Validation of the capability of WRF-Chem model and CAMS to simulate near surface atmospheric CO_2 mixing ratio for the territory of Saint-Petersburg

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Why the monitoring of CO_2 urban emissions is important today?

1. CO_2 – the main anthropogenic greenhouse gas (GHG) - influences the radiation balance of the Erath leading to an increase in tropospheric air temperature

2. CO_2 content in the atmosphere keeps rising due to man-made activity

3. Megacities have essentially determined (~70%) of the anthropogenic CO_2 emissions in the last few decades

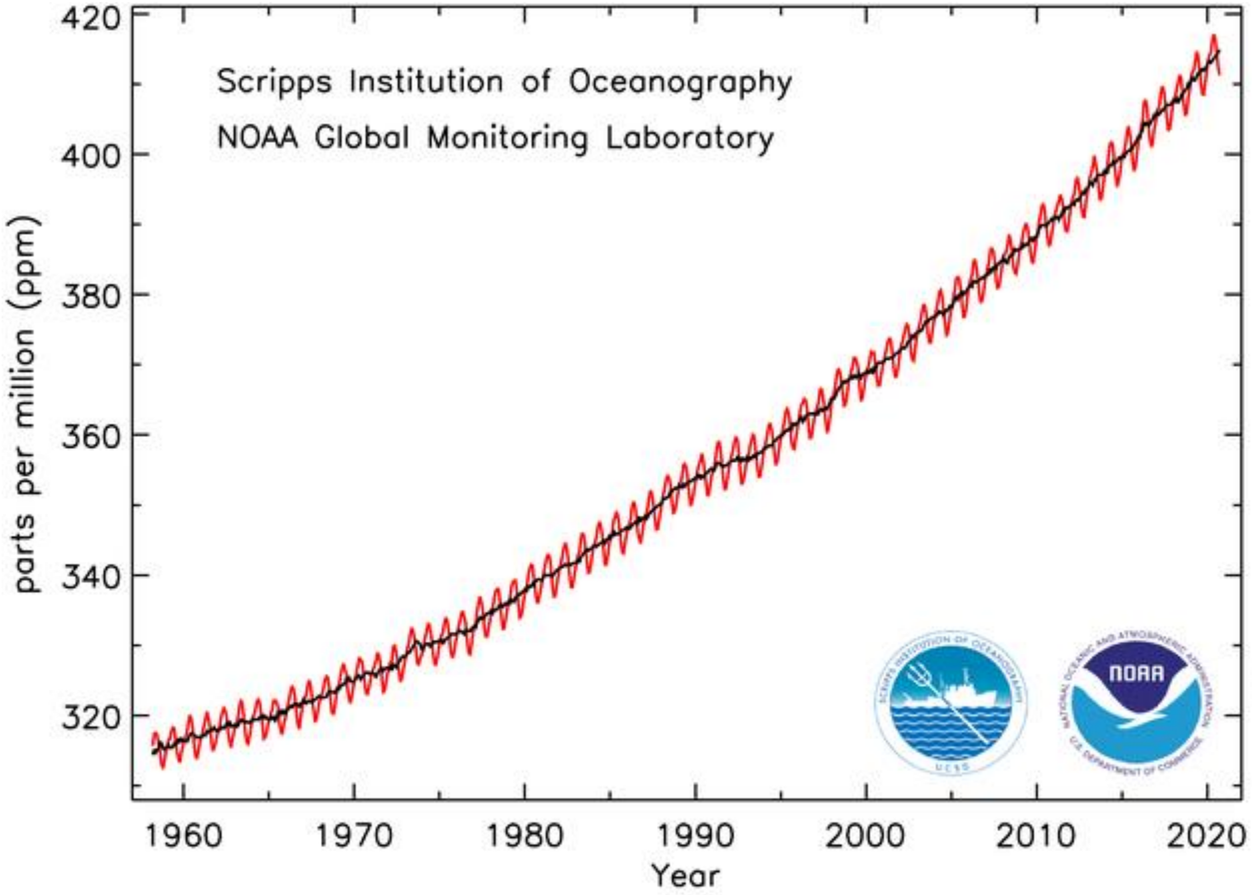

Fig.1 Trend of near-surface atmospheric CO_2 mixing ratio for the period 1958-2020 at Mauna Loa Observatory, Hawaii, USA

Original from https://www.esrl.noaa.gov/gmd/ccgg/trends/

How can we estimate CO_2 urban emissions?

