High-resolution meteorological CO_2 enhancements of German metropolitan areas using WRF

Lukas Pilz[1], Christopher Lüken-Winkels[1], Michał Gałkowski[2], David Ho[2], Fei Chen[3] and Sanam N. Vardag[1,4]

(1) Heidelberg University, Institute of Environmental Physics, Heidelberg, Germany, (2) Max Planck Institute for Biogeochemistry, Biogeochemical Signals, Jena, Germany, (3) National Center for Atmospheric Research, Research Applications Laboratory, Boulder, United States, (4) Heidelberg Center for the Environment, Heidelberg University, Heidelberg, Germany

Introduction

With urban and metropolitan areas being significant sources of greenhouse gas emissions and the sustained trend of urbanization, metropolitan areas are becoming a large focus of mitigation efforts. This has sparked a need for reliable and well-resolved emissions information in order to inform stakeholders.

Internationally, the World Meteorological Organization's Integrated Global Greenhouse Gas Information System (IG3IS) framework is coordinating the push to improve emissions inventories reported to the United Nations Framework Convention on Climate Change (UNFCCC) by states. For Annex-I countries like Germany, it recommends to establish observations-based monitoring systems. The joint research project responsible for implementing Germany's contribution to the IG3IS is called Integrated Greenhouse Gas Monitoring System (ITMS).

Within the scope of this project, we are focussing on optimizing urban sensor networks for CO_2. Our first step is generating realistic atmospheric transport using the WRF model. In order to find a good simulation configuration for realistic simulations, we conducted sensitivity studies. We then used the best configuration in order to simulate one full year of CO_2 and CO concentrations. We compare this simulation with CO_2 concentration measurements of the ICOS network.

References

Demuzere, Matthias, et al. "A global map of local climate zones to support earth system modelling and urban-scale environmental science." Earth System Science Data 14.8 (2022): 3835-3873.
Taylor diagram adapted from Copin, Y. (2012). Taylor diagram for python/matplotlib (2018-12-06). DOI: doi.org/10.5281/zenodo.5548061
Breuer, Hajnalka. (2021). CORINE dataset for WRF-NoahMP model (v4.3, v4.2) [Data set]. DOI: 10.5281/zenodo.4432128
Copernicus Climate Change Service (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47
ICOS Atmospheric CO_2 data products DOI: 10.18160/FZ9P-5KQD, 10.18160/FZ9P-5KQD

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Acknowledgements

This work is part of the joint project ITMS, funded by the German Federal Ministry of Education and Research (BMBF) under reference number 01LK2102D. This work used resources of the Deutsches Klimarechenzentrum (DKRZ), granted by its Scientific Steering Committee (WLA) under project IDs bb1170 and bm1400. The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

Sensitivity Studies to determine optimal simulation configuration


Map data: (C) OpenStreetMap contributors, SRTM | Map style: (C) OpenTopoMap (CC-BY-SA)

