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Carbon Atmospheric Tracer Research to Improve Numerics and Evaluation

SCALE DEPENDENCIES IN URBAN CO_2 INVERSIONS CONSTRAINED BY SATELLITE REMOTE SENSING MEASUREMENTS

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IWGGMS-21: June 12th , 2025

ICOS Integrated Carbon Observation System

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Challenges: Sources of errors in atmospheric inversion systems

Systematic errors in atmospheric transport have been identified as the main source of uncertainty in atmospheric inversion systems in Global Carbon Budget (Friedlingstein et al., 2023)

Sources of uncertainty in atmospheric transport modelling:

Advection schemes and resolution: mass conservation and numerical diffusion (e.g. Agusti-Panareda et al., 2017, Eastham & Jacob, 2017)	**Convective transport** (Schuh and Jacobson, 2023)	**Turbulent mixing** (e.g. Kretschmer et al., 2012)	**NWP analyses** (largest in boundary layer and stratosphere) (e.g. Yu et al., 2018, Zhang et al., 2021)

CATRINE PROJECT

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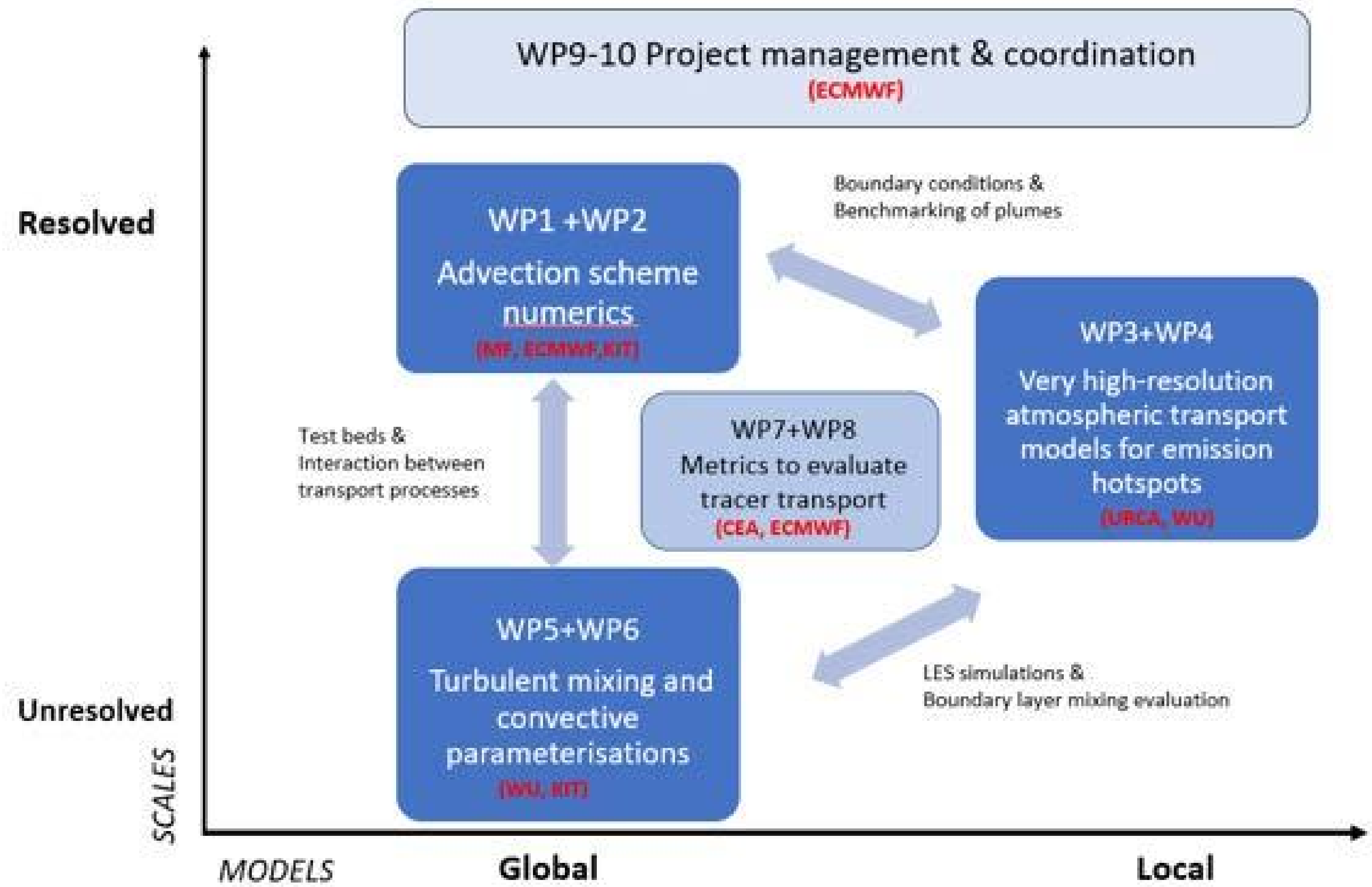
CATRINE: Carbon Atmospheric Tracer Research to Improve Numerical schemes & Evaluation. The project aims to evaluate and improve accuracy of numerical schemes for tracer transport in Copernicus Atmosphere Monitoring Service (CAMS).



Partners	Country
ECMWF	International
CEA	France
METEO-FRANCE	France
WU	Netherlands
KIT	Germany
UH	Finland
URCA	France
UFR	Germany

High-resolution simulation models

- Models inter-comparison:
  - Micro-HH, (Wageningen University)
  - WRF-LES, (Université de Reims Champagne Ardennes)
  - PALM, (University of Helsinki)
- At high resolution < 500 m
- Testing Boundary Conditions
  - From CAMS and ERA5
  - From WP1/2
- **My contribution will focus mainly on the use of WRF-LES model**

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WRF-LES simulation setup over Paris

