_2 plume from a set of given sources of anthropogenic NO_x emission. The model was configured in the same way as in our early studies (Ionov and Poberovskii, 2012; Ionov and Poberovskii, 2015; Ionov and Poberovskii, 2017). Similar to the most recent study by Ionov 200 and Poberovskii (2019), the NO_x emissions were specified according to the official municipal inventory of emission sources. The HYSPLIT grid domain was set with the centre at 58.20°N and 30.75°E, the grid spacing (horizontal spatial resolution) of 0.05° latitude and longitude, and the grid span of 6.8° latitude and 14.1° longitude. The vertical grid consisted of 10 levels with the tops at 1, 25, 50, 100, 150, 250, 350, 500, 1000 and 1500 m. The forecast meteorology data (vertical distributions of the horizontal and vertical wind components, temperature, pressure, etc.) were taken from the National Centers for 205 Environmental Prediction Global Forecast System (NCEP GFS, ftp://arlftp.arlhq.noaa.gov/forecast) on the 1°×1° latitude×longitude spatial grid. The maps of the NO_2 plume, simulated by the HYSPLIT model for 13:00 local time on each day of campaign observations, are presented in Fig. 5. Colour scale represents the spatial distribution of NO_2 column amount integrated within the boundary layer (~1500 m). An animated version of such a forecast, showing the plume evolution, was

generated and shared among the campaign staff ~12 hours before each day of planned observations (an example of the

210 animated forecast for 6 April 2019 is available at https://youtu.be/rgtq6JLPhig, last access 2 March 2020).

Based on the plume evolution forecasts, the optimal pair of the FTIR spectrometer locations for the upcoming day of measurements was chosen. This approach to planning of the city campaign was implemented during 11 days of EMME-2019, and the necessity to change the location of the FTIR spectrometers occurred only once, on April 18 (see Table 1). For this day, the real-time information on the NO_2 tropospheric column (TrC) acquired along the ringroad by the

215 crew #3 using mobile DOAS observations showed that the actual location of the most polluted city plume area was different from one which had been predicted by the HYSPLIT simulations. It should be noted that the mobile DOAS observations were organised in such a way that the data on the TrC of NO_2 for the location outside the city plume were collected first. There were two days of FTIR measurements without mobile DOAS observations due to technical issues. Our experience has shown that the HYSPLIT forecast was precise enough to ensure proper selection of FTIR locations on these days.

220 **3.2 Side-by-side calibration of FTIR spectrometers**

The target quantity of our observations is the small difference between two large values that are measured by different instruments of the same type. Therefore, a careful cross-calibration of the instruments is of primary importance for the considered experiment. Side-by-side calibrations of FTS#80 and FTS#84 were carried out during four days: 12 April, 26 April, 15 May, and 16 May, 2019. The instruments were installed at the observational site of St. Petersburg State

225 University in Peterhof and operated simultaneously for the time period of clear sky weather which lasted from half an hour to several hours. The total number of spectra acquired during cross-calibrations was 604. They were collected during about 10 h of simultaneous measurements. The scatter plots showing cross-comparison of the data are given in Fig. 6. For all considered gases (CO_2, CH_4, CO), the results for average mole fractions (Xgas) delivered by two FTS are in a very good agreement. The determination coefficients for CO_2, CH_4 and CO are 0.9999(99), 0.9999(99), and 0.9999(89) respectively.

230 The RMS differences between time series of simultaneous measurements by FTS#80 and FTS#84 are equal to 0.10 ppm (0.025%) for CO_2, 0.59 ppb (0.032%) for CH_4, and 0.38 ppb (0.38 %) for CO.

The results of the side-by-side measurements of XCO_2, XCH_4, and XCO by FTS#80 and FTS#84 on 12 April 2019 at the St. Petersburg observational site are presented in Fig. 7. The individual results and 15 min running average data are shown. We used the side-by-side measurements for estimating the optimal averaging period for the Xgas data. Averaging is

235 the necessary prerequisite for using these data for the evaluation of emission and for comparison with the results of modelling. It should be emphasized that the data sampling for other input parameters is varying considerably. In order that all datasets are consistent, the optimal sampling intervals were determined. For the FTIR measurements, the averaging interval has been selected in such a way that short term variations of measured quantities can be detected. As an example, we

point at three local maxima of XCH$_4$ and XCO during the time period of 13:00-15:00. One can see that these maxima with
240 the "half width" of about 15-20 min and with the amplitudes of ~0.5 ppbv and of 0.1 ppbv for XCH$_4$ and XCO respectively
are nicely covered as well as the increase of the greenhouse gases around noon, so the chosen value of averaging interval of
15 min seems reasonable.

4 Methods and algorithms of the experimental data processing

4.1 FTIR and DOAS data processing

245 The processing of the raw FTIR data (generation of spectra from raw interferograms and trace gas retrievals) is performed
using the software tools provided by the COCCON (Frey et al., 2019; COCCON, 2019). The required software is source-
open and freely available; the development of these tools has been supported by ESA. The interferograms recorded with
FTS#80 and FTS#84 were the main input data. In the first processing step, spectra are generated from the recorded
DC-coupled interferograms, including a DC correction (Keppel-Aleks et al., 2007) and quality filtering. In the second
250 processing step, column-averaged abundances of the target species are derived from the spectra. The required auxiliary data
are the local ground pressure, the temperature profile and the a priori mixing ratio profiles of the gases. For ensuring
consistency with the TCCON reference network in this regard, these atmospheric profiles were provided by TCCON. As a
result, the time series of Xgas and total column (TC) were obtained for CO$_2$, CO and CH$_4$ for each day of measurements at
each observational location. For the interpretation of spectral UV-VIS measurements and the derivation of tropospheric NO$_2$
255 content, the well known DOAS method is used (Platt and Stutz, 2008).

4.2 Mass balance approach for area flux estimation

The estimation of the area fluxes F were obtained on the basis of a mass balance approach implemented in the form of a one-
box model. Box models are a widely used technique for the evaluation of urban and other emission fluxes (Hanna et al.,
1982; Reid and Steyn, 1997; Arya, 1999; Zinchenko et al., 2002; Zimnoch et al., 2010; Strong et al., 2011; Hiller et al.,
260 2014a; Chen et al., 2016; Makarova et al., 2018). In our case the following equation for the calculation of area flux was used:

$$F_j(t_k) = \frac{\Delta_{TC}(t_k) \cdot V_j(t_k)}{L_j(t_k)}, \qquad (1)$$

where F is the area flux, t_k denotes the day of a single field experiment in the frame of the observational campaign. It should
be emphasized that we used the steady-state approximation for all involved processes within the duration of a single field
experiment, so Δ_{TC} is the mean TC difference between downwind and upwind observations, V is the mean wind speed, and L
265 is the mean length of a path of an air parcel which goes through the urban territory of St. Petersburg agglomeration. The data

for wind speed and direction were taken from different sources of meteorological information (see section 4.3), and these sources are identified as j in Eq. 1. So, as a result, we obtained the set of values of $F(t)$ for each of the meteorological data sources and for each day of field measurements. We note that below we will use the units t km^{-2} yr^{-1} for the values of $F(t)$.

4.3 Wind field data

270 Obviously, reliable wind field information is an important prerequisite to get an accurate estimate of the target emissions from the data of remote spectroscopic measurements. For instance, it has been noted by Ionov and Poberovskii (2015), that the indeterminacy of the surface wind direction is the main contributor to the total error of NO$_x$ emission by the megacity of St. Petersburg, estimated from circular DOAS measurements. It was also found that the direction of the surface wind acquired by ground-based meteorological observations often does not match the results of modelling of the pollution plume 275 and the results of the NO$_2$ mobile measurements (Ionov and Poberovskii, 2017). Apparently, the routine wind observations in the city are subject to significant local perturbations due to unavoidable interactions of the wind flow and the adjacent city buildings. Along with that, simulated fields of tropospheric NO$_2$ demonstrate reasonable agreement with the plume dispersion observed by the circular mobile observations (Ionov and Poberovskii, 2017; Ionov and Poberovskii, 2019).

The latter is also true for plume simulations, presented in the current study in Fig. 5. However, one can easily notice 280 inconsistencies between the dominant directions of plume movement and the surface winds as specified in Table 2: e.g. days March 21, March 27, April 1 and April 24, when the city plume was moving southeast but the surface wind was west-southwest (see Fig. 5). In order to get more accurate wind information, we have considered additional sources of wind data:
- in situ measurements of Vaisala weather transmitter WXT520 with an ultrasonic wind sensor, installed locally on the roof of the building of the Institute of Physics of SPbU (~60 m a.s.l, 59.88°N, 29.83°E, point A1 in Fig. 2); hereafter mentioned 285 as "LOCAL";
- the data of Global Data Assimilation System (GDAS) from NCEP GFS model, which is similar to the one used to initialize the HYSPLIT dispersion calculations as specified in Section 3.1; hereafter mentioned as "GDAS";
- the wind speed and direction data retrieved from the backward trajectory calculations of HYSPLIT at the location of downwind FTIR observation; hereafter mentioned as "HYSPLIT".

290 Both "GDAS" and "HYSPLIT" wind data are taken at the altitude level that approximately corresponds to the middle of the daytime boundary layer height. An average wind is calculated for the time period of FTIR observations. Resulting wind speeds and directions from the three different data sources are given in Table 3. As expected, wind speeds at elevated altitude levels from GDAS and HYSPLIT are much higher than the surface wind speeds given in Table 2. On some days, e.g. April 6 and April 18, in situ wind directions ("LOCAL") differ considerably from "GDAS" and "HYSPLIT", although the 295 latter two are consistent with each other. Note that compared to surface, the elevated wind directions better reproduce the

city plume movement – e.g. northwest and west-northwest directions on days March 21, March 27, April 1 (see Fig. 5) instead of west-southwest at the surface (see Table 2).

4.4 Air parcel path length

The determination of the air parcel path length L (Eq. 1) is a sophisticated task due to the fact that the application of a box 300 model suggests that the pollutants are well mixed in the entire air box volume, but it is not true, especially for megacities with complex structure of the urban terrain and distribution of emission sources. Thus, different approaches have been tested to calculate L:

- Simplified box model setup with a fixed path length $L_j(t_k)=L=$const for each day of field observations. The box is designed to represent the major part of high density residential and industrial area of the St. Petersburg agglomeration, so that 305 respective L is derived from the value of that area. Since the locations of our field observations are mostly placed on the outer side of the ring road, this road was set to be a boundary for the target emission area. Accordingly, given that the land area inside the ring is equal to 706 km^2, we get an estimate of $L=\sqrt{706}\approx27$ km. Hereafter the results of data interpretation by means of this approach are indicated by "L_{const}".