1. GHGs Inventories (Bottom-up)

- Based on documented data of potential CO_2 sources (amount of fossil fuel used, number of active cement manufactures, etc.)

<u>Inaccuracies can reach 50% and more!</u>

2. Inverse modelling (Top-down)

Observation data

- In-situ
- Remote

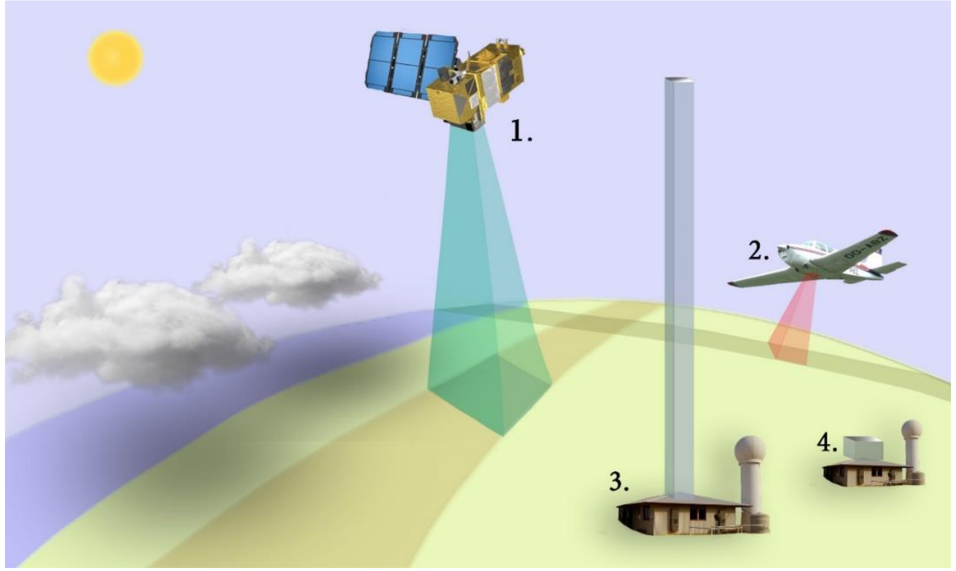

Fig.2 Main methods of atmospheric observations
(1 – satellite, 2 – airplane, 3 – remote ground-based, 4- in-situ)

+ Modelling of CO_2 transport in the atmosphere

- 3-D numerical chemistry transport modelling;
- Lagrangian dispersion models;
- Box models;
- Others