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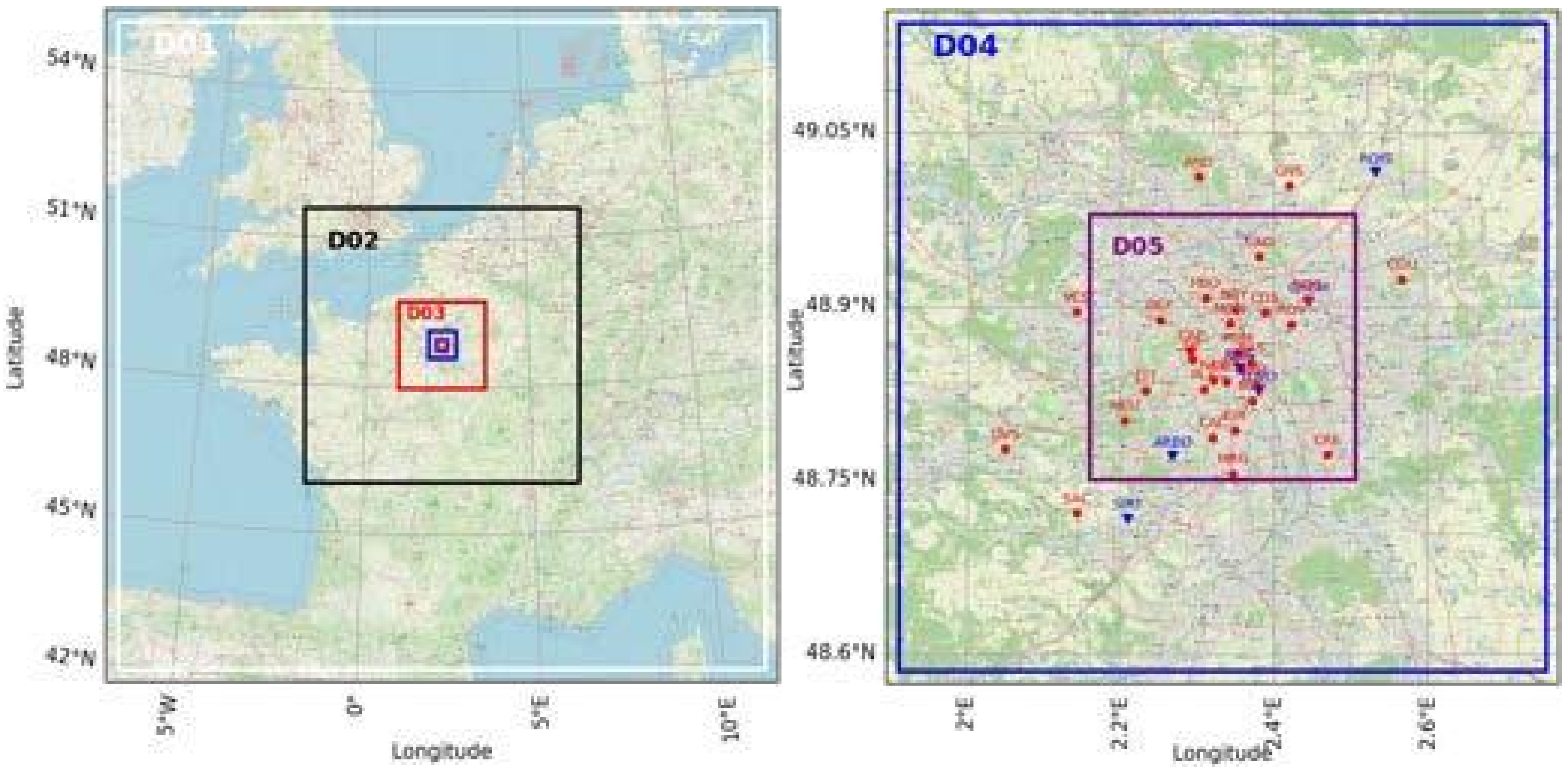
5 nested domains	D01	D02	D03	D04 -LES	D05-LES
Horizontal resolution (m)	8100	2700	900	300	100
Grid number	182 x 182	232 x 232	220 x 220	208 x 208	256 x 256
Vertical level number	51				



The red dots represent CO_2 and XCO_2 in-situ station locations, while the blue triangles denote wind lidar profiler positions.

Initial and lateral boundary data from **ERA5** and **CAMS**

Topography: **SRTM** 1 arcs(~30m), 3 arcs(~90m) and **GMTED** 30 arcs (~1km)

Land use data: Hybrid **100-m CGLC-MODIS-LCZ**

Inventory data from **TNO** and **Airparif.**

SRTM: Shuttle Radar Topography Mission
GMTED: Global Multi-resolution Terrain Elevation Data
ERA5: fifth generation ECMWF atmospheric reanalysis
MODIS: Moderate Resolution Imaging Spectroradiometer
CGLC-MODIS-LCZ: Copernicus Global Land Service Land Cover-MODIS-Local Climate Zone