- The variable effective path is calculated using the actual wind direction and the land use pattern on the route of the linear 310 air trajectory. Only those sections of path are being taken into account that cross the area of supposed anthropogenic emission. The input wind directions are those mentioned above in Table 3, and the resulting path length calculations hereafter are indicated as "L_{LOCAL} ", "L_{GDAS} " and "$L_{HYSPLIT}$ ". The use of the effective path in Eq. 1 takes into account to some extent the inhomogeneity of the anthropogenic emissions in the megacity.

For the purpose of effective paths calculation, a special gridded model of land use coverage has been constructed on 315 the basis of the visual classification of publicly available map (https://yandex.ru/maps/2/saint-petersburg/? ll=30.163886%2C59.911377&z=11, access date 28 January 2020) that covers the St. Petersburg agglomeration with its surroundings (see Fig. 8). The spatial domain of the model covers 76 km in south-north direction and 128 km in east-west direction (59.60-60.29°N, 29.05-31.33°E). It has been assumed that there are no significant emission sources outside this domain. The model resolution (grid size) is 25 m × 25 m. The following major land use classes are considered: residential 320 buildings/industrial areas, roads/highways, water bodies, parks/forests/fields, and swamps/wetlands. Effective path length is calculated as a sum of elementary paths through the grid pixels which contain residential buildings, industrial areas, and roads/highways. Pixels containing water bodies, swamps, and parks are excluded from the variable path calculations. To minimize errors that may occur due to the land use misclassification and to take into account the airflow spatial extension, the 10 km wide band of 11 equidistant and parallel paths is analyzed and an average path length is calculated. Finally, the 325 difference between the "polluted" path (backward from the downwind location) and "clean" path (backward from the upwind

location) provides an estimate of the effective path *L*. Fig. 8 presents an example of linear backward paths for the days of FTIR observations with the major land use classes shown by different colours.

4.5 Case study: two examples

In order to illustrate the interpretation of experimental data and describe the main error sources of final results, we consider 330 two days of field measurements. The first one, April 4, seems to be the most successful in terms of observational conditions, functioning of the equipment, data quality and clarity of the interpretation. It is characterised by stable weather conditions with a moderate south-southwest wind, similarly identified by different wind data sources – from the surface (see Table 2) to higher altitude levels (see Table 3). The simulated city plume picture demonstrates a jet-like flow of air mass on that day, with almost perfect location of both FTS, upwind and downwind almost on one line (see Fig. 5). Besides, according to the 335 model simulation for April 4, the upwind FTS was located in the clean area, while the downwind one was installed very close to the plume jet. Another example is April 25, when both FTS locations appeared to be inside the polluted area. This happened due to the specific weather conditions that contribute to the accumulation of air pollutants in the boundary layer: calm night before and light winds of 1 m s^{-1} in the day time (see Table 2 and 3). Moreover, the wind direction on April 25 at the surface (south-southwest, Table 2) is very different from that in the middle of the boundary layer (east and east-northeast, 340 Table 3).

According to the analysis of the air samples collected in air bags, the surface air on April 25 was extremely polluted. The downwind NO_2 concentration was found to be 138 μg m^{-3}, while it was varying within the range of 12-74 μg m^{-3} during the other days of field observations. Another indication of heavy anthropogenic pollution comes from the data of our mobile DOAS measurements: the maximum of NO_2 TrC registered along the circular route was 92·10^{15} molecules cm^{-2} on April 25, 345 while it was in the range of 15-58·10^{15} molecules cm^{-2} on the other days of field observations. According to the data of municipal air quality monitoring, the daily average concentration of the particulated matter (PM10) was very high and exceeded 60 μg m^{-3} (http://www.infoeco.ru/, last access 4 March 2020). High pollution event was registered also by the CIMEL sun photometer installed at St. Petersburg State University (point A1, Fig. 2) within the AERONET international programme (Volkova et al., 2018): the daily averaged value of aerosol optical thickness (AOT) at 500 nm was found to be 350 0.40 on April 25 which is considerably higher than its long term average value (0.12 for the period of 2013-2019); similar increase of AOT was registered by the satellite measurements of the MODIS satellite instrument over St. Petersburg on that day.

The TC data of CO_2 measurements on April 4 and April 25, with a 15-min running averages, are presented in Fig. 9. Compared to April 4, the TC of CO_2 on April 25 demonstrates higher levels and variation, both at upwind and downwind 355 locations. Although the downwind TC is generally below the upwind level, as expected, the upwind TC starts to exceed

downwind level at the end of FTS observations on April 25. Accordingly, while the "downwind-upwind" difference is relatively stable within the range of $2\text{-}4\cdot10^{19}$ molecules cm^{-2} on April 4, it reaches $10\cdot10^{19}$ molecules cm^{-2} at 12:00 on April 25, but becomes zero and then negative (up to $-1\cdot10^{19}$ molecules cm^{-2}) after 14:30 on April 25. In order to explain this behaviour, a special run of HYSPLIT dispersion model was performed, with an output of CO_2 TC within a boundary layer

360 every 15 minutes, at both FTS locations, upwind and downwind (see Fig. 9). As the first approximation, the CO_2 emission sources were assumed to be located similar to the NO_x emission sources but scaled to match the level of our FTS measurements. These calculations qualitatively reproduce the time series of the CO_2 measurements and the different character of the results of field experiments on April 4 and April 25. Moreover, we can suggest that the origin of high CO_2 TC values observed at the upwind FTS location on April 25 was the thermal power station located about 5 km towards north

365 from the upwind point (see Fig. 8). When the emission by the thermal power station is turned off in the HYSPLIT calculation, the CO_2 TC drops down to the level of upwind FTS measurements on April 4 (see Fig. 9b, blue dashed line).

The time series of Xgas for CO_2, CO and CH_4 obtained from the data of FTS measurements on April 4 and April 25 are shown in Fig. 10. Since the Xgas variability at clean location (upwind) is usually much smaller as compared to a polluted location, it is possible to use time extrapolation of measured data for the periods with data gaps. Fig. 11 demonstrates the

370 difference between TC for each of three gases measured by upwind and downwind FTS on April 4 and April 25; the extrapolated data are specially marked. Fig. 11 also shows the wind speed and wind direction for the time period of FTS observations by the "LOCAL" weather station (see section 4.3).

5 Results and discussion

5.1 Overview of obtained results

375 The campaign consisted of 11 days of field measurements. On 30 April the clouds (altocumulus translucidus) started to develop quickly during the field experiment (see Table 1 and Fig. 4). On 18 April the upwind FTS location was close to the thermal power station. Owing to the prevailing north-northeast wind (see Table 3), the upwind FTS location appeared to be polluted on 18 April (see Fig. 5). Consequently, 18 April and 30 April were excluded from final analysis, and the evaluation of the target fluxes (F) of the investigated gases was limited to remaining 9 days of campaign. For these 9 days the cross-

380 correlations (Pearson's correlation coefficient r) between Δ_{TC} values obtained for the pairs CO/CO_2 and CH_4/CO_2 were calculated: $r_{CO/CO2} = (0.88 \pm 0.02)$; $r_{CH4/CO2} = (0.82 \pm 0.03)$. The high correlation is the evidence of the fact that the measurements in most cases were conducted inside the plume coming from a regional/mesoscale relatively compact powerful source of emission. We can attribute this source to the centre of St. Petersburg.

To further consolidate our flux estimates, some additional restrictions were imposed on the experimental data, which
385 resulted in keeping only 4 days out of 9: March 21, March 27, April 3 and April 4. The first requirement was the wind field
stability. The analysis of the wind field stability during each day was carried out using the GDAS and HYSPLIT
meteorological data, as well as local meteorological observations. The second criterion was the homogeneity of the megacity
pollution plume. It was estimated on the basis of the analysis of the daily variability of enhancement ratios $EnhR =$
$\Delta_{TC,gas1}/\Delta_{TC,gas2}$. The $EnhR$ values for the following pairs were considered: CO/CO_2 and CH_4/CO_2. For selected days, the upper
390 limit of the daily relative variability of $EnhR$ was set as 30%. If we compare the flux values obtained for the 4-day and 9-day
sets, we see that the fluxes for CO_2 are the same, but the fluxes for CH_4 and CO are different (Table 4, columns 2 and 3). The
fluxes estimated for the selected 4 days appeared to be 1.3 times higher than corresponding values obtained for all 9 days of
field observations. The uncertainty of the obtained flux values for the 4-day subset decreased for CO_2 and CH_4. We stress
that during these selected 4 days not only the specific meteorological conditions corresponded in the best way to the
395 assumptions of the box model, but also the locations of the observational points were nearly perfect.

The summary of the EMME-2019 results and the comparison with the flux estimates for St. Petersburg based on in
situ measurements, as well as independent literature data, are presented in Table 4 for CO_2, CH_4, CO and NO_x (the latter were
derived from mobile DOAS measurements of tropospheric NO_2 in the vicinity of upwind and downwind FTIR observations).
Prior to analysis of the results, a short overview of the error and uncertainty analysis should be presented. The uncertainty of
400 mean F values of CO_2, CH_4, CO, and NO_x indicated in Table 4 was calculated as STD of daily means of area fluxes. This
uncertainty includes two components. The first component is the natural flux variability and the second component
comprises the measurement errors and the errors introduced by approximations and simplifications of the model approach
which was used. It should be specially emphasised that these two components cannot be identified separately. Therefore,
below we will use the terms "variability" or "uncertainty" keeping in mind that these terms denote natural variations,
405 measurement errors and model errors together. The relative uncertainty of F for one specific day of measurements (daily
uncertainty) can be estimated using the following expression:

$$\delta F = \delta V + \delta L + \delta \Delta_{TC} \qquad (2)$$

where δV is the relative variation of the wind speed over a day, δL is the relative uncertainty of the air parcel path length, and
$\delta \Delta_{TC}$ is the relative daily variation of Δ_{TC}. The δF values calculated in this way can be considered as an upper limit of the F
410 uncertainty. The average values of δL, δV and $\delta \Delta_{TC}$ estimated for 9(4) days of the city campaign are as follows: $\delta L =$
23(24)%, $\delta V = 23(13)\%$, $\Delta_{TC}(CO_2) = 33(28)\%$, $\Delta_{TC}(CH_4) = 50(22)\%$ and $\Delta_{TC}(CO) = 42(28)\%$. Finally, the average values of
relative daily uncertainty of area fluxes are equal to $\delta F_{CO2} = 79(65)\%$, $\delta F_{CH4} = 96(59)\%$ and $\delta F_{CO} = 88(65)\%$. As an example,

daily mean values of CO_2 area flux obtained during the city campaign are presented in Fig.12 where the "error bars" are the absolute uncertainties of F values derived from corresponding relative mean uncertainties for 9(4)-day sets.