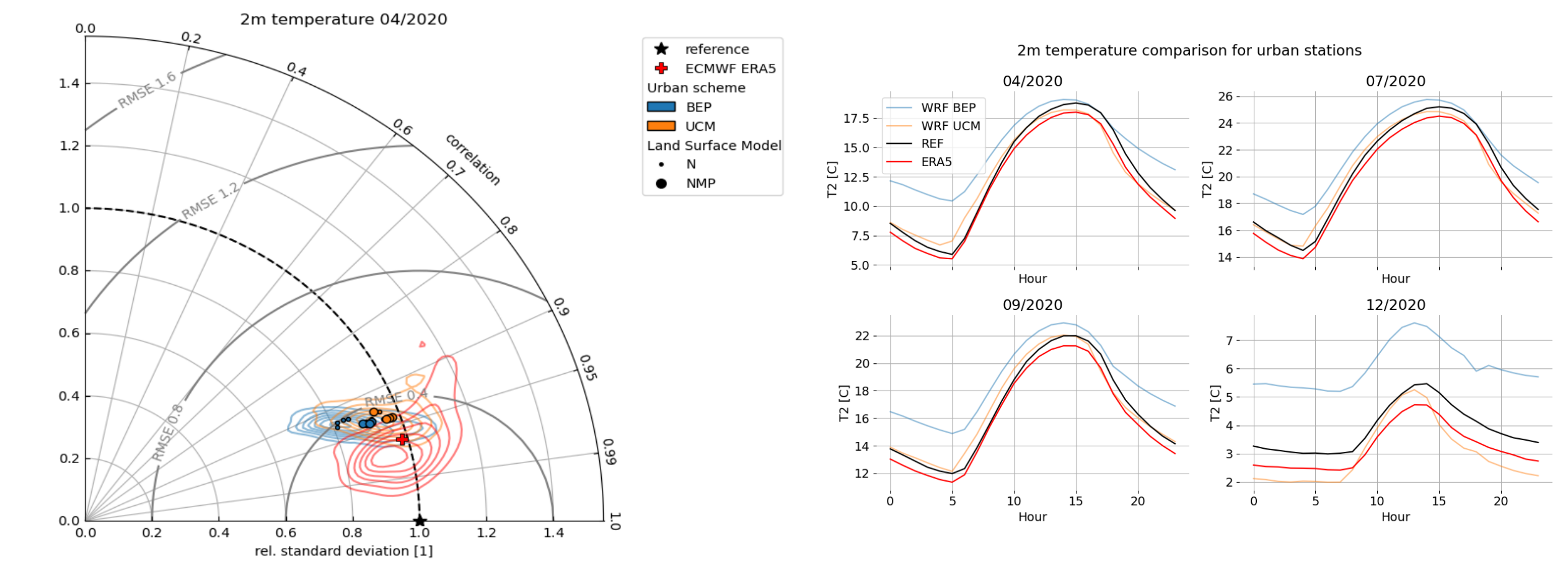
WRF configuration:
- 3 domains (25, 5, 1km) focussing on Rhine-Neckar region
- 42 vertical layers, 14 layers below 1.5km
  - BEP: lowest level @15m
  - UCM: lowest level @90m
- 3 hourly GFDDA to ERA5 data, re-initialization every 7 days
- high resolution input data (CORINE + LCZ landuse [Breuer, 2016; Demuzere, 2022], COP DEM topography)

Sensitivity studies:
- 16 combinations of parameters investigated:
  - PBL scheme (Bou-Lac, MYJ, YSU)
  - LSM (Noah, Noah MP)
  - SL model (MO, MM5)
  - URB model (UCM/BEP parametrization)

Time period:
- April, July, September, December 2020

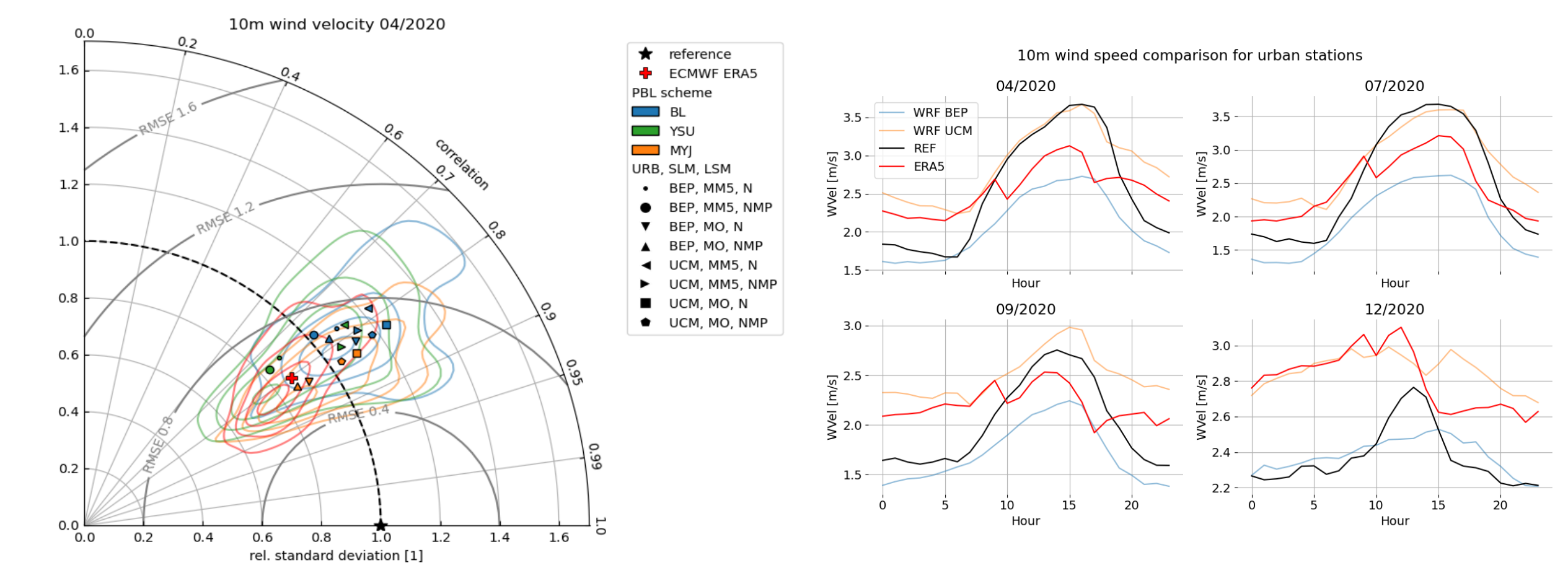
Reference data:
- 19 German Weather Service (DWD) stations
- 2 radiosonde stations