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WRF vs weather stations

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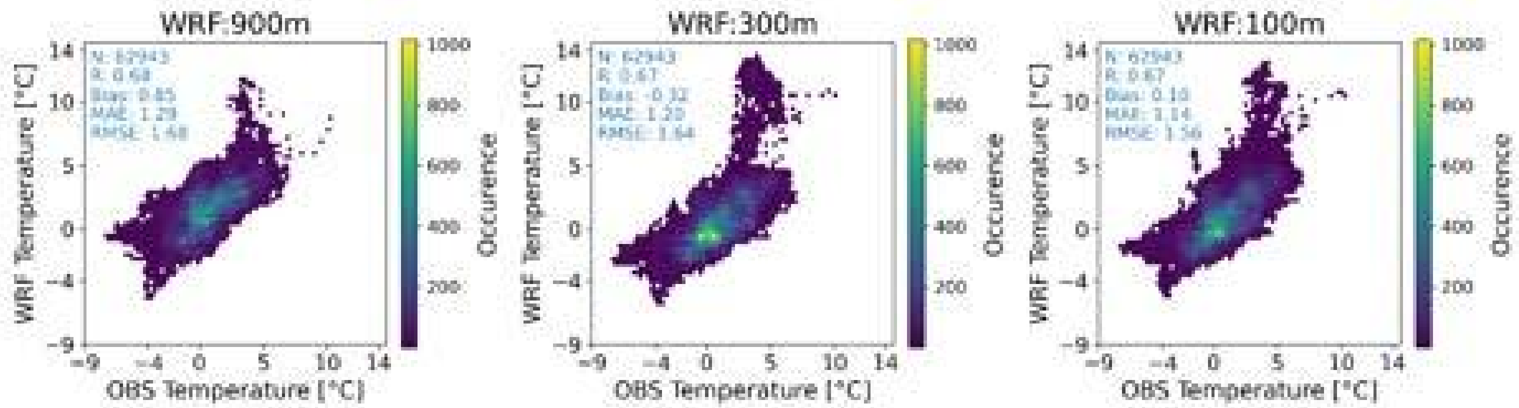
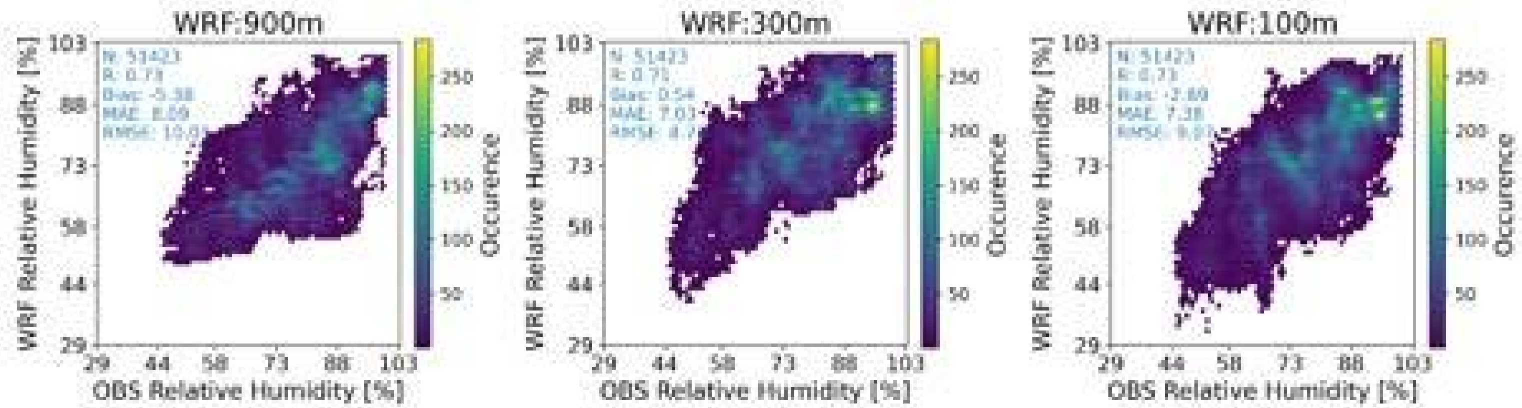
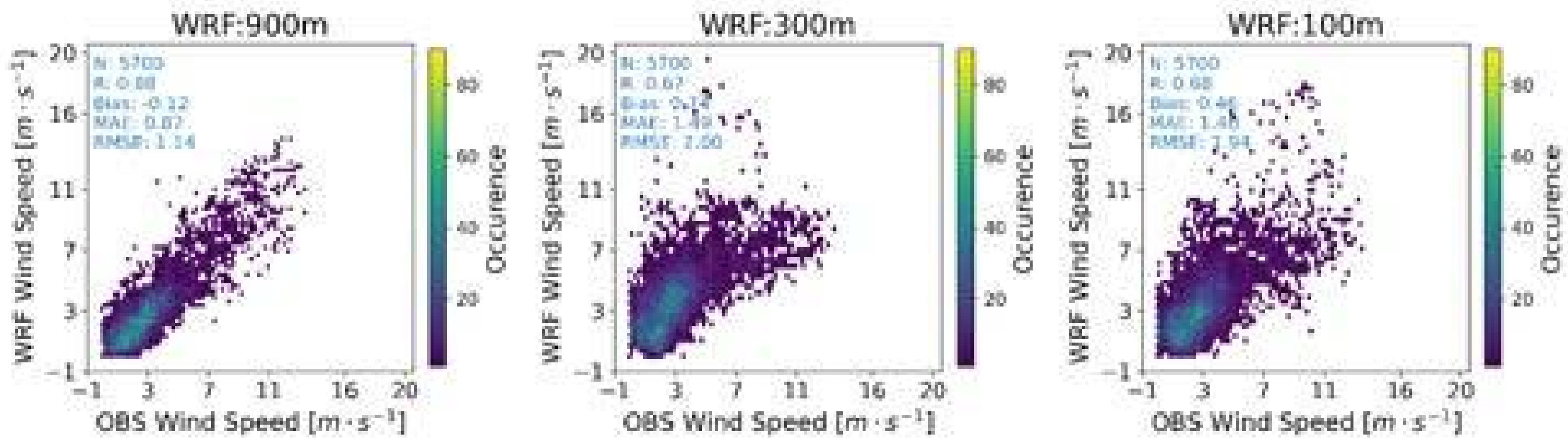
Temperature



Humidity



Wind speed



The IOT weather stations network used here, around 40 stations over WRF:100m domain, available from the AERIS data portal (https://www.aeris-data.fr/)

- The WRF model shows slight improvements in temperature and relative humidity accuracy with increasing resolution, as seen in lower bias, MAE, and RMSE, though correlation remains similar across all resolutions.

- However, for wind speed, the coarser 900m resolution outperforms finer resolutions, showing the highest correlation and least error, while 300m and 100m simulations exhibit greater scatter and overestimation at higher wind speeds.