415   As it has been described above, there were several different scenarios of the F calculations in which different sources of meteorological information (LOCAL, GDAS, and HYSPLIT) and different methods of the air parcel path calculations were used. The comparison of the obtained results has shown that the minimum variability of F is observed when the HYSPLIT meteorological data are combined with the variable effective path L (see section 4.4). When selecting the results for final analysis, we suggest that the application of the criterion of minimal variability is a good choice because in this case 420 the corresponding estimates of area flux are more reliable. This statement can be confirmed in particular by comparison of the CO_2 fluxes obtained for the 9-day and 4-day sets. For the 4-day set, the variability is considerably lower (12 vs. 28 kt km^{-2} yr^{-1}), and we should reiterate, that these 4 days were the days with the most favourable observational conditions during the observational campaign. So, we do not present the results of all scenarios, and show in Table 4 (columns 2 and 3) only the values obtained for the combination of HYSPLIT meteorological data with the variable effective path.

425 **5.2 Estimation of the CH4 emissions by means of in situ measurements of its mixing ratio**

The fourth column of Table 4 contains the estimations of F for the territory of St. Petersburg, which were made on the basis of the joint analysis of the CH_4 local concentrations monitored in the ambient air during March-April 2013 and April 2019 at the SPbU atmospheric monitoring station (point A1) (Makarova et al., 2018) and Voeikovo station (59.95°N, 30.70°E, 72 m above sea level) of the Voeikov Main Geophysical Observatory (MGO) (Zinchenko, 2002). The CH_4 measurements are 430 carried out by MGO in accordance with WMO recommendations for GAW stations (WMO, 2009; WMO, 2014). The high quality of the data obtained by MGO is confirmed by the results of WMO/IAEA Round Robin Comparison Experiment 2014-2015 (https://www.esrl.noaa.gov/gmd/ccgg/wmorr/wmorr_results.php, last access 3 March, 2020). The data of Voeikovo station together with 17 other European stations were used to estimate European methane emissions in the framework of the InGOS project (Bergamaschi et.al., 2018). The measurements of these stations have been rigorously 435 quality controlled (Lopez et al., 2015; Schmidt et al., 2014). The Voeikovo measurements are calibrated against the NOAA-2004 standard scale (which is equivalent to the World Meteorological Organization Global Atmosphere Watch WMO-CH4-X2004 CH_4 mole fraction scale) (Dlugokencky et al., 2005). The comparability of the SPbU and Voeikovo station data was ensured by calibrating the SPbU equipment against the working standard prepared by MGO.

Determination of the CH_4 fluxes is possible due to the beneficial location of the observational stations of SPbU and 440 MGO - on the western and eastern sides of the megacity. For the wind directions of 75-85° and 255-265°, the air mass on the way from one station to another passes through the centre of St. Petersburg. It should be emphasised that only the time periods with the wind speed of at least 2.5 m s^{-1} were considered. Using the difference in the CH_4 concentrations obtained at

15   1

the monitoring stations, it is possible to estimate the CH_4 flux for the central part of the St. Petersburg agglomeration on the basis of a simple box model similar to that used in the present work. It was assumed that all contaminations emitted by

445 St. Petersburg into the atmosphere stay within the boundary layer. The calculation of the variable effective path L between these two monitoring stations gives (21 ± 7) km. The HYSPLIT backward trajectory outputs were used as a source of meteorological data (wind field, boundary layer height data). Finally, the F values for CO_2 and CO were estimated using the obtained average CH_4 flux (120 ± 80 t km^{-2} yr^{-1}) and average $EnhR$ values derived from the in situ measurements of the CO_2, CH_4, and CO concentrations at SPbU atmospheric monitoring station (point A1) in 2013-2019 (Table 5, the third column).

450 The flux values for CO_2 and CO evaluated in this way are 2-3 times lower than the corresponding results of EMME-2019. This difference can be partially explained by the presence on the territory of St. Petersburg of a significant number of elevated stationary sources of CO_2 and CO – industrial and power/heat plant pipes (pipes of the power plant stations can have a height of ~200 m), which emit products of combustion and oxidation of various types of fossil fuels. The effect of elevated sources on gas concentrations measured at the surface layer is often minimal, but this impact can be considerable

455 for total/tropospheric columns and can be detected using remote sensing techniques such as those used during the Berlin campaign (Hase, et al., 2015) and EMME-2019. In order to detect the presence of the elevated sources, the air sampling using kite launches was performed during EMME-2019. The air sampling by kite launching technique was possible only twice when suitable wind speed conditions occurred and there was enough free space for launching. The results of comparison of the gas concentrations in air samples collected at the surface and elevated levels on 24 April 2019 and on

460 25 April 2019 at the locations of FTS measurements inside the city plume are presented in Table 6. In most cases the concentrations of considered gases at the elevated level are lower if compared to the surface level. There were only two cases with the concentration enhancement in the air samples collected by kite: for CH_4 on 24 April and for CO_2 on 25 April, however these enhancements were negligibly small (1 ppbv for CH_4 and 1 ppmv for CO_2). So, one can come to the conclusion that these two kite launches revealed no elevated pollution plumes.

465 **5.3 Comparison with inventories**

Official reports on the environmental conditions of St. Petersburg (Serebritsky, 2018, 2019) contain information on the annual emissions of CO_2, CH_4, CO and NO_x for the entire territory of the metropolis. For comparison with our flux estimates, these total rates were divided by the area of St. Petersburg within its administrative boundaries (1439 km^2). The best agreement of the results of the EMME-2019 campaign with the official emission inventory was obtained for NO_x and CO.

470 For NO_x, the results of the field campaign and the official emission inventory demonstrated close values: 66 t km^{-2} yr^{-1} and 47 t km^{-2} yr^{-1}. The average CO flux for the territory of St. Petersburg, according to official data, is 280 t km^{-2} yr^{-1}, which is also in good agreement with the values obtained in the current work (251-333 t km^{-2} yr^{-1}). At the same time, a significant differences in the F estimates for CH_4 and CO_2 were obtained: the official data are by 8-10 and 4 times lower than the

corresponding values obtained during field observations in March-April 2019. Hiller et al. (2014a) showed that the
475 application of the boundary layer budget approach in the form of a box model could give the CH_4 area fluxes of about 1.5-2
times higher in comparison with corresponding values estimated by eddy covariance technique and 2.5-6 times higher than F
derived from the emission inventory data.

The results of independent studies of anthropogenic emissions reported in the scientific literature show that the
estimates of the CO_2, CH_4, CO, and NO_x fluxes can vary in a very wide range depending on season, meteorological situation,
480 location of observation points, measurement technique, and used approach for estimation of emission (Vaughan et al., 2016;
Hiller et al., 2014a; and also see the references indicated in Table 4). The CO_2 flux for the St. Petersburg agglomeration
obtained in this paper is approximately three times higher than those for London and Berlin and ~7 times higher than for
Tokyo and Mexico City (see Table 4). We would like to note that when comparing the results of different observational
campaigns one should pay attention to the seasonal features of emissions. For example, the Berlin campaign took place in
485 early summer when space heating was off. The EMME-2019 campaign in St. Petersburg was carried out in March-April. The
space heating in St. Petersburg is mainly organised as the system of district heating which is running in the winter mode
during this period. The district heating in St. Petersburg is usually turned off in the beginning of May. For CH_4, the emission
intensity is about 2-3 times higher than the results for London. The CO fluxes for megacities, according to published data,
can demonstrate a wide range of values, for example, varying from 106 t km^{-2} yr^{-1} (London) to 1520 t km^{-2} yr^{-1} (Mexico
490 City). This range covers our estimates for St. Petersburg: ~251-333 t km^{-2} yr^{-1}.

One of the most important characteristics of the air pollution source is the emission ratio $ER_{gas1/gas2}$:

$$ER_{gas1/gas2} = F_{gas1} \, M_{gas2}/(F_{gas2} \, M_{gas1}), \tag{3}$$

where F_{gas} is the gas flux, M_{gas} is the molecular weight of gas. For gases, such as CO_2, CH_4, and CO, whose lifetime in the
troposphere is significantly longer than the duration of field measurements (several hours), the following equality is valid:
495 $ER = EnhR$. The ER values obtained from the results of the EMME-2019 campaign and in situ measurements at the SPbU
atmospheric monitoring station (point A1) in 2013-2019, as well as ER calculated for the official emission inventory and the
ER taken from literature are presented in Table 5. The emission ratios for St. Petersburg obtained as a result of the
EMME-2019 campaign and of the in situ monitoring of CH_4 at the observational stations located near St. Petersburg have
similar values, which are in good agreement with the information on ER for the world's largest cities reported in literature.
500 For the official emission inventory, the ER values for CO/CO_2 and CH_4/CO_2 correspond to the upper and lower limits of the
given literature data, respectively. Thus, the relative contributions of CO_2, CH_4 and CO to the total emissions of the
St. Petersburg agglomeration are very similar to the corresponding values for the world megacities.

5.4 Identification of problems

When studying the application of the remote sensing instruments to the problem of the air pollution meteorology, Beran and
505 Hall (1974) noted:

> "Every urban region is a unique entity and the correct location and sensor distribution for one city may be
> totally unacceptable for another. Certain features are, however, common to all and can be used to generate
> a hypothetical city."

Such hypothetical city usually contains industrial region and line sources of emission in the form of highways. Beran and
510 Hall (1974) also made the following important remark:

> "Terrain features are another important influence on urban meteorology, many times controlling the local
> flow which advects or concentrates effluent in a given region. For example, a river valley is a natural
> place for cold air drainage, while a coast line produces local land and sea breeze circulation, alternately
> cleansing a region and concentrating pollution at the sea breeze front."

515 All these mentioned terrain features are present on the territory of the St. Petersburg agglomeration. St. Petersburg is located at the estuary of the Neva River which flows in the Gulf of Finland. The territory of St. Petersburg occupies northern, eastern and southern coastlines of the Gulf of Finland (Fig. 2). About 40 km to the north-east from the centre of St. Petersburg, the southern coastline of the Ladoga Lake is located. The Ladoga Lake is the largest lake in Europe. All these facts define the weather and climate in St. Petersburg. The complex terrain of St. Petersburg agglomeration requires special attention due to
520 its influence on the air pollution meteorology.