+ A priori information

- CO_2 sources/sinks
- Initial and boundary conditions

Methods: CO_2 in-situ observations in Peterhof

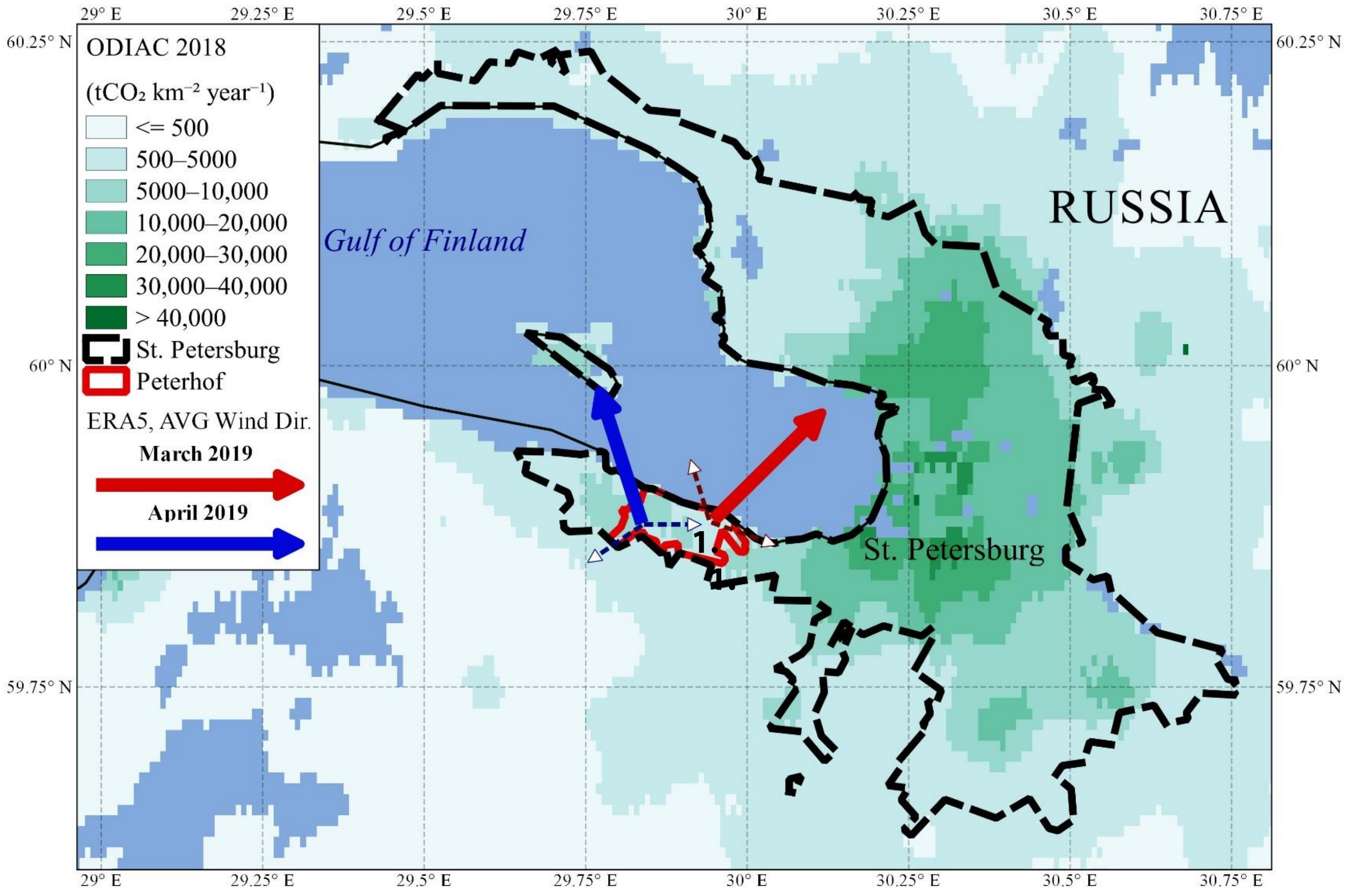

Fig.3 Territory of Saint-Petersburg (black dashed line) and Peterhof (1)

Instrument:

- Los Gatos Research Greenhouse Gas Analyzer (LGR GGA-24-r-EP) at SPbU Faculty of Physics.

Station and observation data:

- Coordinates - 59.88°N, 29.83°E;
- Height – ~ 30 m AMSL (~ 6 m AGL);
- Measurement error - 50-150 ppb depending on accumulation time (100-5 s respectively);
- Data processing – averaging of 15-minutes medians.