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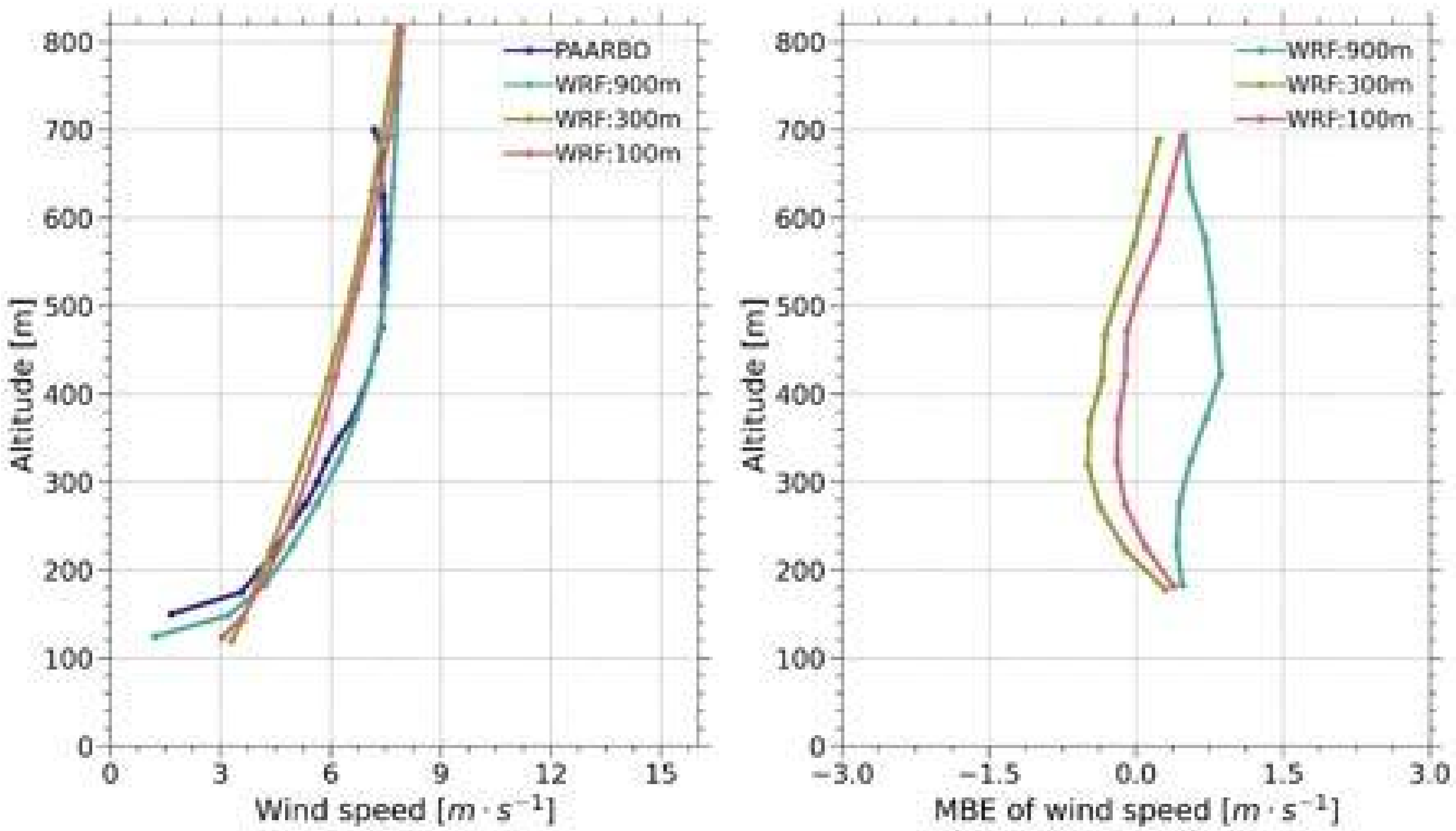
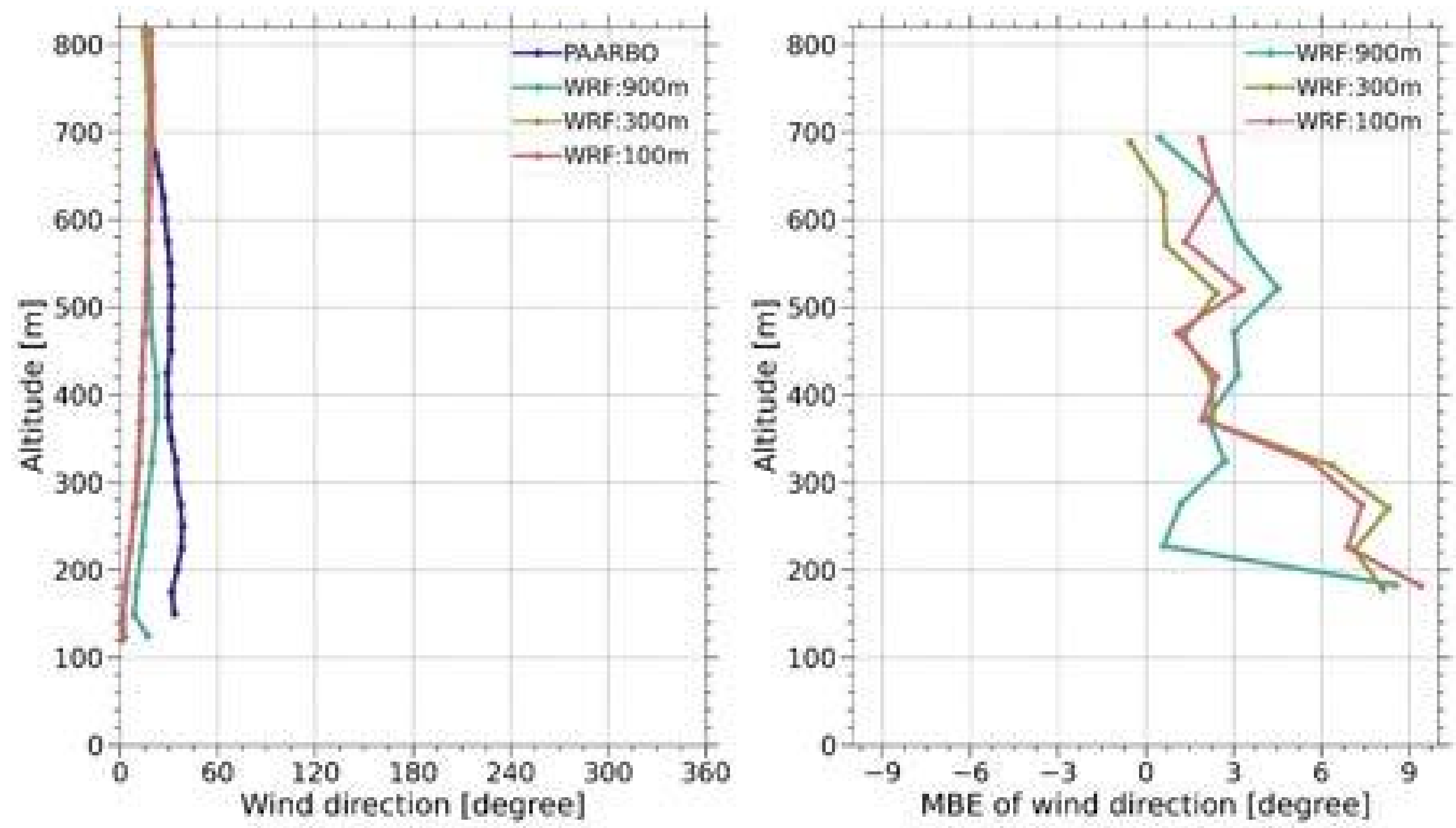
WRF vs LIDAR at PAARBO

Mean and MBE of wind speed



Mean and MBE of wind direction



- The wind speed MBE indicates a slight overestimation at all levels for the 900 m run,
- While the 300 m and 100 m runs show more vertical variability, alternating between over and underestimation.
- Mean wind direction differences decrease with altitude across all resolutions.

WRF CO2 for 2024-01-11 at 13UTC at 10m above the surface

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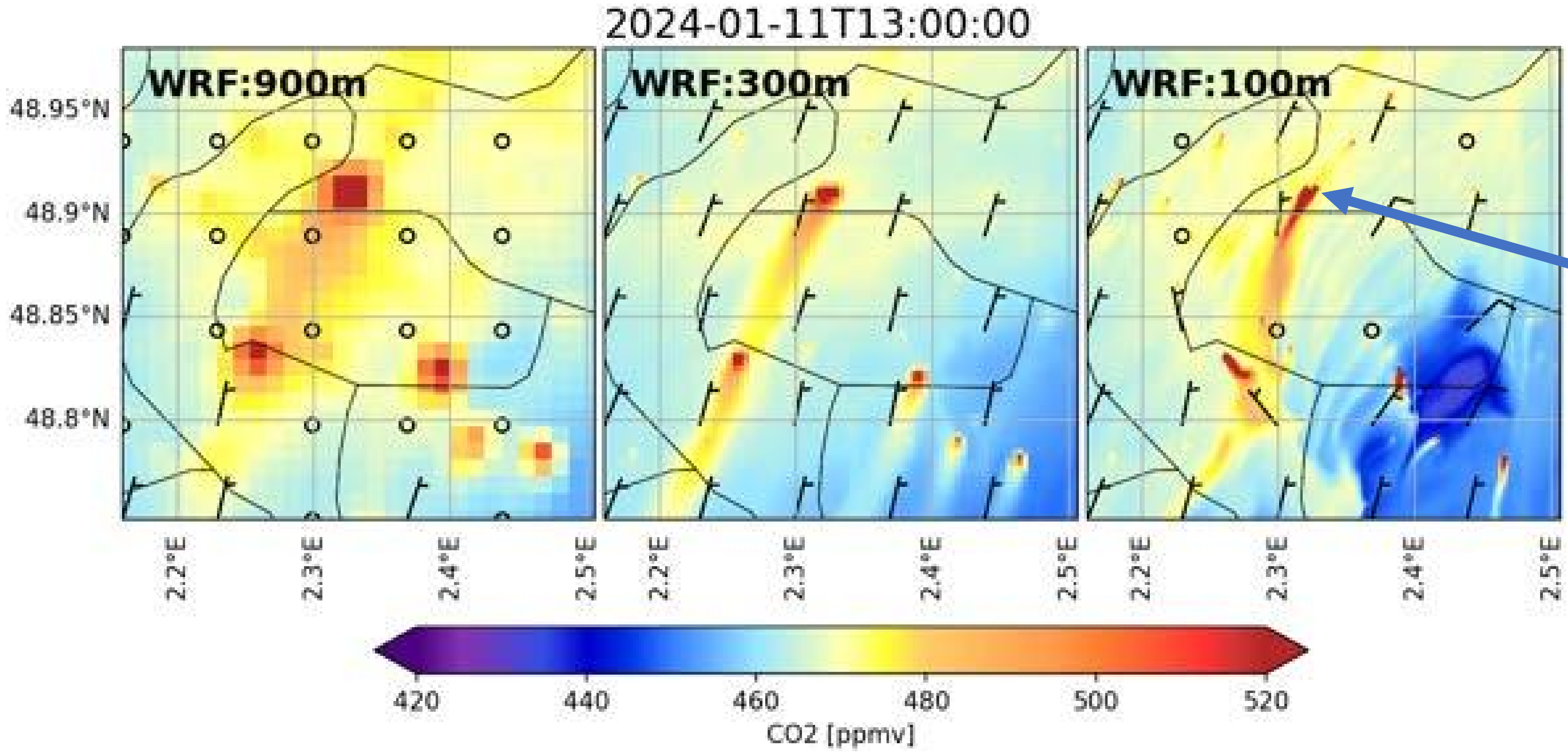

- At 100 m resolution, **two distinct point sources** are clearly resolved, whereas they appear merged into one at 900 m
- Finer resolutions better capture localized features that are smoothed out at coarser scales.

- In the **low-resolution domains**: the plume appears larger and less concentrated
- In the **high-resolution domain**: the plume appears smaller, more concentrated, and better defined.
- **Local wind patterns** influence the dispersion of CO_2, resulting in differences across the various resolutions.

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CO2 concentration: WRF vs Picarro/Midcost