The number of sunny days in St. Petersburg is not large. We tried to use every clear-sky day. But the weather in St. Petersburg is unstable and in several cases the forecast for clear-sky was wrong. When it happened the field measurements which were already prepared for start were cancelled. On the other hand, there were clear-sky periods which were not forecasted. In some of such cases we managed to quickly organise and perform the field observations. As a result of
525 unstable weather, the experiment appeared to be time consuming and interfering with other ongoing activities.

The measurement locations for two EM27/SUN instruments were appointed about 12 hours prior to the day of field campaign on the basis of the HYSPLIT forecast of the city plume dispersion. Moreover, during the field measurements there was a possibility to correct the locations on the basis of the NO_2 tropospheric column mobile measurements along the ringroad. Nevertheless, we could not implement the perfect setup of the experiment when both measurement locations of
530 EM27/SUN were strictly on the straight line parallel to the wind direction. The problem arises from the sparsely distributed sites suitable for installing the equipment and making observations. Also, we were limited in time since the travel time to the initial destination points was about 1 h and more. Changing of position is also time consuming process which includes the

equipment loading, unloading and the travel time itself. The air sampling at different elevations by means of kite launching technique was possible only twice when the wind speed was suitable and there was enough free space for launching.

535   There is a certain problem relevant to the meteorological data obtained from different sources. First of all, a kind of ambiguity exists in selecting the optimal data source. The reason for that is different spatial and temporal distribution of data provided by different sources. Second, the data can be updated, for example we noted the updates of GDAS data sets which contained the considerable alteration of information.

6 Summary and outlook

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We presented the description and the first results of the Emission Monitoring Mobile Experiment (EMME-2019) which was carried out in March-April 2019 in St. Petersburg, Russia. The main goal of this activity was the evaluation of emissions of CO_2, CH_4, CO and NO_x for the megacity with the population of 5 million. The field campaign was performed in the area of the St. Petersburg agglomeration by joint efforts of St. Petersburg State University (Russia), Karlsruhe Institute of 545 Technology (Germany) and the University of Bremen (Germany). The principal feature of EMME is its integrated character: several different instruments are used, and besides, the planning of the field experiment and data processing are performed with the help of numerical modelling of the transport of the megacity pollution plume. The concept of EMME is based on remote measurements of the total column amount of CO_2, CH_4 and CO from two mobile platforms located inside and outside the city plume combined with the mobile circular measurements of tropospheric column amount of NO_2 from the third non- 550 stop moving platform, the latter measurements are used for the real-time control of the megacity plume evolution.

The results demonstrate that a combination of daytime synchronous upwind and downwind FTIR observations by two well-calibrated ground-based EM27/SUN FTIR spectrometers allow the reliable detection of XCO_2, XCH_4 and XCO enhancements due to urban emissions in the area of our study. The origin and temporal evolution of these enhancements were confirmed by simultaneous mobile DOAS measurements of tropospheric NO_2 around the city, the upwind and 555 downwind in situ air sampling (with further analysis of CO_2, CH_4, CO and NO_x concentrations), and by the simulations of urban pollution transport with the help of the HYSPLIT dispersion model calculations.

The collected data of our field campaign, supplemented with the precise in situ measurements of the CH_4 local concentrations at two sites in the suburbs of the city, allowed to get an estimates of the emission fluxes of greenhouse (CO_2, CH_4) and reactive (CO, NO_x) gases by the megacity of St. Petersburg. Resulting values reveal considerably higher emissions 560 of CH_4 (135 ± 68 t km^{-2} yr^{-1}) and CO_2 (89 ± 28 kt km^{-2} yr^{-1}) if compared to the existing inventories, while our estimates of the CO emission (251 ± 104 t km^{-2} yr^{-1}) and NO_x emission (66 ± 28 t km^{-2} yr^{-1}) are in agreement with the inventories.

The terrain of the St. Petersburg agglomeration is complex. It comprises the Neva river estuary and the coastline of the Gulf of Finland which influence the urban meteorology. Besides, multiple emission sources of different types and origin are inhomogeneously distributed over the main city and the suburbs. In the present study we used a simple box model 565 approach for the derivation of the area fluxes of CO_2, CH_4, CO, and NO_x. Obviously, the application of more sophisticated models in combination with the detailed information on the emission inventory for the territory of St. Petersburg seems promising for the continuation of the present study.

Data availability

The datasets containing the EM27/SUN measurements during EMME-2019 can be provided upon request; please contact 570 Maria Makarova (m.makarova@spbu.ru) and Frank Hase (Frank.Hase@kit.edu)).

Author contributions

MVM, FH, TB, and DVI conceived the study together. MVM, DVI, YAV, CA, VSK, SCF, MF, TW, AnVP, KAV, NAZ, YMT, EYB, SIO, BKM, AlVP, EFM and HKhI contributed greatly to the experimental part of the study. SCF, CA, and MVM were in charge of processing FTIR spectrometer data. DVI was in charge of numerical modelling of gas plumes and 575 of conducting mobile DOAS measurements. Together MVM, FH, TB, DVI, SCF, CA, VSK, NNP, and VMI analysed and interpreted the results. MVM, VSK, DVI, and SCF prepared the original draft of the manuscript with contributions from FH, TB, CA, MF, YMT, NNP, and VMI. MVM, FH, TB, DVI, VSK, MF, AlVP, and YMT reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. EMME-2019 observation details: the field experiment setup (up- and downwind "u&d" or cross sectional "cs"), the FTS location (Loc), the FTS identifier (FTS#), the number of bags of air samples (AS), indication
780 **of the kite launch and the corresponding air sampling altitude.**

Date of 2019	Outside the city plume				Inside the city plume				DOAS mobile	Comment
	Loc	FTS#	AS	Kite	Loc	FTS#	AS	Kite		
21.03	A1	#80	2	no	B7	#84	2	yes	no	U&d setup,test FTIR field measurements, test flight of the kite without air sampling
27.03	A2	#84	2	no	B2	#80	2	no	yes	U&d setup, A2 – no clouds, B2 – groups of clouds
01.04	A2	#84	2	no	B2	#80	2	no	yes	U&d setup, A2 – no clouds, B2 – groups of clouds
03.04	A1	#84	2	no	B3	#80	2	no	yes	U&d setup, clear sky for both locations
04.04	A5	#84	2	no	B3	#80	2	no	yes	U&d setup, clear sky for both locations
06.04	B7	#84	2	no	A2	#80	2	no	no	U&d setup, clear sky and burning grass for both locations
16.04	A2	#84	2	no	A5+	#80	2	no	yes	Cs setup, clear sky for both locations
18.04	B3	#80	2	no	A5, A6+	#84	2	no	yes	U&d setup, clear sky for both locations
24.04	A2	#84	2	no	B2	#80	2	Yes, 100 m	yes	U&d setup, A2 – clear sky, B2 – light cirrostratus, sun halo
25.04	B3	#80	2	no	A5	#84	2	Yes, 70 m	yes	U&d setup, B3 – smoke plum in the field of view of FTIR spectrometer, A5 – light cirrostratus
30.04	B2	#80	2	no	A2	#84	2	no	yes	U&d setup, B2 – cirrostratus, A2 – quickly developing altocumulus translucidus

785 **Table 2. Basic meteorological data for the days of the field campaign: surface air temperature (T), relative humidity (RH), wind speed (WS) and wind direction (WD) at local noon. The meteorological data refers to one of the observational sites in the city of St. Petersburg (http://rp5.ru/Weather_archive_in_Saint_Petersburg, last access 5 March 2020).**

Date	T (ºC)	RH (%)	WD	WS (m s^{-1})
21 March (Th)	2.3	84	WSW	3
27 March (We)	0.1	64	WSW	2
1 April (Mo)	3.2	76	WSW	3
3 April (We)	9.8	24	S	3
4 April (Th)	12.5	24	SW	3
6 April (Sa)	12.5	21	SE	2
16 April (Su)	12.0	39	NE	2
18 April (Tu)	12.5	35	NE	2
24 April (We)	16.7	40	WSW	1
25 April (Th)	20.9	23	WSW	1
30 April (Tu)	10.7	27	SSE	2

790

Table 3. **The wind speed and the wind direction for the days of the field campaign, as retrieved from different data**
795 **sources: in situ observations (LOCAL), globally gridded assimilated data (GDAS) and backward trajectory**
calculations (HYSPLIT).

Date	Wind speed, m s^{-1}			Wind direction, °		
	LOCAL	GDAS	HYSPLIT	LOCAL	GDAS	HYSPLIT
21 March	6	7	10	293	270	277
27 March	2	5	5	292	332	324
1 April	3	5	8	329	307	310
3 April	3	5	5	212	193	199
4 April	3	6	6	214	194	202
6 April	1	3	3	58	104	103
16 April	1	5	6	36	42	40
18 April	1	5	7	25	34	26
24 April	3	5	6	357	286	291
25 April	1	2	1	69	95	71
30 April	2	4	4	78	112	40

800 **Table 4. 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 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	Literature sources	
	(9 days)	(4 days)		St. Petersburg	The world's cities
1	**2**	**3**	**4**	**5**	**6**
CO$_2$, kt km^{-2} yr^{-1}	89 ± 28	85 ± 12	40 ± 30	21 (Serebritsky, 2018), 46 (EDGAR database, 2018) 6 (suburbs, Makarova, 2018)	29 (London, O'Shea, 2014) 35.5 (London, Helfter, 2011) 12.8 (Mexico City, Velasco, 2005) 12.3 (Tokyo, Moriwaki and Kanda, 2004) 770 – 7710 (Krakow, Zimnoch, 2010) 28.3 (Berlin, Hase, 2015)
CH$_4$, t km^{-2} yr^{-1}	135 ± 68	178 ± 30	120 ± 80	17 (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	333 ± 103	90 ± 50	280 (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	-	-	47 (Serebritsky, 2018, 2019)	63-252 (London, Lee, 2015) 13- 300 (Norfolk, Marr, 2013)