2m temperature



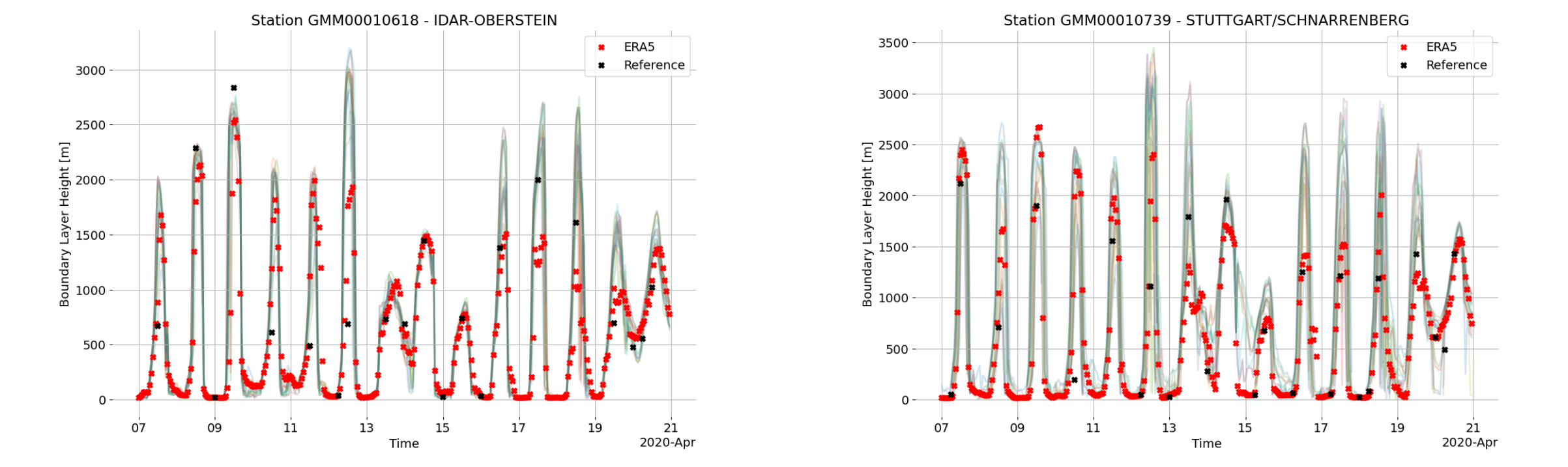
Findings:
- In general, overestimation of 2m temperature by BEP (especially during night and winter)
- ERA5 outperforms UCM and BEP
  - Bad performance at Kleiner Feldberg/Taunus (ID 2601) and Stötten (ID 4887)
- Better performance of UCM vs. BEP and Noah MP vs. Noah
- MAB of best WRF configuration vs. ERA5
  - Config: UCM, YSU, NMP, MM5
  - WRF: 1.7, 1.4, 1.5, 1.3 °C
  - ERA5: 1.4, 1.3, 1.3, 1.0 °C

10m wind velocity



Findings:
- In general, underestimation of 10m wind velocity by BEP (esp. during day)
- WRF outperforms ERA5
  - Especially diurnal cycle is better
- Better performance of MYJ vs. YSU and BL and MO vs. MM5
- MAB of best WRF configuration vs. ERA5
  - Config: UCM, MYJ, NMP, MO
  - WRF: 0.9, 0.8, 0.9, 1.0 m/s
  - ERA5: 1.0, 0.9, 0.9, 1.0 m/s

Planetary boundary layer height



Findings:
- PBL heights match reasonably well
- Some differences possibly attributable to timing issues
- Overall larger errors at Stuttgart/Schnarrenberg
- MAB of best WRF configuration vs. ERA5
  - Config: UCM, MYJ, N/NMP, MO/MM5
  - WRF: 252, 241, 196, 153 m
  - ERA5: 186, 196, 148, 115 m