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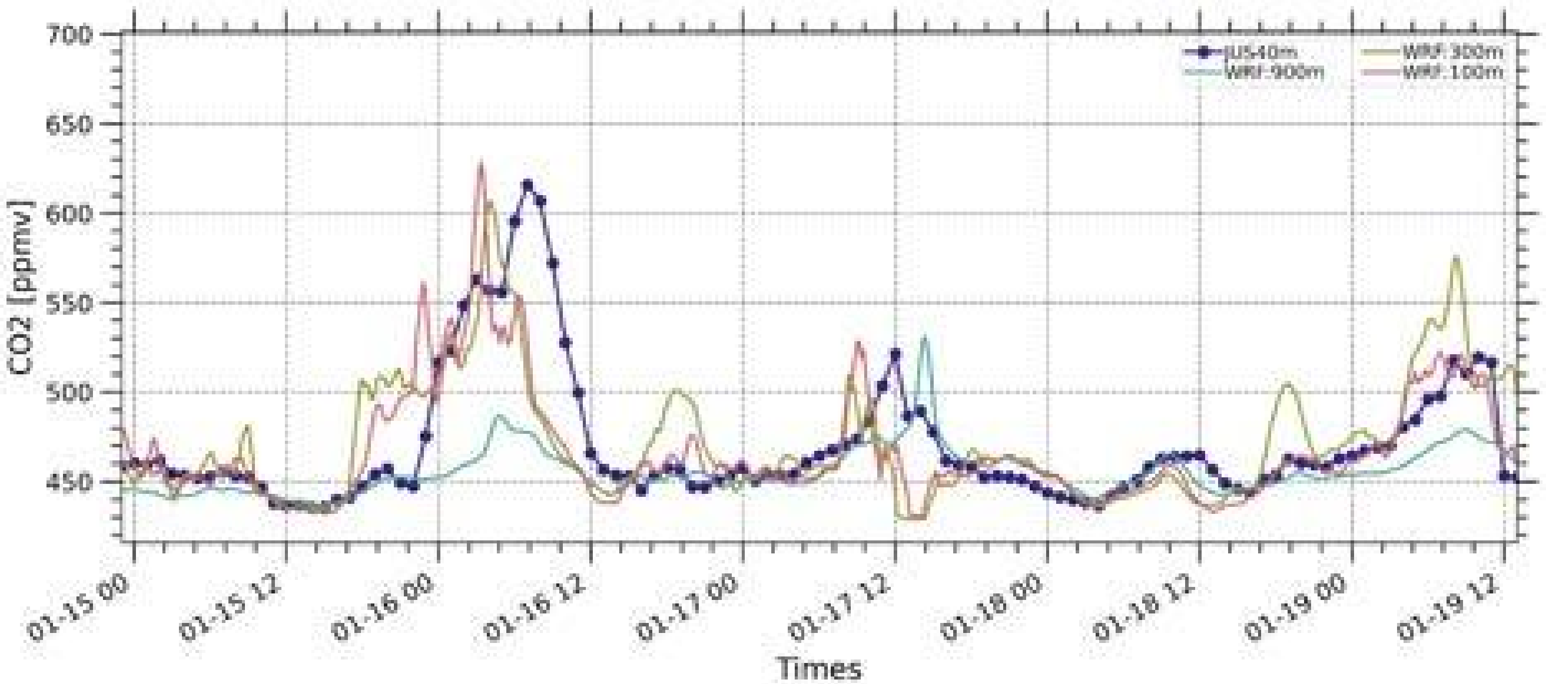
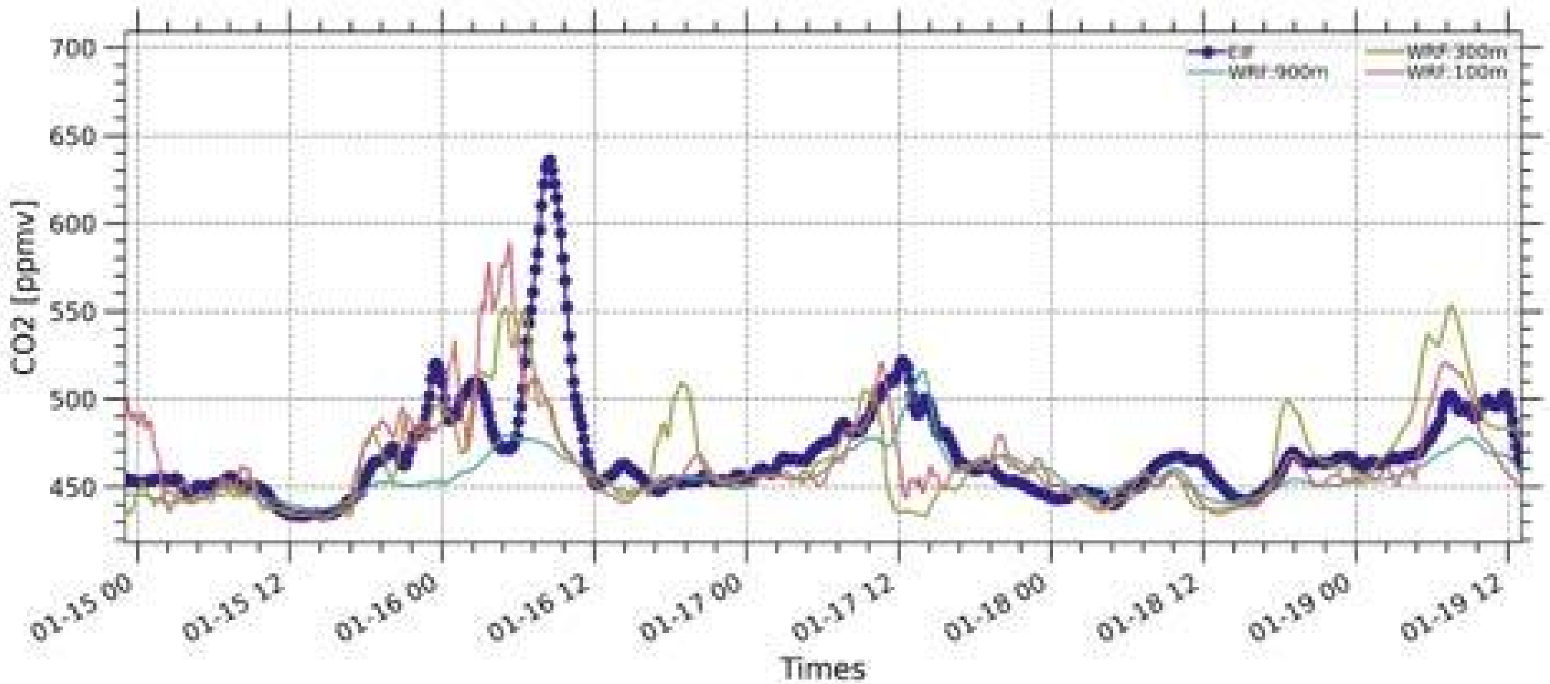


Time series of CO2 concentration: WRF vs Picarro at Jussieu



Time series of CO2 concentration: WRF vs Midcost at the Eiffel Tower

- The 100 m resolution run captures the high CO_2 concentration event on January 16 at both Jussieu and the Eiffel Tower, which is missed at 900 m, highlighting the ability of high-resolution simulations to detect sharp, localized peaks.

- However, the 100 m run occasionally overestimates concentrations during periods without observed peaks, suggesting increased sensitivity to local emissions or model dynamics at finer scales.

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Daytime CO2 concentration: WRF vs Picarro