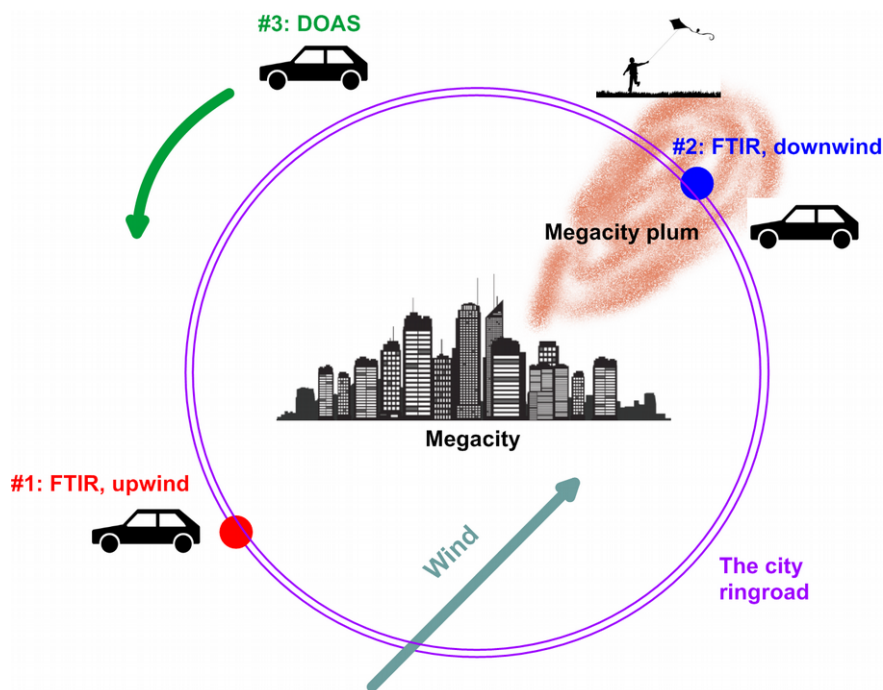
805

Table 5. Emission ratios *ER*, obtained during EMME-2019 and the *ER* estimates for St. Petersburg based on in situ measurements. The values previously reported in literature are also presented. In columns 2, 3, and 4 the values of the correlation coefficient (*r*) for corresponding datasets are given in parentheses.

Emission ratio	St. Petersburg				Literature sources
	EMME		In situ measurements	Official emission inventory	
	(9 days)	(4 days)			
1	2	3	4	5	6
CO/CO_2, ppbv/ppmv	5.9 (r=0.88±0.02)	6.2 (r=0.97±0.01)	6.0 ± 2.4 (r=0.76±0.04)	21 (Serebritsky, 2018, 2019)	5.68, 8.44 (Paris, Ammoura, 2014), 1.92 – 6.6 (London, O'Shea, 2014), 6-9 (Indianapolis, Turnbull, 2015) 14 (Sacramento, Turnbull, 2011)
CH_4/CO_2, ppbv/ppmv	6.8 (r=0.82±0.03)	5.8 (r=0.96±0.02)	7.8 ± 2.6 (r=0.70±0.04)	2.2 (Serebritsky, 2018, 2019)	3.9 - 6.9 (London, O'Shea, 2014), 5.2 ± 0.5 (London, Helfter, 2011),

815 **Table 6. Comparison of the gas concentrations in air samples collected at the surface and elevated levels on 24 April 2019 and 25 April 2019 at the locations of FTS measurements inside the city plume.**

820

Gas	24 April 2019 (location B2)		25 April 2019 (location A5)	
	Surface level	Kite (~100 m)	Surface level	Kite (~70 m)
NO [mg m-3]	0	0	6	5
NO_2 [mg m-3]	26.5	23.5	138.1	122.4
CH_4 [ppmv]	1.958	1.959	2.338	2.278
CO_2 [ppmv]	422.5	417.1	444.0	445.0
CO [ppbv]	191.1	185.8	-	-

825 **Figure 1: Illustration of the concept of EMME: two FTIR spectrometers at the upwind and downwind locations on the opposite sides of the city (#1 and #2, red and blue dots) and circular moving DOAS technique spectrometer (#3). Ground-level air samples were collected at locations #2 and #3. Collecting air portions with the help of a kite was done usually at the downwind location under suitable weather and landscape conditions. Pictogram png-images: https://www.cleanpng.com/, last access 6 November 2019.**

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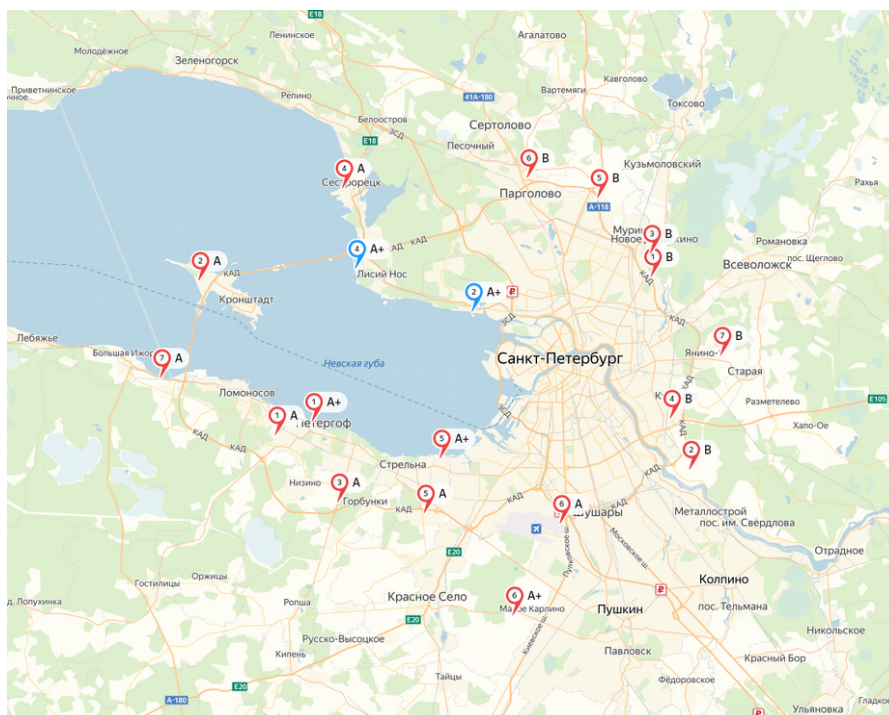
835 **Figure 2: The set of FTS locations around the St. Petersburg agglomeration. Locations are marked by letters "A" and "B" with numbers. The "plus" sign near a location mark denotes that there is a possibility to use local power supply at this location. Red colour denotes primary locations, blue colour denotes secondary locations. Map data © 2019 Yandex.**

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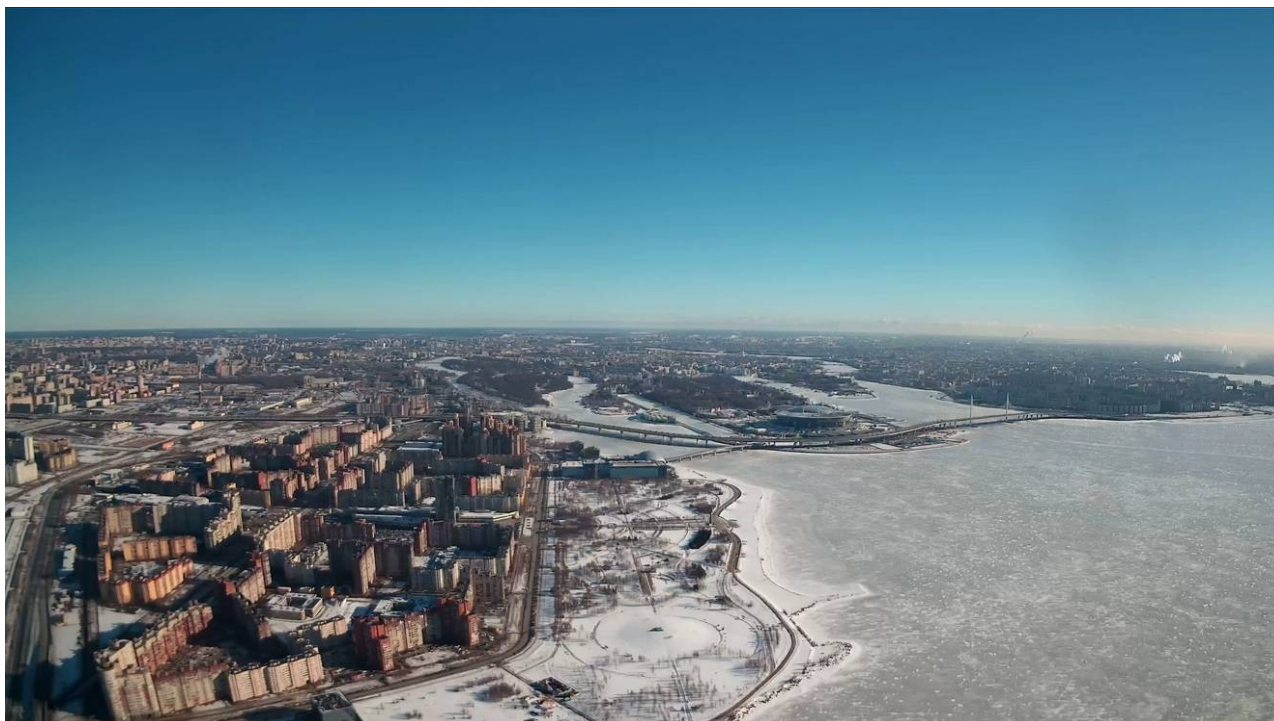


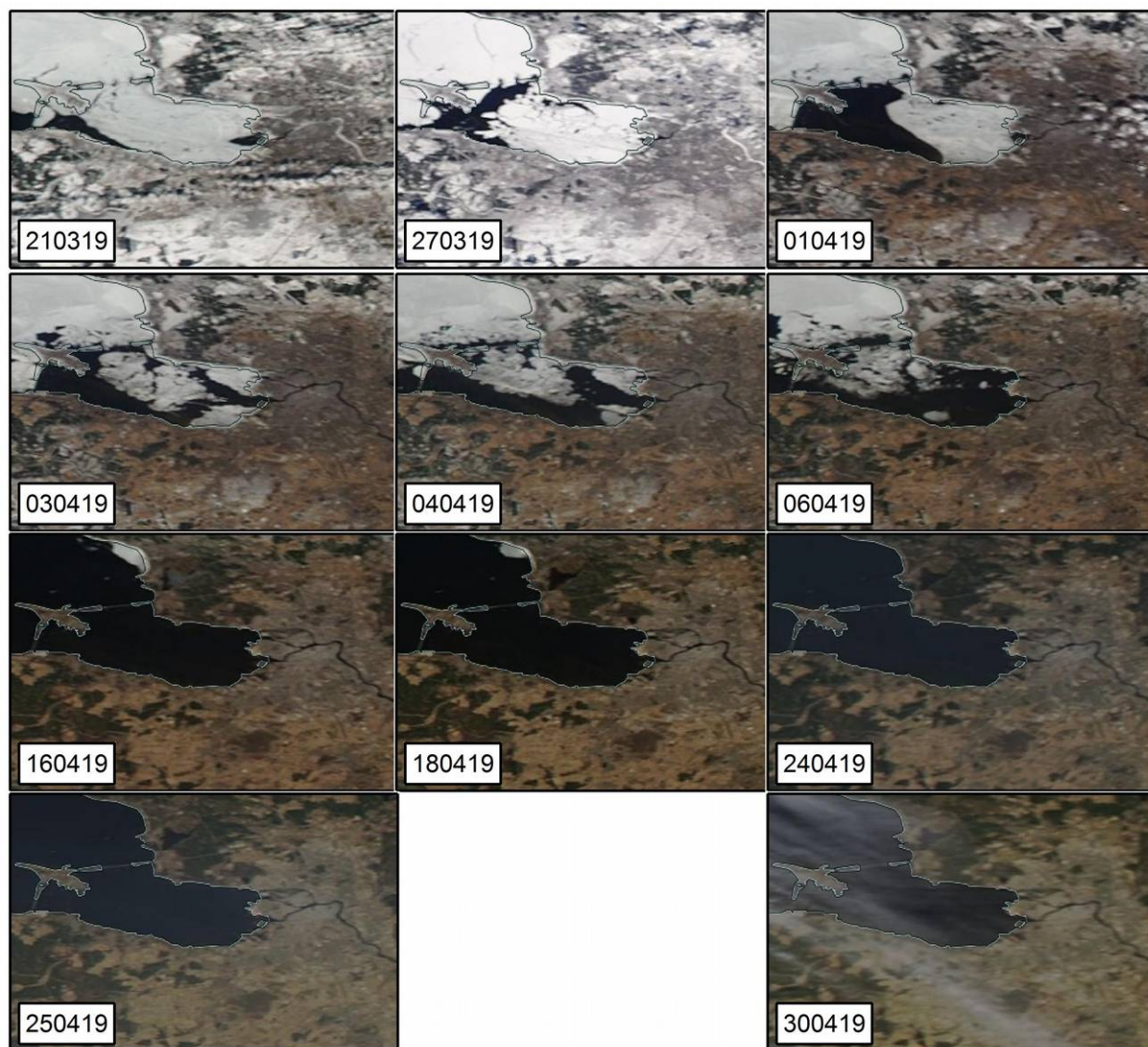
Figure 3: Screenshot made from the web camera installed on top of the highest building in St. Petersburg – Lakhta Centre (462 m). This web camera was used for online monitoring of cloud cover to the east and south-east from St. Petersburg.
845**(https://www.geocam.ru/en/online/lakhta-center-360/, last access 3 December 2019)**

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Figure 4: The MODIS satellite images of cloud cover in the vicinity of St. Petersburg taken on the days of field campaign.

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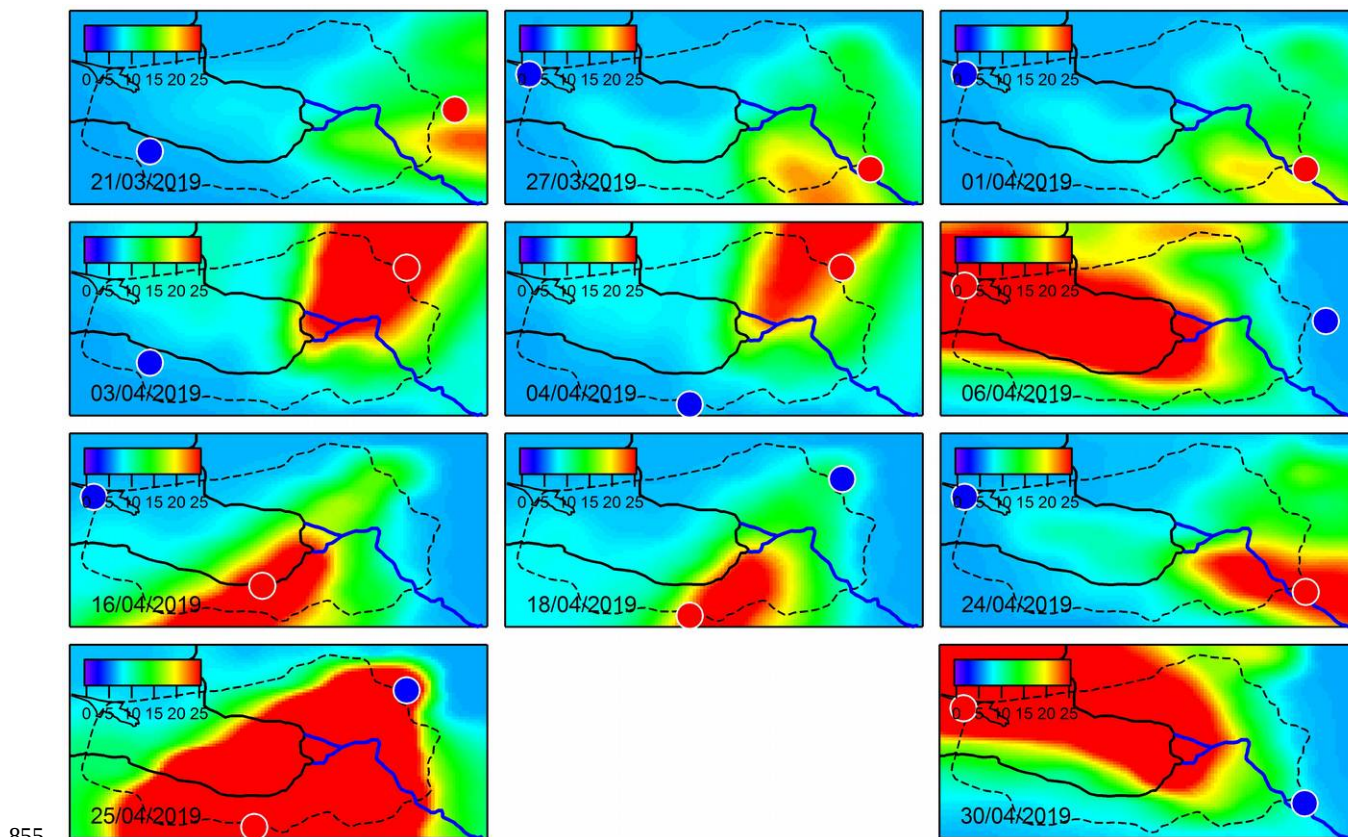
Figure 5: The forecast of the megacity plume used for planning the field campaign. The HYSPLIT model output for each of the campaign days, 10:00 UTC.

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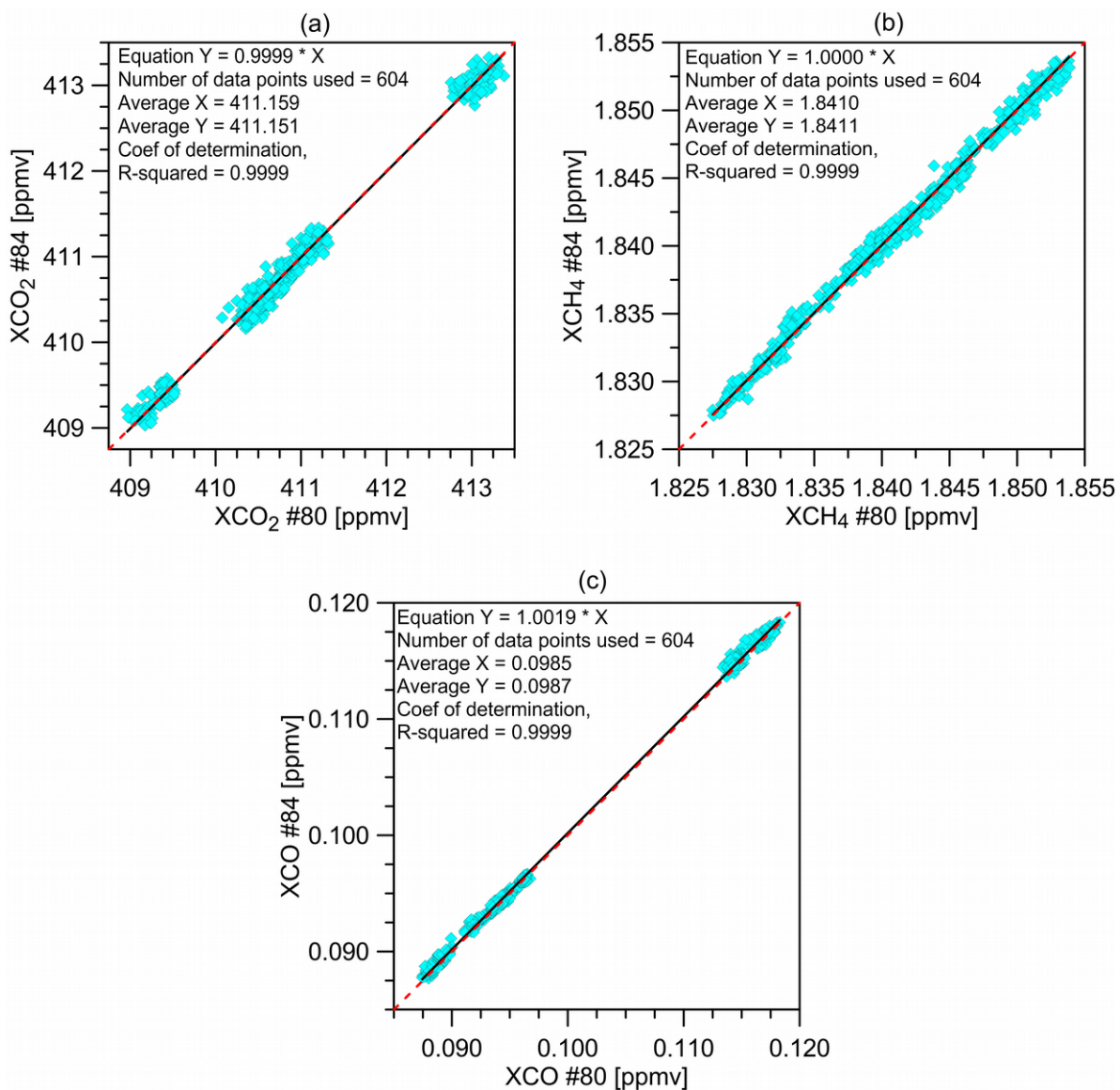
Figure 6: The scatter plots of cross-comparison of the average mole fraction data during side-by-side calibrations.