Best configuration: UCM, MYJ, NPM, MO

One year of CO_2 concentrations for German metropolitan areas

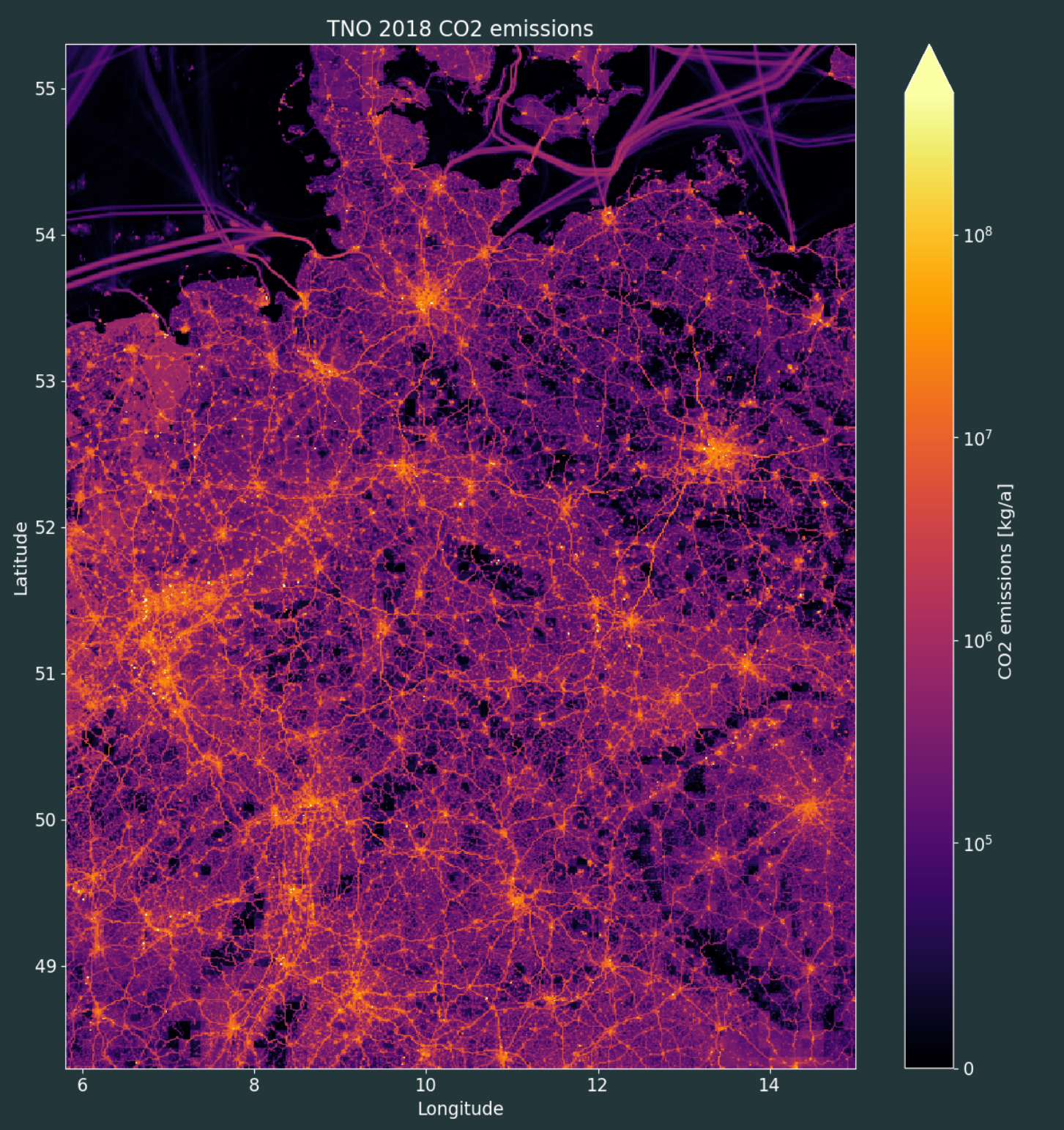

Map data: (C) OpenStreetMap contributors, SRTM | Map style: (C) OpenTopoMap (CC-BY-SA)