Methods: CO_2 in-situ observations in Peterhof

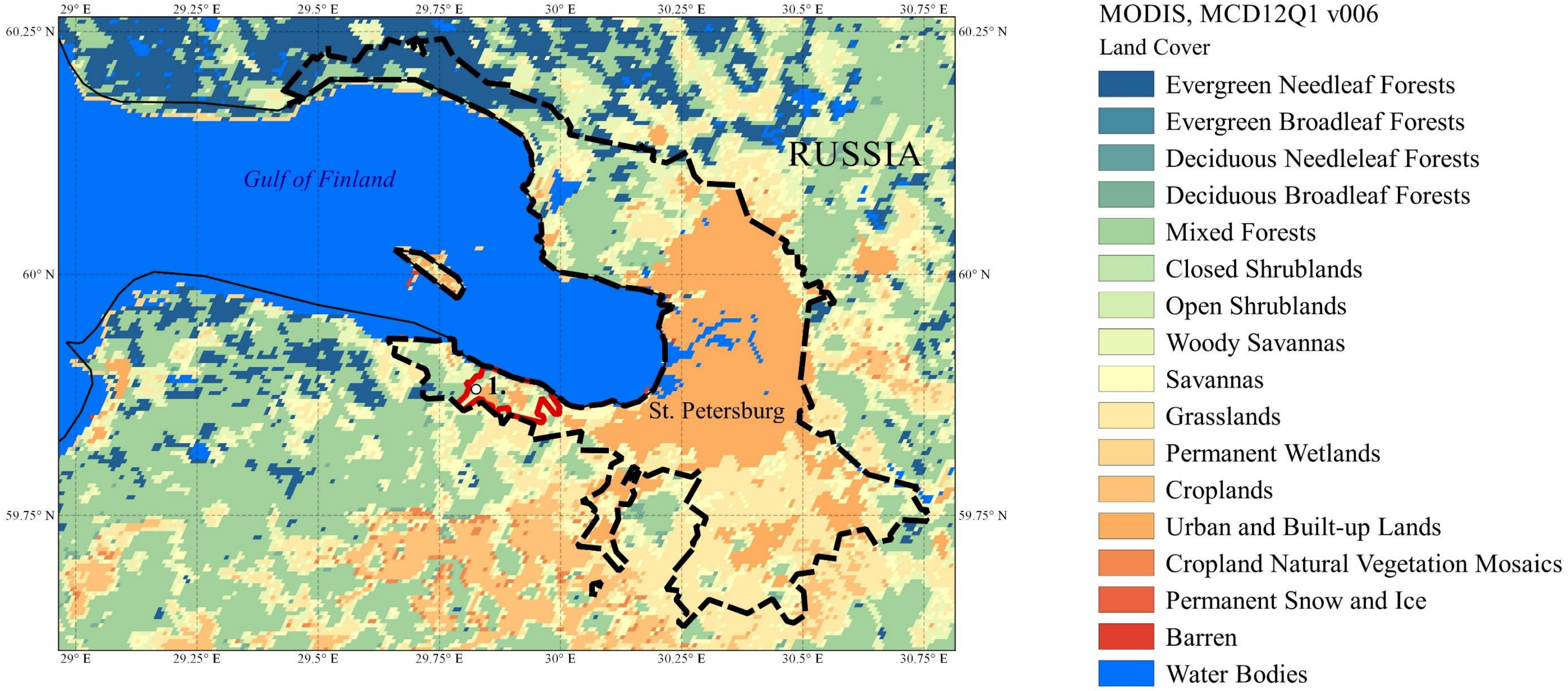

Fig.4 Territory of Saint-Petersburg (black dashed line) and Peterhof (1); the white circle depicts the position of the Peterhof measurement station

Methods: numerical modelling of CO_2 atmospheric transport

Copernicus **A**tmosphere **M**onitoring **S**ervice (CAMS)

- Product type - reanalysis and analysis of the spatio-temporal variation in CO_2 on a global scale;
- Horizontal resolution – 1.9 and 3.8° (reanalysis), 0.15° (analysis); Data assimilation – only reanalysis.

Weather **R**esearch and **F**orecasting – **Chem**istry (WRF-Chem)

- Numerical weather prediction and atmospheric chemistry transport model on regional scale;
- Spatial resolution – from tens to ~ 1 km;
- Ability to consider time-varying fluxes of gases.