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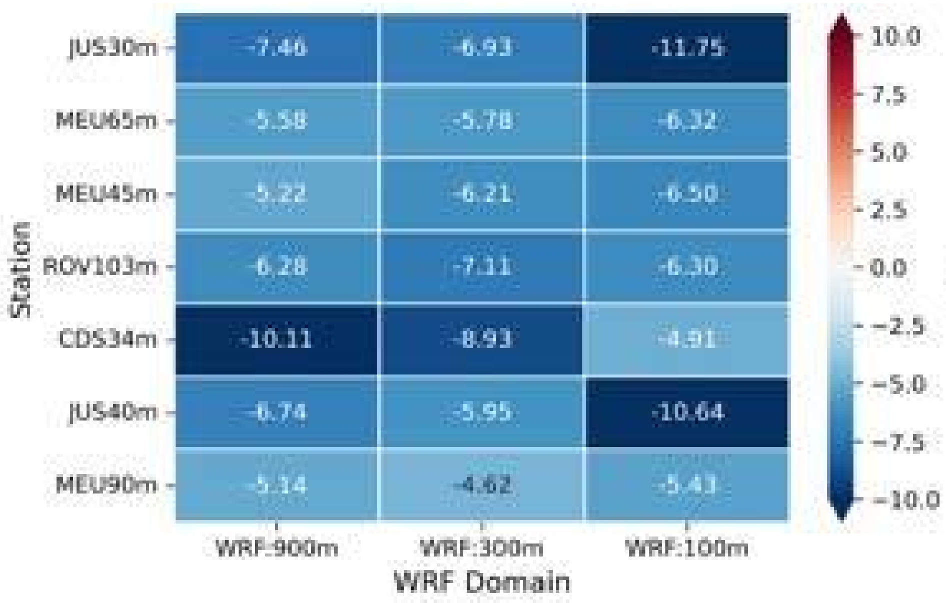
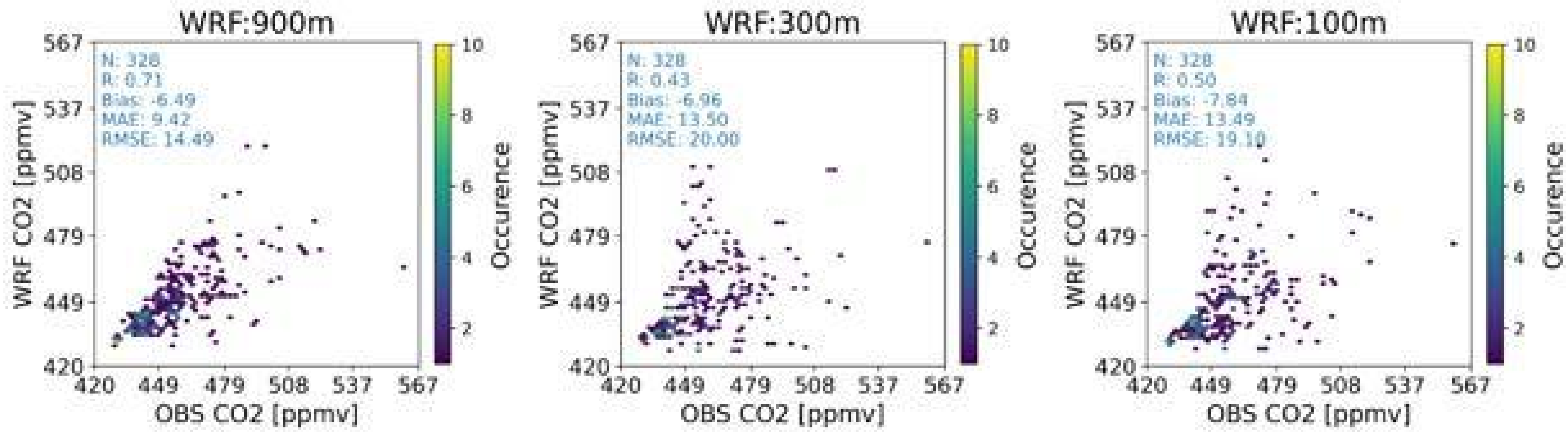
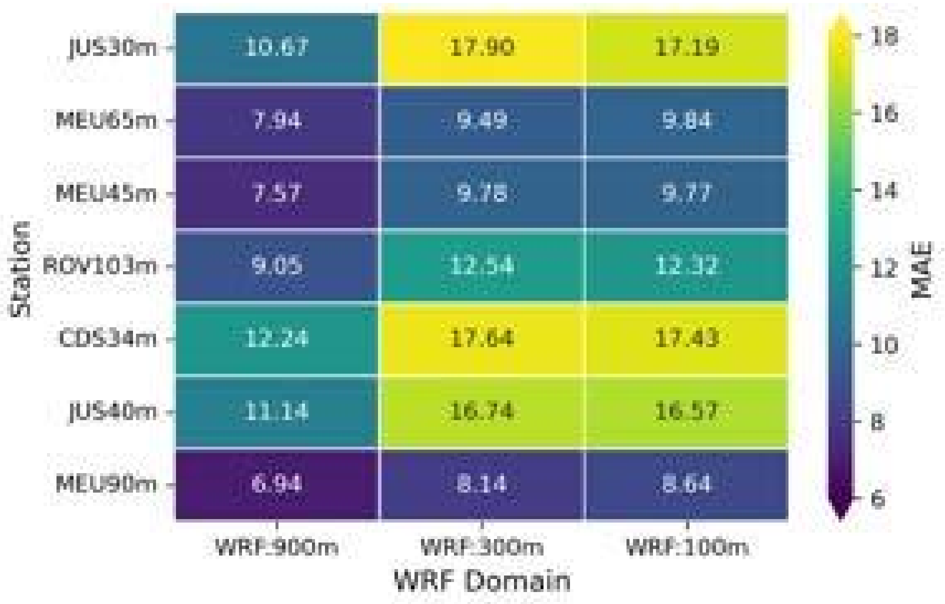
MBE across Stations and WRF domains





MAE across Stations and WRF domains



- A consistent negative bias across all resolutions
- The 900 m run performs better statistically because its coarser resolution smooths CO_2 fields, providing more consistent values that align better with station observations, even if localized peaks are missed.
- In contrast, the finer 300 m and 100 m runs capture more spatial detail, but if a station is not directly located within a high-concentration area, the model may underestimate or overestimate compared to observations, leading to greater variability and error.

WRF XCO2: 100m and 300m aggregated at 900m

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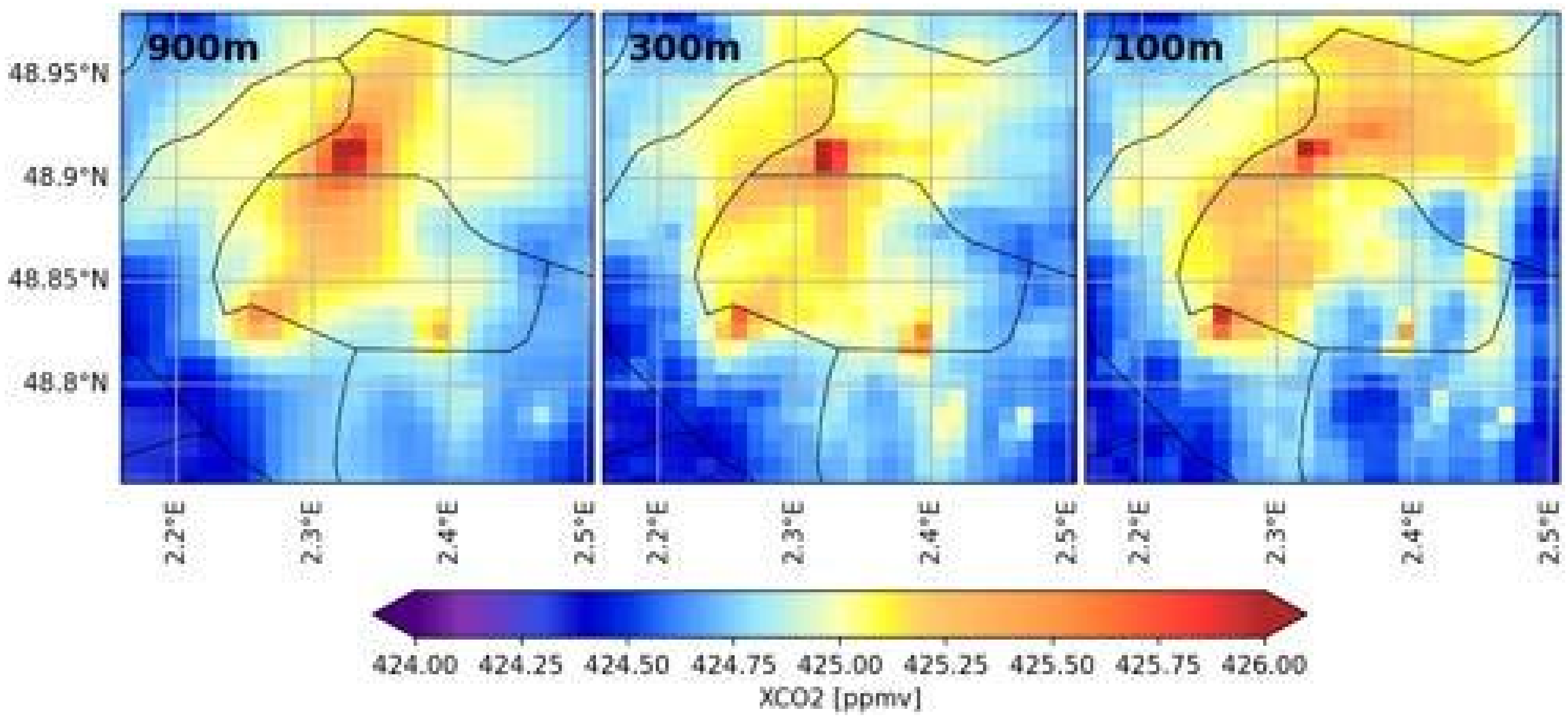
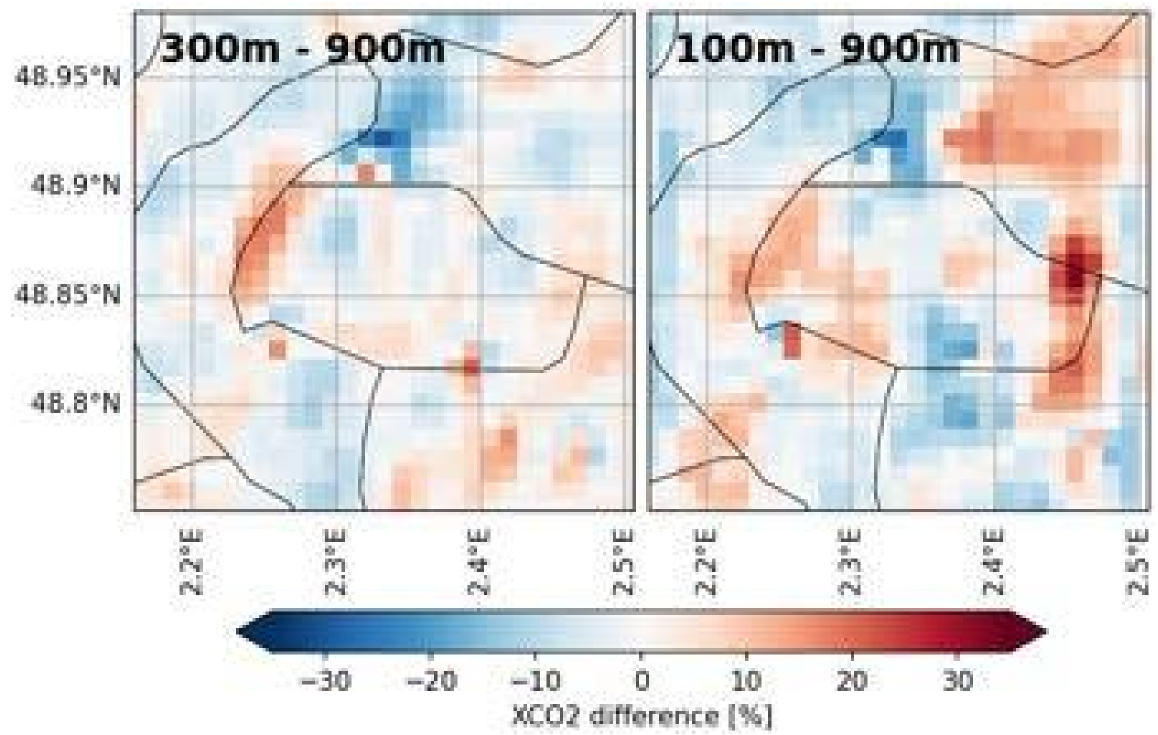
Average for the 10 days, for 13-14h of the days



The average relative difference



- Aggregating 100 m and 300 m XCO_2 to 900 m shows differences up to 35%
- Also reveals differences in plume shape and spatial distribution.
- Aggregated outputs do not fully match native 900 m fields in magnitude or shape
- **Raises key questions:** Are these differences significant for inversion accuracy? And is 900 m resolution sufficient to represent urban CO_2 variability?

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Conclusion and Perspectives

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Conclusion

- Meteorological variables show comparable correlations across resolutions.
- High-resolution (100 m) WRF simulations better capture localized features and sharp CO_2 peak events that coarser resolutions, but 900 m resolution provides more consistent statistical performance overall.
- Aggregating fine resolution CO_2 fields to coarser grids results in differences in plume shape and magnitude, raising important questions about the impact of resolution on inversion accuracy and emission estimates.

Perspectives

- Create a pseudo-data from the high resolution and run the inversion model
- Quantify how resolution-driven differences affect inversion results
- Develop aggregation/downscaling methods to better preserve plume features
- Test approach in other cities (e.g., Tokyo) with different topography and emissions

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Thank you!

ECMWF cea METEO FRANCE WAGENINGEN UNIVERSITY & RESEARCH KIT UNIVERSITY OF HELSINKI UNIVERSITÉ DE REIMS CHAMPAGNE-ARDENNE UNI FREIBURG

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