WRF configuration:
- 7 domains at 3 resolutions (15, 5, 1km)
- Innermost nests:
  - Rhine-Main-Neckar region
  - Berlin
  - Rhine-Ruhr region
  - Nuremberg
  - Munich
- 42 vertical layers, 14 layers below 1.5km
- Physics schemes: BEP, MYJ, NMP, MO
  - Using BEP because of higher vertical resolution than UCM
- 3 hourly GFDDA to ERA5 data, re-initialization every 7 days
- high resolution input data (CORINE + LCZ landuse [Breuer, 2016; Demuzere, 2022], COP DEM topography)

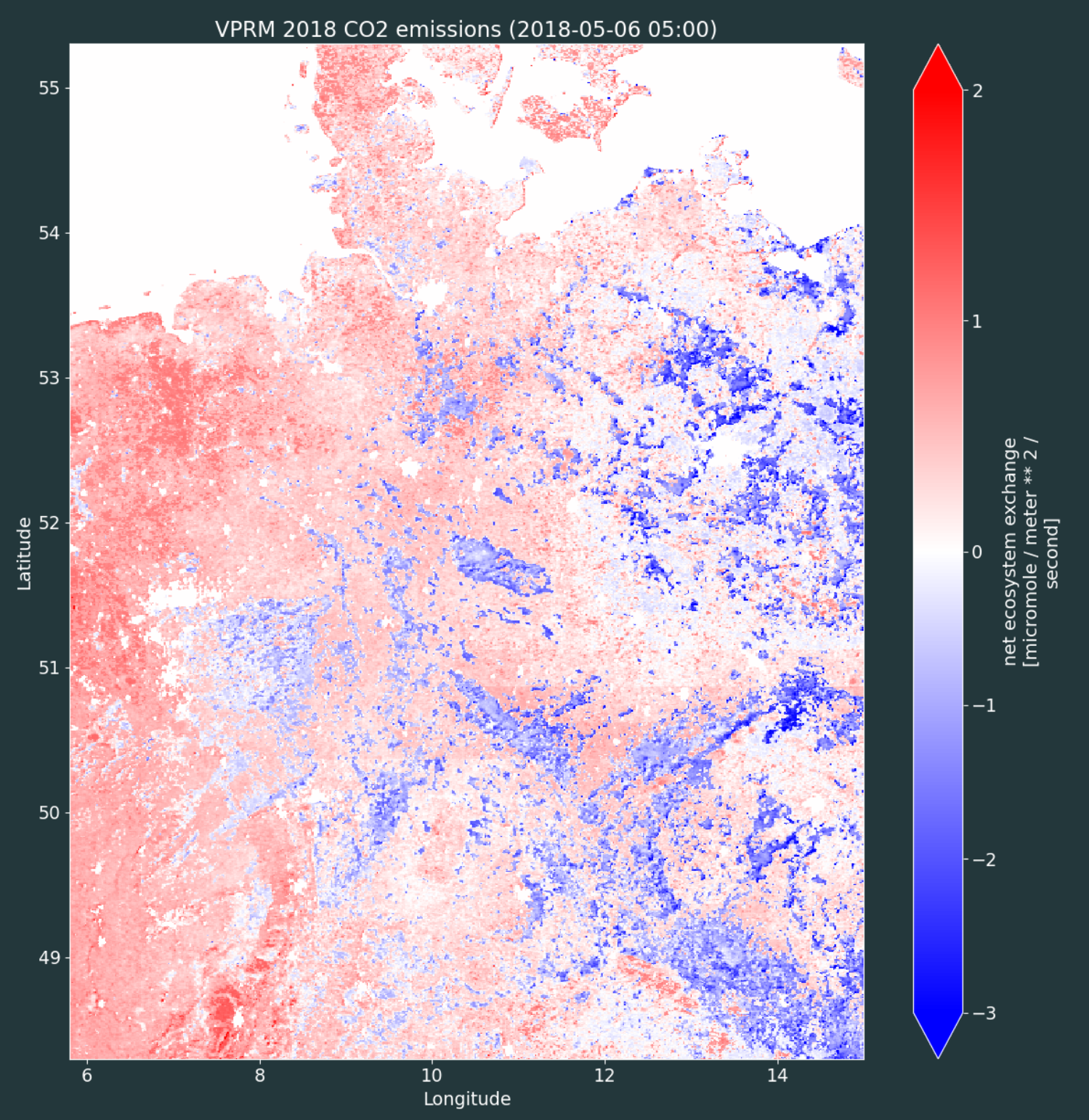
Greenhouse Gas setup:
- CO_2 background concentration fixed to 407 ppm