Methods: WRF-Chem modelling

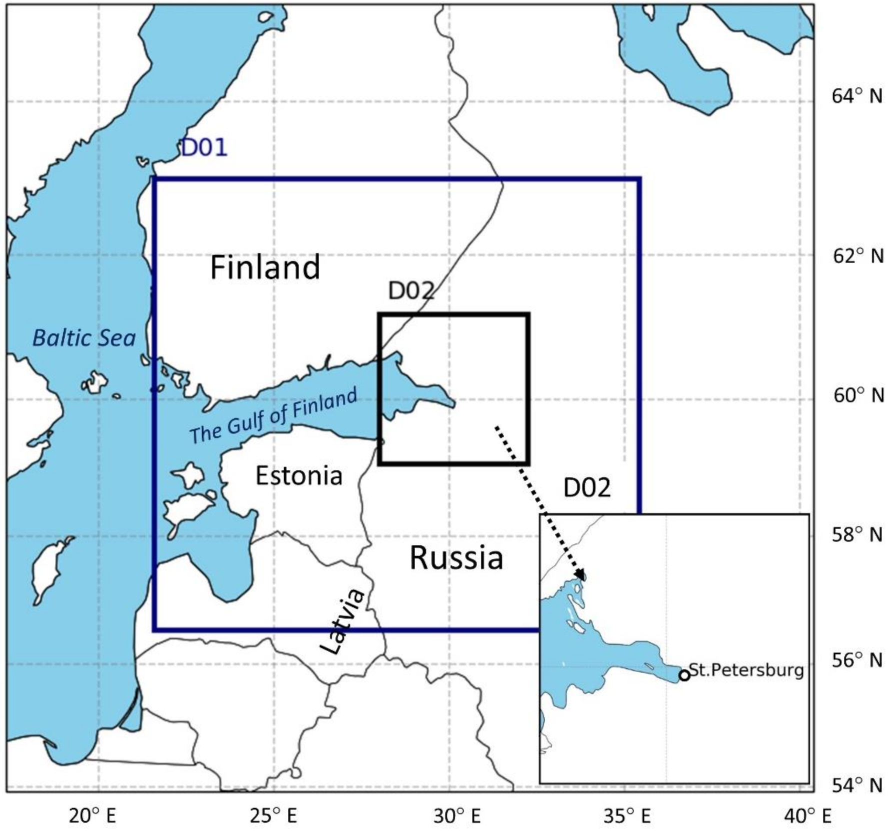

Fig. 5. Modelling domains

Table 1. The main characteristics of the WRF-Chem runs

No of WRF-Chem Model Run		1a	1b	2a	2b	3a	3b
Horizontal resolution		D01—9 km, D02—3 km					
Vertical resolution		39 hybrid vertical layers (up to 50 hPa)					
Initial and boundary conditions	**Meteorology**	GFS ANL (0.5°, 3 h)					
	Atmospheric CO_2 mixing ratio	CAMS Global analysis of CO_2 (0.15°, 6 h)					
Length of simulation		March 2019	April 2019	March 2019	April 2019	March 2019	April 2019
CO_2 sources and sinks	**Anthropogenic emissions (1)**	ODIAC 2018, diurnal temporal variation				ODIAC 2018, no temporal variation	
	Biogenic fluxes (2)	VPRM, temporal variation—3 h		No biogenic fluxes		No biogenic fluxes	

1. **O**pen-source **D**ata **I**nventory for **A**nthropogenic **C**O_2 (**ODIAC**) – CO_2 anthropogenic emissions inventory of high spatial resolution (~1 km) (*Oda & Maksyutov, 2015*).

2. **V**egetation **P**hotosynthesis and **R**espiration **M**odel (**VPRM**) – model of CO_2 biogenic fluxes (*Mahadevan et al., 2008*).

CAMS vs in-situ measurements of CO_2

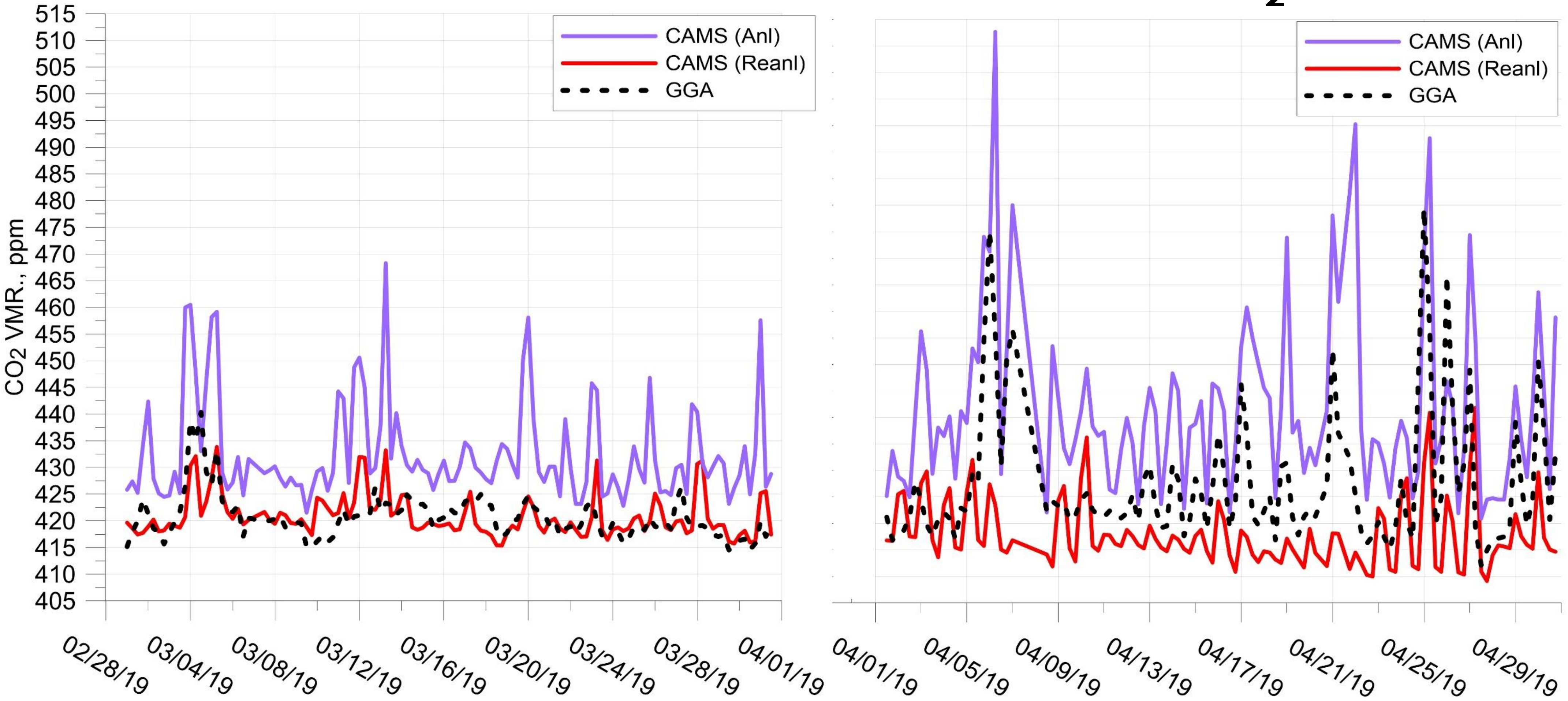

Fig.6 Temporal variation (6 h) in the surface atmospheric CO_2 mixing ratio according to the CAMS and in-situ observation data in Peterhof in March (left) and April (right) 2019

CAMS vs in-situ measurements of CO_2

Table 2. Statistical characteristics of the difference between the CAMS and observation data for Peterhof in March and April 2019; Reanl: reanalysis; Anl: analysis

Period	March 2019		April 2019	
	GGA–CAMS (Reanl)	GGA–CAMS (Anl)	GGA–CAMS (Reanl)	GGA–CAMS (Anl)
M, ppm	–0.1	**–11.8**	9.4	**–14.3**
RMSD, ppm	4.2	**14.4**	15.1	**19.0**
R	0.46 ± 0.16	0.52 ± 0.15	0.37 ± 0.18	**0.69** ± **0.14**

CAMS Reanalysis – observation assimilation
CAMS Analysis – **no** observation assimilation

WRF-Chem vs in-situ measurements of CO_2

Fig.7 Temporal variation (1 h) in the surface atmospheric CO_2 mixing ratio according to the WRF-Chem runs and in-situ observation data (top) and daily average wind direction in near-surface level according to ERA5 and WRF-Chem data (bottom) in Peterhof in March (left) and April (right) 2019

WRF-Chem vs in-situ measurements of CO_2

Table 3. Statistical characteristics of the difference between the WRF-Chem and observation data for Peterhof in March-April 2019; t.v. - temporal variation, const. - time constant

Period	March 2019			April 2019			March–April 2019		
GGA–WRF- Chem	t.v. Anth + Bio	t.v. Anth	Const. Anth	t.v. Anth + Bio	t.v. Anth	Const. Anth	t.v. Anth + Bio	t.v. Anth	Const. Anth
M, ppm	−1.7	−2.7	−2.7	1.3	1.2	1.0	−0.3	−0.8	−0.9
RMSD, ppm	4.7	4.6	4.6	11.5	11.4	11.6	8.7	8.6	8.8
R	0.55 ± 0.06	0.69 ± 0.05	0.70 ± 0.05	0.60 ± 0.06	0.60 ± 0.06	0.58 ± 0.06	0.61 ± 0.04	0.62 ± 0.04	0.61 ± 0.04

Statistics of the three WRF-Chem runs modelled data look pretty much the same!

WRF-Chem vs in-situ measurements of CO_2

Monthly average **diurnal variation** shows the **distinguishable differences** between **the three WRF-Chem runs**.