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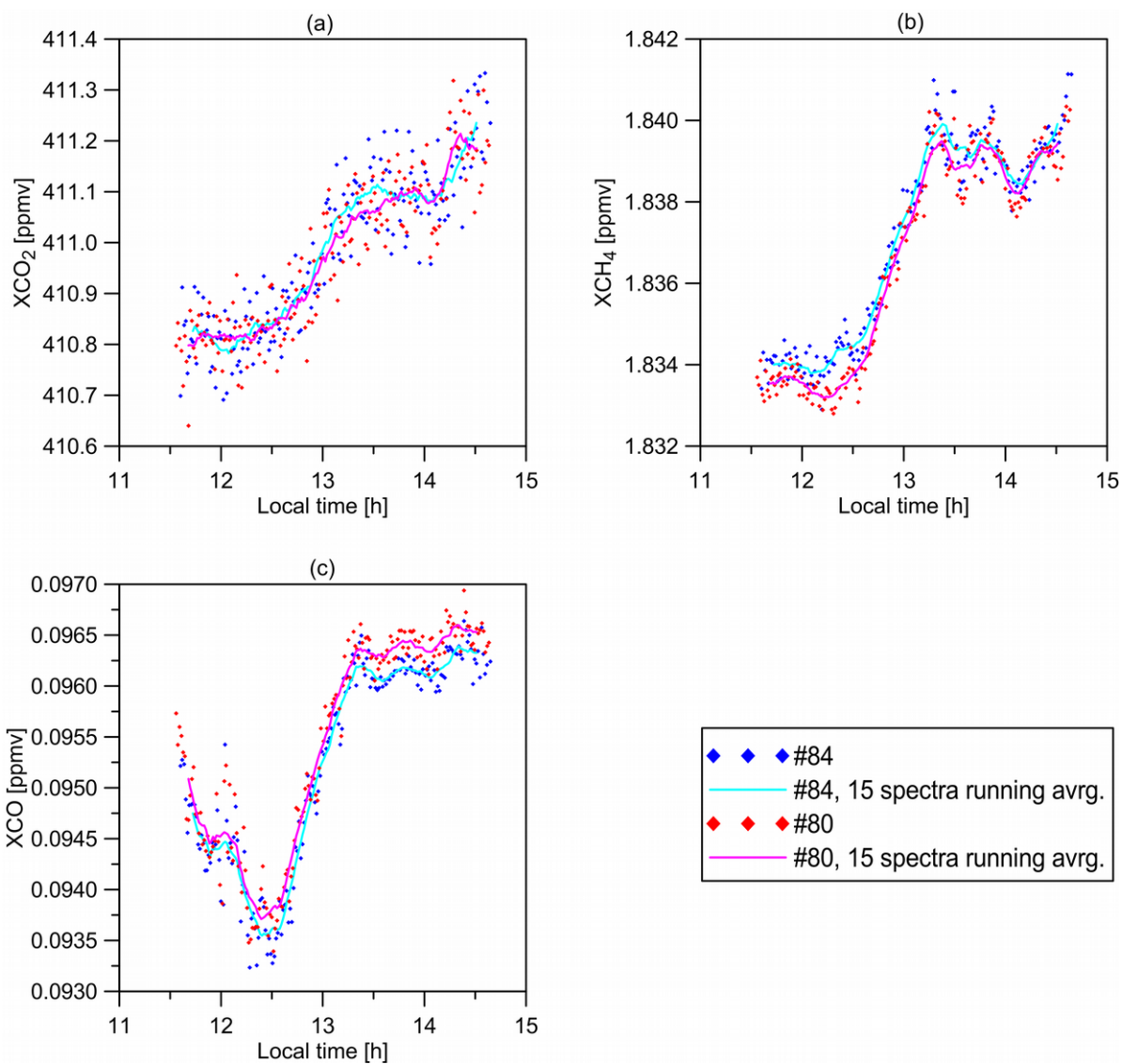
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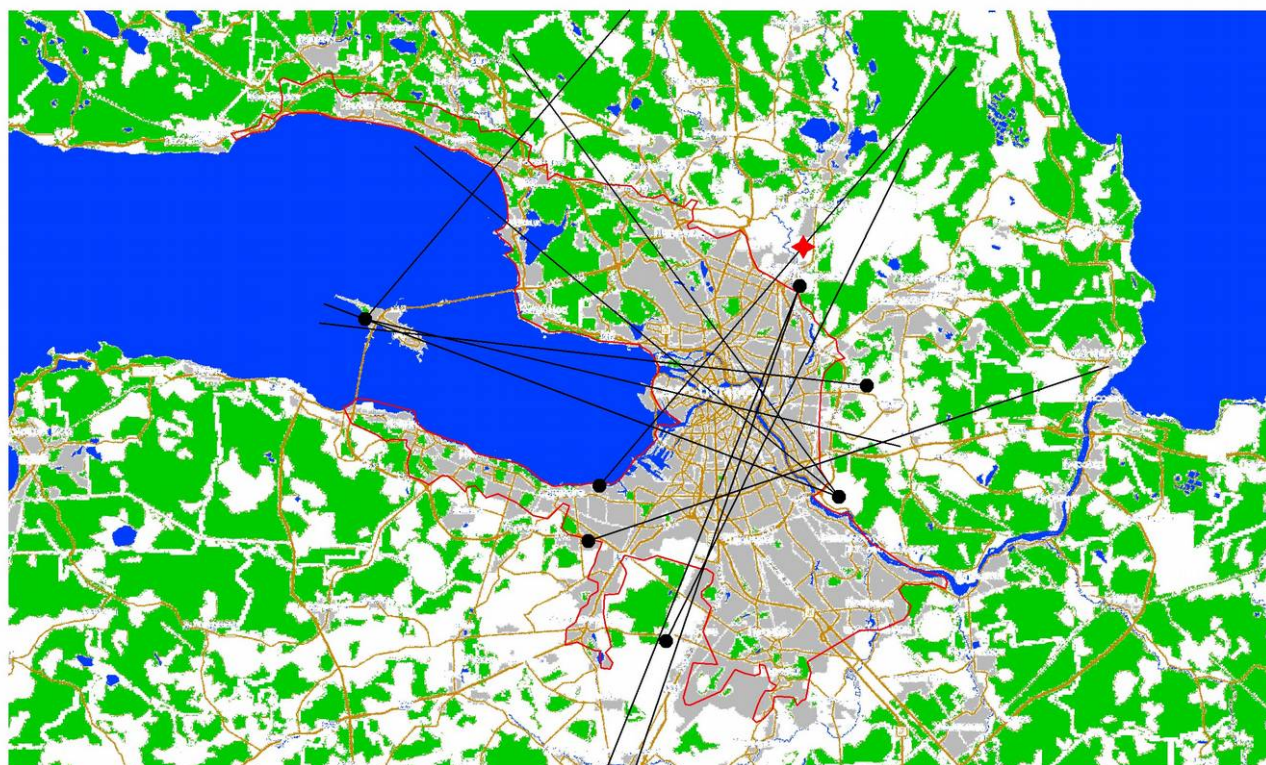
Figure 7: The results of the side-by-side measurements of XCO_2, XCH_4, and XCO by FTS#80 and FTS#84 on 12 April 2019.

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Figure 8: An example of linear backward paths (black straight lines, black dots show the downwind FTS locations) for the days of FTIR observations. The major land use classes are shown by different colours (blue for the water bodies, grey for the residential buildings/industrial areas, green for the parks and forests). For simplicity, the path lengths on the map are equal. Corresponding wind directions were taken from the "HYSPLIT" data source (see Section 4.3). Red line depicts the official administrative
880 **boundary of the St. Petersburg agglomeration. Red "star" depicts the location of one of the major thermal power stations (TPS) located to the north of St. Petersburg. Map data © 2019 Yandex.**

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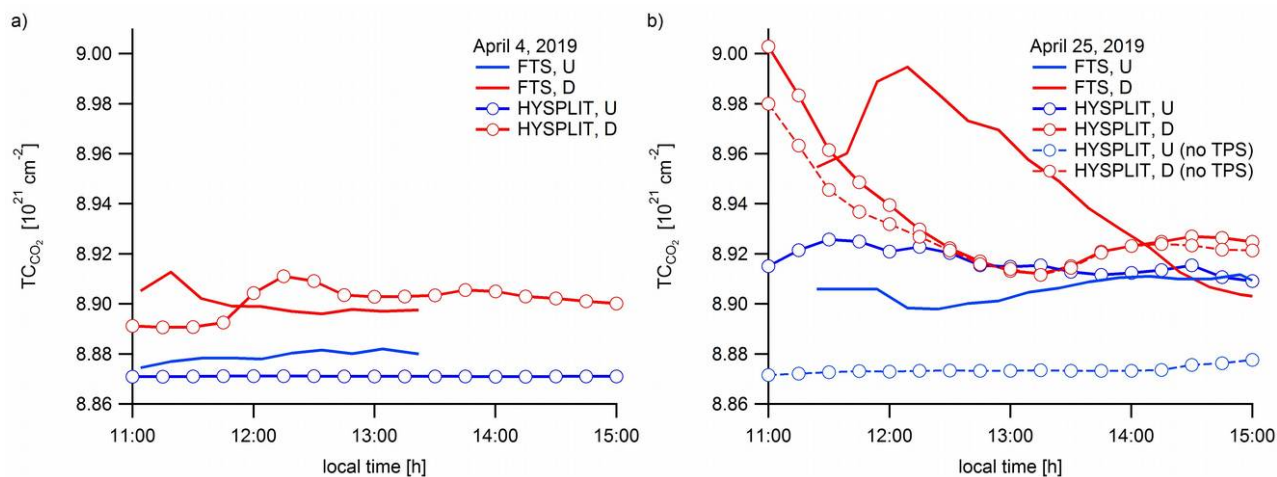
890 **Figure 9: Time series of the CO₂ TC measurements by mobile FTS at upwind (U, blue) and downwind (D, red) locations on two days, April 4 and April 25, 2019. The measurements are compared with the results of the HYSPLIT simulations at both locations, upwind and downwind. For the day of April 25, special HYSPLIT scenario is added for comparison: the emission of the major thermal power station (TPS) of St. Petersburg nearby the upwind FTS location is turned off ("no TPS", see Fig. 8 and the text for details).**

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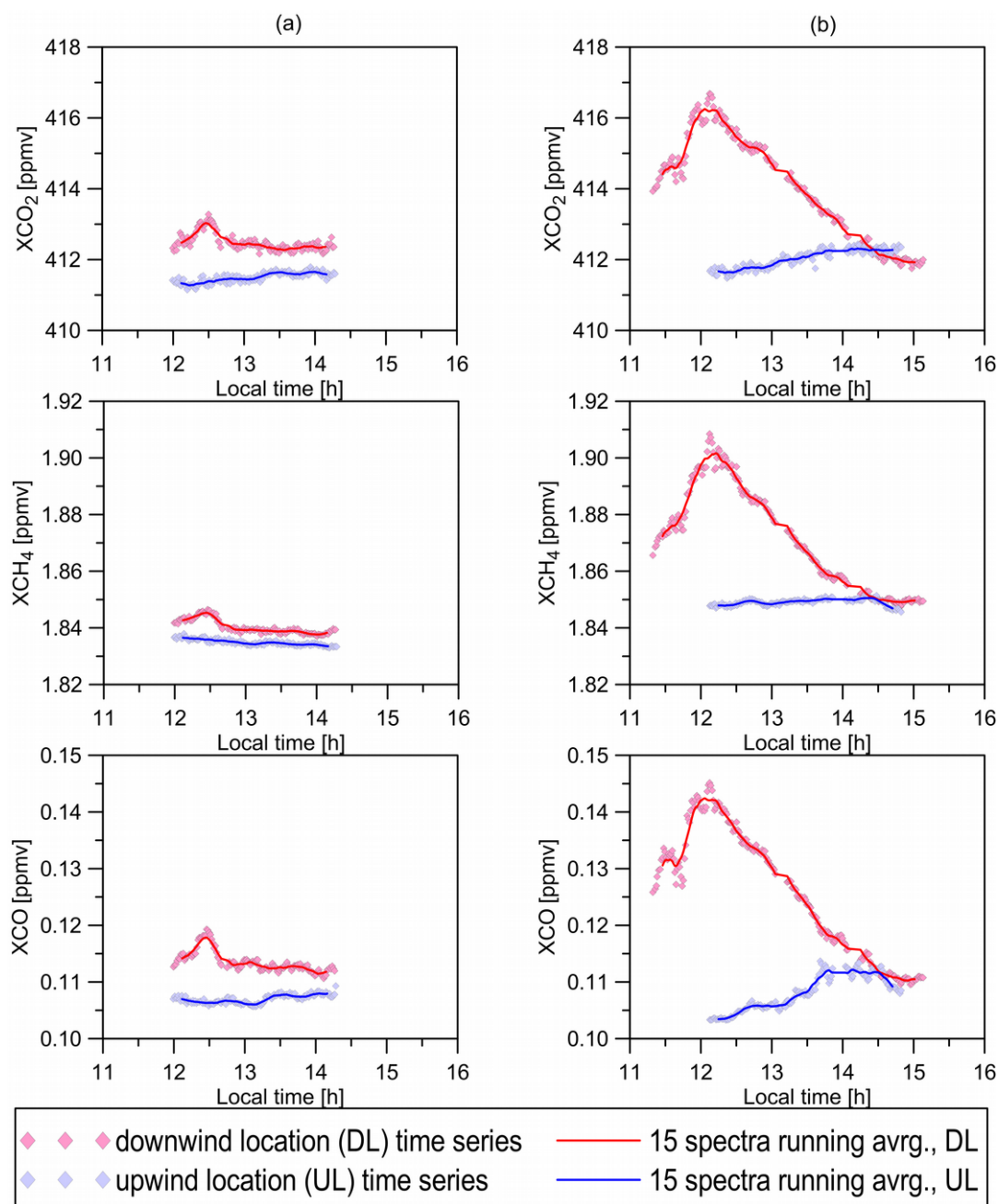
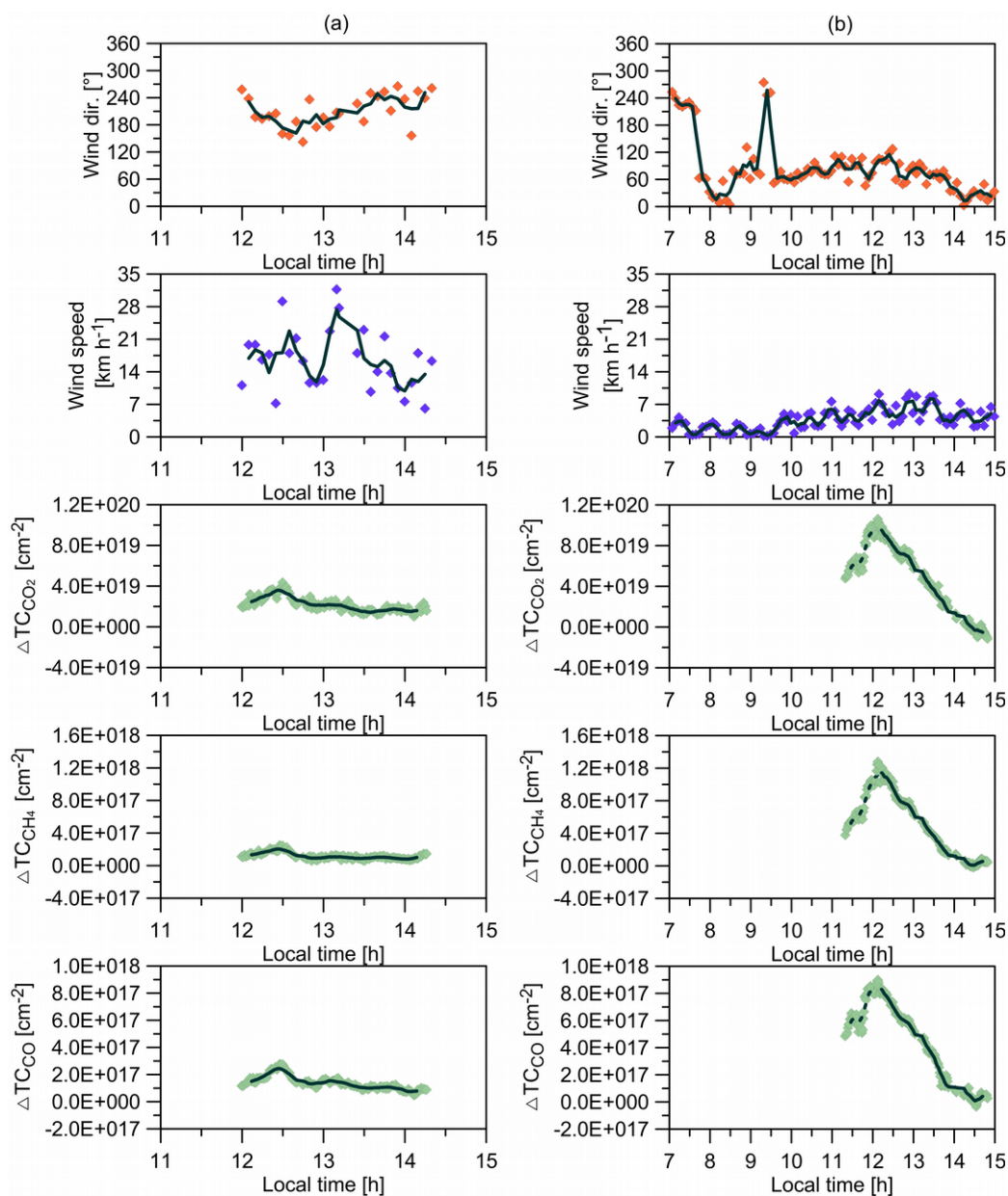

900 **Figure 10: Time series of Xgas for 4 April (a) and 25 April (b) at the clean location of FTS (blue dots) and at the polluted location of FTS (red dots). Solid lines of corresponding colours denote 15 min running average.**

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Figure 11: The difference between the TC values at the polluted and clean locations of FTS on 4 April (a) and 25 April (b). The wind speed and direction are also shown.. Solid lines denote 15 min running average. Dashed lines denote time interval when extrapolated input data from the clean location were used (see text).

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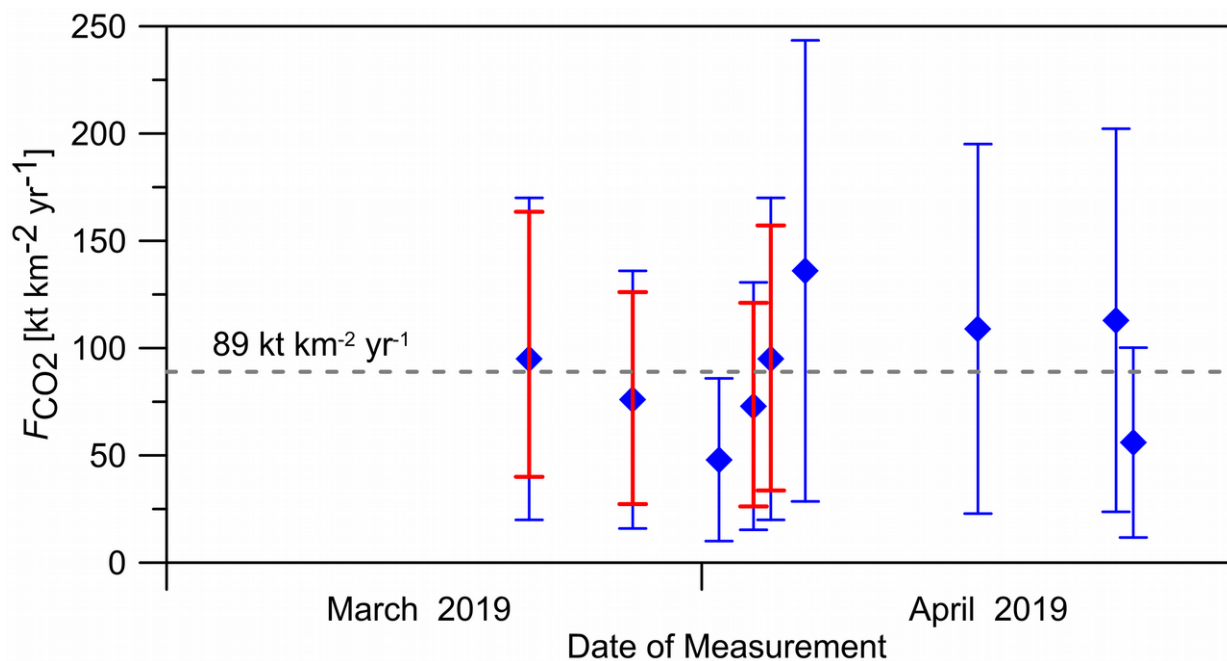
Figure 12: Daily mean values of the CO_2 area flux F obtained during the city campaign. Error bars show the uncertainties of F values estimated for the 9-day and 4-day data sets (blue and red respectively).