Time period:
- Full 12 months of 2018

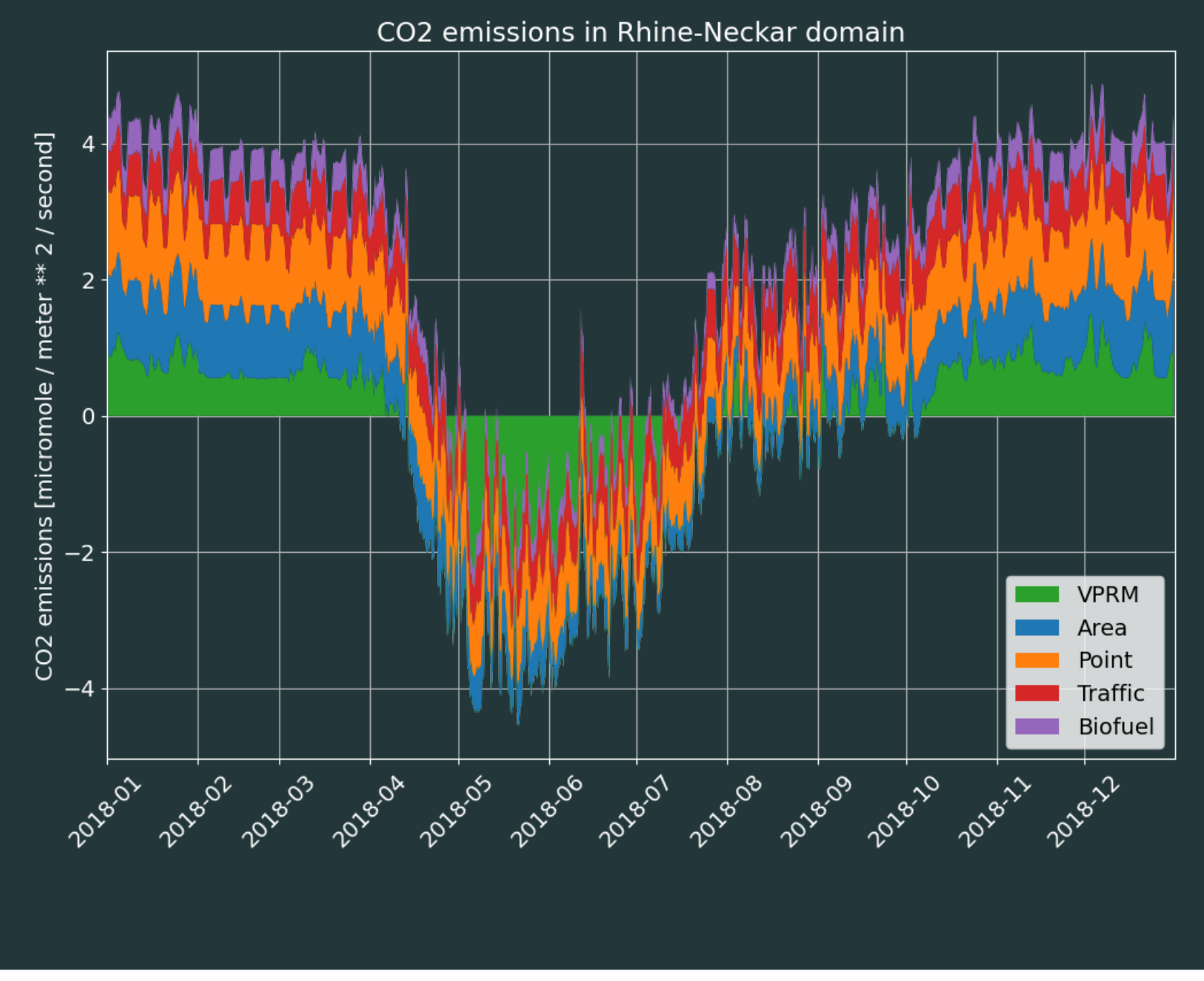
Anthropogenic emissions from TNO



Biospheric emissions from VPRM



Total CO_2 emissions



Comparison of CO_2 simulations with ICOS measurement stations

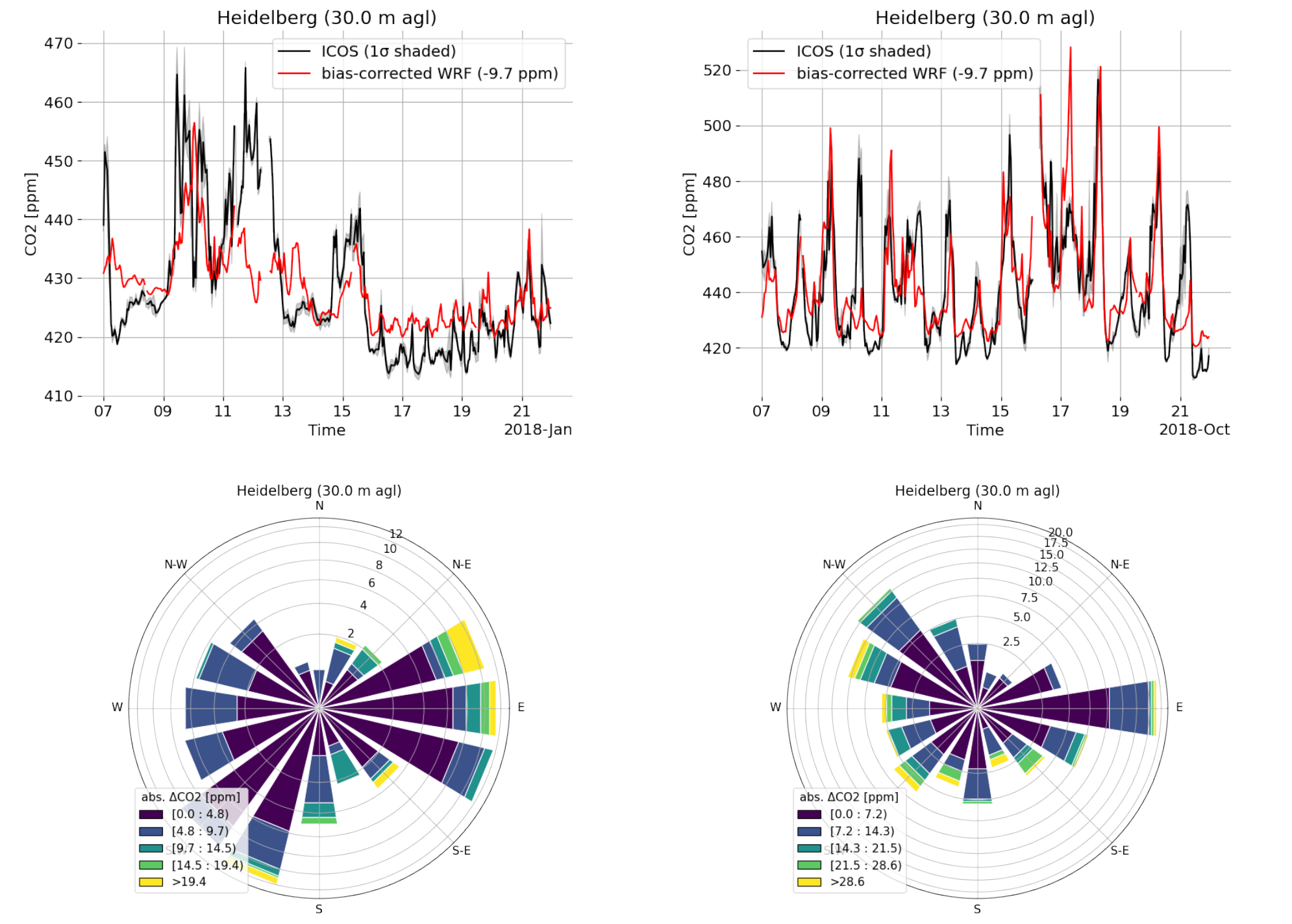

Map data: (C) OpenStreetMap contributors, SRTM | Map style: (C) OpenTopoMap (CC-BY-SA)

ICOS measurement network configuration:
- 8 stations within 5km domain

Stations for comparison:
- Karlsruhe (KIT):
  - Measurements at 30, 60, 100, 200 m agl
  - Instrument: $CO_2/CH_4/H_2O$ Picarro Analyzer G2301
- Heidelberg (HEI):
  - Measurements at 30 m agl
  - Instrument: $CO/CO_2/CH_4/H_2O$ Picarro Analyzer G2401