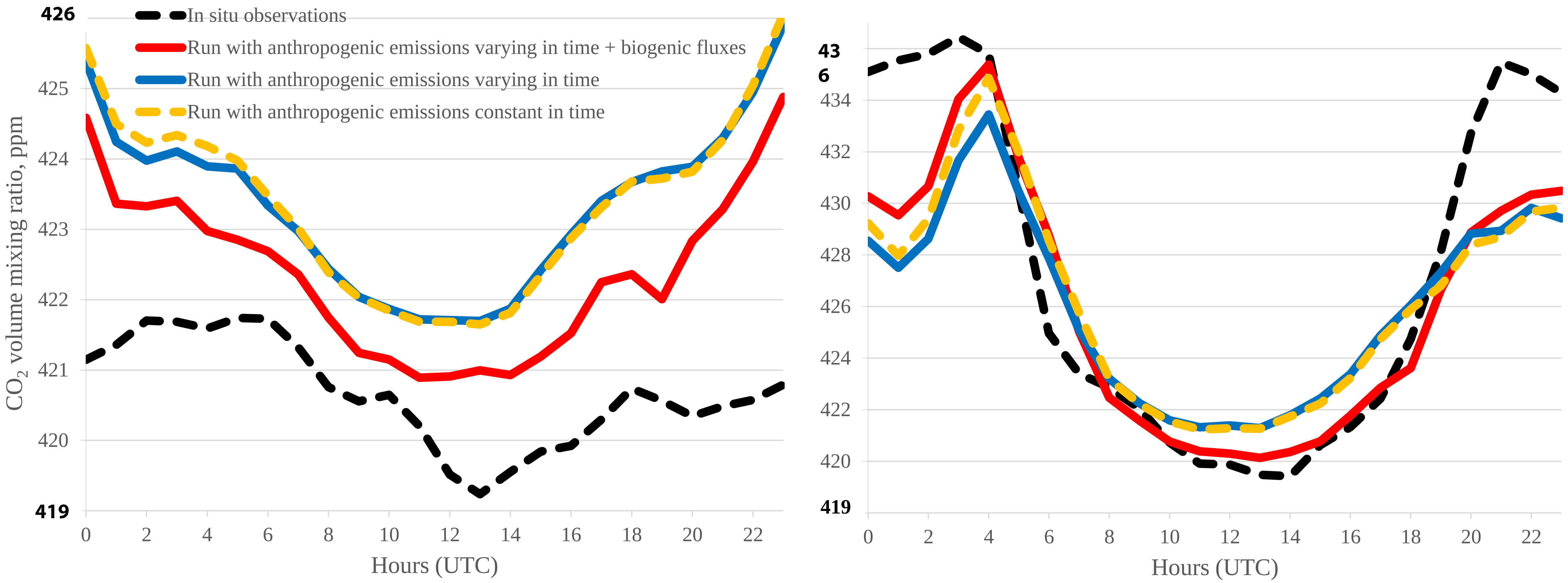

Fig.8 Monthly-averaged diurnal variation of near-surface CO_2 mixing ratio according to the WRF-Chem runs and in situ observations in Peterhof in March (**a**) and April (**b**) 2019.

<u>WRF-Chem run with **anthropogenic** and **biogenic CO_2 fluxes** had **the best fit** with the **observations**.</u>

Conclusions

1. Differences between the CAMS data and in-situ observations of CO_2 surface-level mixing ratio in Peterhof in March and April 2019 varied from 4.3 to 19.0 ppm depending on CAMS product type and meteorological conditions. The data may be used in inverse modelling of CO_2 anthropogenic emissions on the scales larger than Saint-Petersburg territory;

2. The WRF-Chem adequately simulated the temporal variation in the near-surface CO_2 mixing ratio on a high spatial resolution (3 km) in Peterhof (Saint Petersburg) in March and April 2019 - differences and correlation coefficients were in range 4.6-11.6 ppm and 0.6-0.7 respectively depending on meteorological conditions;

3. Using the biogenic CO_2 fluxes made WRF-Chem data to fit the in-situ observations a bit better;

4. According to the WRF-Chem modelling the main factors determining the near-surface CO_2 mixing ratio in Peterhof in March and April 2019 were the wind in the surface layer and the anthropogenic CO_2 emissions from the Saint Petersburg urban area;

5. To investigate whether the WRF-Chem model is suitable for the inverse modelling of the CO_2 anthropogenic emissions from the territory of Saint Petersburg, the analysis of modelled CO_2 total column is needed.

Reference

Nerobelov G, Timofeyev Y, Smyshlyaev S, Foka S, Mammarella I, Virolainen Y. Validation of WRF-Chem Model and CAMS Performance in Estimating Near-Surface Atmospheric CO_2 Mixing Ratio in the Area of Saint Petersburg (Russia). *Atmosphere*. 2021; 12(3):387. https://doi.org/10.3390/atmos12030387

Thank you!

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