Heidelberg

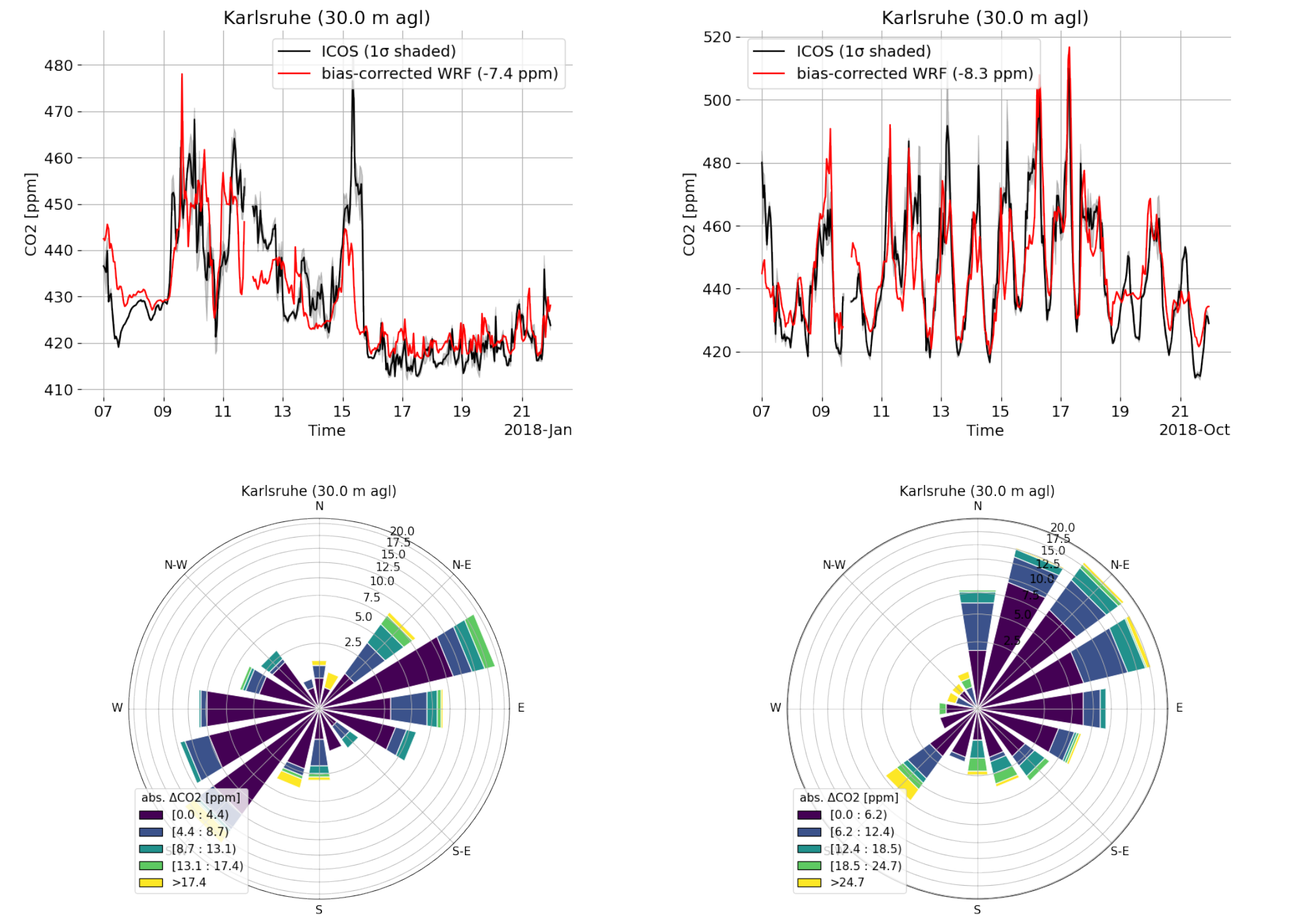
Jan 2018 **Oct 2018**



Findings:
- Simulated CO_2 concentrations are realistic
  - Misses one peak-feature in January
  - Diurnal cycle accurately represented
  - Changes in background (Jan) difficult to capture
- Some slight overestimation of night-time CO_2 in October
- Largest CO_2 difference in Jan during N-E winds
- Mean absolute bias:
  - Jan 2018: 6.2 ppm
  - Oct 2018: 10.6 ppm

Karlsruhe

Jan 2018 **Oct 2018**



Findings:
- Simulated CO_2 concentrations are realistic
  - Misses same peak-feature in January as at HEI, maybe larger-scale background faulty
  - Diurnal cycle accurately represented
- Some slight overestimation of night-time CO_2 in October
- Mean absolute bias:
  - Jan 2018: 6.0 ppm
  - Oct 2018: 8.7 ppm

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DKRZ
DEUTSCHES KLIMARECHENZENTRUM
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung