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D6.4: Mid-term Report on air quality/dust forecasting

August 2023

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D6.4	Mid-term Report on air quality/dust forecasting & hazard risk assessments	2 – MPG	Report	PUBLIC	M48

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V1	03/07/2023	Initial version	Initial version	MPG
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I. Introduction

I.1. Contribution to WP6

This document is Deliverable D6.4 "***Mid-term Report on air quality/dust forecasting***" which describes the efforts and outcome of the work of Task 6.5. A brief overview of how this Task is contributing to WP6 "***Environmental Predictions Department***" is summarized below.

- **Task 6.1. Creation of an Environmental Predictions Department (Lead: MPG) (M1 to M24).**
Status: Completed. Submission on M24 of Deliverable D6.1 "***Report on the structure of the Environmental Predictions Department***"
- **Task 6.2. New modelling and data analysis tools (Lead: MPG) (M1 to M48).**
Status: Completed. Submission on M48 of Deliverable D6.2 "***Report on new modelling and data analysis tools***"
- **Task 6.3. Emission analyses for the EMME region. (Lead: CEA, contrib. MPG). (M1 to M48).**
Status: Completed. Submission on M48 of Deliverable D6.3 "***Emission Analyses for the EMME region***"
- **Task 6.4. Dynamical downscaling of climate change and weather extremes (Lead: MPG) (M1 to M72).** Status: On-going. To be completed upon submission of Deliverable D6.5 "***Report on dynamical downscaling of climate change and weather extremes***" planned on M72.

- **Task 6.5. Air quality and dust forecasting; hazard risk assessments (Lead: MPG) (M1 to M84)**
Status: On-going.
a. Air quality modelling with the WRF model in support of atmospheric observations (Tasks 5.2.a and 5.4.a) and apportionment of pollution sources to support policy making (M1 to M24).
b. Air quality and dust forecasting system operational with WRF (M1-M24) and ICON (M25-M48). New forecasting products for economic sectors (e.g. agriculture, tourism, energy generation (M25-M84).
c. Policy relevant information provided through risk assessments (atmospheric dispersion of accidental releases, droughts, heat waves, radioactivity, fires, floods, vector-borne diseases) (M25 to M84).

This Task will be finalized with the submission on M84 of Deliverable D6.6 "***Final Report on air quality/dust forecasting & hazard risk assessments***"

- **Task 6.6. Earth System Modelling (ESM); connections to impacts and policy (Lead: MPG) (M12 to M84)** Status: On-going. To be completed upon submission of Deliverable D6.7 "***Report on dynamical downscaling of climate change and weather extremes***" planned on M84.

I.2. Executive summary

An air quality modelling system over the Eastern Mediterranean based on **a regional, online coupled atmospheric chemistry and aerosol model was developed and deployed** based on the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) (Task 6.5a).

The model system is assessed to be used to perform daily, **3-day-ahead forecasts of regulated pollutants (NO2, O3, PM2.5)** over the Eastern Mediterranean, in nested domains with horizontal resolutions of 50, 10 and 2 km, the latter focusing on Cyprus (Task 6.5b). Natural (dust, sea-salt, biogenic) emissions are calculated online, while anthropogenic emissions are based on the Emissions Database for Global Atmospheric Research – Hemispheric Transport of Air Pollution (EDGAR-HTAP) global emission inventory.

A **high spatial (1 km) and temporal (hourly) anthropogenic emission inventory developed for the island of Cyprus** (Task 6.3c) is used in the high-resolution innermost domain of the model. The model's skill to simulate the concentrations of atmospheric pollutants is evaluated using measurements from a network of nine ground stations in Cyprus and compared with the EU Copernicus Atmosphere Monitoring Service (CAMS). Surface temperature, pressure, and wind speed are found to be accurate, with minor discrepancies between the modelled and observed 10 m wind speed at mountainous and coastal sites attributed to the limited representation of the complex topography of Cyprus. Compared to CAMS, the implemented air quality/dust model simulates with higher accuracy the NO2 mixing ratios at the residential site with a normalized mean bias (NMB) of 7 % during winter and −44 % during summer, whereas the corresponding biases for CAMS are −81 % and −84 %. We have also **incorporated an ad-hoc high temporal resolution (hour by hour) in the anthropogenic emission inventory** (Task 6.3). This has enabled the model to capture more accurately the diurnal profiles of NO2 and O3 mixing ratios at the residential sites. More details are available in the Section II.3. Model Skill and Forecast Capability.

In the future, we aim to unify the modelling effort using the Icosahedral Nonhydrostatic (ICON) model (as mentioned in Task 6.5.b), once atmospheric chemistry and aerosols are incorporated by the upstream developers in the context of the MESSy international multi-institutional consortium, in which CARE-C is participating in association with the advanced partner MPIC (https://messy-interface.org/). The benefits and adoption of ICON are described in Deliverable D6.2: "***Report on new modelling and data analysis tools***"**.**

Regarding the initial activity on Hazard Risk Assessment (Task 6.5c, M25-84), we have studied the diurnal and seasonal changes in the dispersion of CBRN gaseous and aerosol tracers using a four-member ensemble based on FLEXPART and FLEXPAR-WRF. We found that simulations are affected by the spatio-temporal resolution of meteorological inputs, the seasonal and diurnal changes in meteorological conditions, and the simulation code of choice. The preparedness programs for potential spills and/or accidents, the FLEXPART community, and CBRN dispersion hazard modelers may benefit from our findings. The initial activity is outlined in Section Hazard Risk Assessments.

The outcomes of this Deliverable D6.5 are published in three (3) papers in peer-reviewed scientific journals (see Section V). In addition, the air quality forecasting activity in EMME-CARE has been instrumental in **attracting additional funding through competitive processes** to facilitate complementary and synergistic activities, and in establishing EPD as a regional centre of excellence in atmospheric composition modelling. The list of projects that directly benefit from and contribute to the air quality and dust forecasting activity are listed in the Section Projects and Future Plans.

II. Air Quality Modelling & Forecasting (Tasks 6.5.a & b)

II.1. Regional Air Quality Forecasting

The term air quality is used to describe to what extent the troposphere is contaminated with atmospheric pollutants. High concentrations of atmospheric pollutants can be hazardous to human health. The atmospheric pollutants with the strongest evidence for public health concern, include ozone (O3), nitrogen oxides (NOx), and particulate matter (PM) (World Health Organization, 2018).
The effects of increased concentrations of air pollution on human health highlight the need for real-time air quality forecasting (RT-AQF) in detail in space and time. RT-AQFs can provide the environmental authorities and citizens information in advance, to take measures and actions to eventually be protected from pollution episodes.

The establishment of an operational air quality forecasting system aims to serve the needs and requirements of the private and public sectors in Cyprus and the EMME region:

- Facilitate risk assessments and contributions to early warning systems associated with environmental disasters.
- Improve air quality and public health with personalized and actionable advice against air pollution.
- Adapt to and prepare for extreme events and atmospheric hazards through model scenarios and sensitivity tests.

II.2. Model Configuration

We use WRF-Chem version 3.9.1.1 to perform **3-day-ahead meteorological and air quality forecasts** starting at 00:00 LST every day on the computational cluster acquired through EMME-CARE and housed in and operated by the Cyprus Institute HPC facility.

We deploy three (3) one-way nested domains (Figure 1) with horizontal resolutions of 50, 10, and 2 km:
1. The outermost domain (d01) includes the Black Sea region, the largest part of Europe, and the Middle East and north Africa deserts which have an important contribution to the background concentrations of gas-phase and aerosol pollutants over the EMME region.
2. The second domain (d02) focuses over the Eastern Mediterranean and includes the major urban centres in the Middle East.
3. The third domain (d03) is focused over the island of Cyprus. We use 33 vertical layers, while adaptive time stepping is used to meet the Courant–Friedrichs–Lewy (CFL) stability criterion (Figure 1).

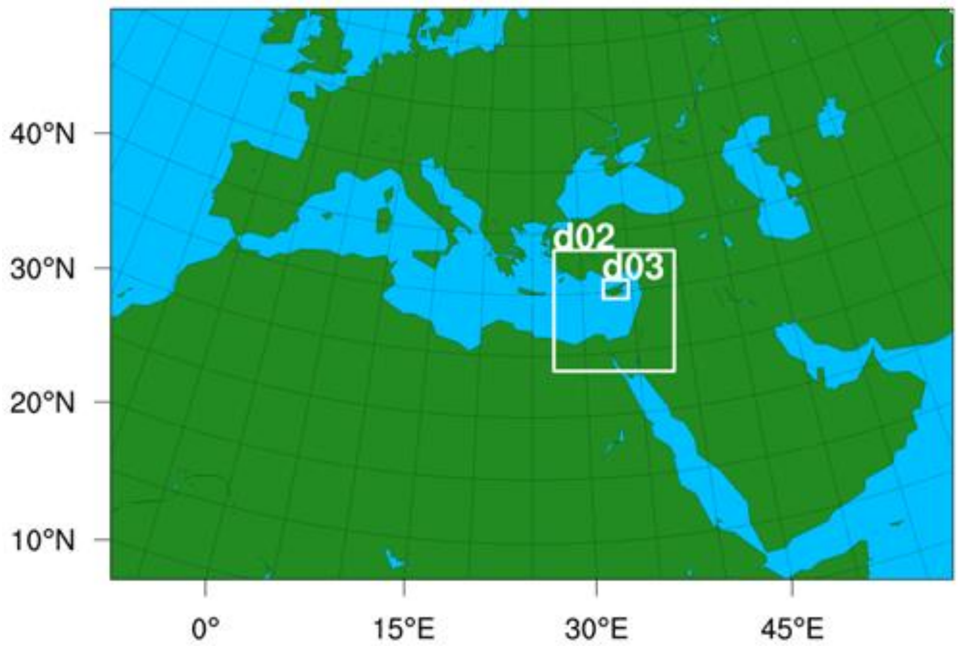

Figure 1: Air Quality Forecast Domain with high-resolution nested sub-domains (d02, d03)

In order to have optimal representation of the meteorological fields, for our setup we are using physics parameterizations which have been optimized for Cyprus by the Department of Meteorology for weather forecast and as well as physics parameterizations that have been shown by Zittis et al. (2014) to have the optimal performance in terms of simulating several meteorological variables including total precipitation and air temperature over the Eastern Mediterranean and the Middle East region. **Detailed description of the model physics configuration and evaluation of its accuracy was published in the Open Access journal Geoscientific Model Development (GMD) by Georgiou et al. (2020)** (see Reference in Section V).

The Regional Atmospheric Chemistry Mechanism (RACM) mechanism is applied to simulate gas-phase chemistry. RACM is based on the Regional Acid Deposition Model, version 2 (RADM2) mechanism and has been shown by Georgiou et al. (2017) that it produces the lowest Mean Bias (MB) regarding O3, NOx, and CO concentrations over the island of Cyprus compared to other gas-phase chemistry mechanisms (Figure 2). The Modal Aerosol Dynamics Model for Europe (MADE) and the secondary organic aerosol (SOA) parameterization based on the volatility basis set (VBS) are employed to simulate aerosol inorganic species and SOA, respectively.

The model configuration options are summarized in the following table:

PROCESS	OPTION	Reference
Microphysics	Morrison 2-moment scheme	Morrison et al., 2015
Land-Surface	NOAH Land surface model	Chen and Dudhia, 2001
Boundary Layer	Yonsei University (YSU) Planetary Boundary Layer	Hong et al., 2006
Cumulus	Grell 3D Ensemble Scheme	Grell and Dévényi, 2002
Surface Layer	MM5 Similarity surface layer scheme	Zhang and Anthes, 1982
Radiation	Rapid Radiative Transfer Model (RRTTM)	Iacono et al., 2008
Gas Phase Chemistry	RACM regional atmospheric chemistry mechanism	Stockwell et al., 1997

Aerosols	Modal Aerosol Dynamics Model for Europe (MADE), Secondary Organic Aerosol Model (SORGAM)	Ackermann et al., 1998 Schell et al., 2001

We set up and configured WRF/Chem to encompass the major dust sources in the region with several sensitivity tests to assess computational requirements. The use of a wide parent domain allows for all dust sources to be captured intrinsically by the model.

The Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model which is coupled with the MADE/SORGAM aerosol mechanism within the framework of WRF-Chem is used to simulate dust emission. The dust emission flux Fp in the GOCART model is calculated scaled by an empirical proportionality constant C. The value of C estimated was initially based on regional data for the US. We have evaluated the performance of the WRF/Chem model for different values of C and initially found that for C = 0.4 $\mu g s^2 m^{-5}$, the WRF/Chem simulated mean AOD was consistent with the AERONET measurements over the Sahel region. Several high-resolution sensitivity tests performed over Cyprus and the East Mediterranean lead to a best performing value of 0.36 μgs2m−5 (Georgiou et al. 2018), based on the study of modelling sensitivities to dust emissions and aerosol size treatments over North Africa. Therefore, as that is the most prevalent source of dust emissions in the EMME region, a value of C equal 0.36 $\mu g s^2 m^{-5}$ is used in the operational forecast system.

II.3. Model Skill and Forecast Capability

The model concentrations of the air pollutants are compared against hourly observational data from nine air quality monitoring ground stations, provided by the Cyprus Department of Labour Inspection (DLI) for the three winter (January, February, December) and three summer (June, July, August) months of 2020. During these periods, there were no restrictions in place due to the COVID-19 pandemic.
Modelled 2m Temperature (T2m) is in good agreement with observations (NMB < 11 % for both winter and summer). The diurnal cycle of T2m is also reproduced by the model (R>0.78) during both seasons. Modelled surface Pressure is in very good agreement with observations with a normalized mean bias of less than 1 %.

II.3.1. NOx

The seasonal average NO_2 mixing ratios from the observations and the first day of the WRF-Chem forecast for winter and summer are shown in Figure 2, first row. During both seasons, the higher NO_2 mixing ratios appear near the urban centres and the power-generation stations. NO_2 emitted within the island is shown to affect the eastern part of Cyprus through the prevailing westerly winds (Figure 2).

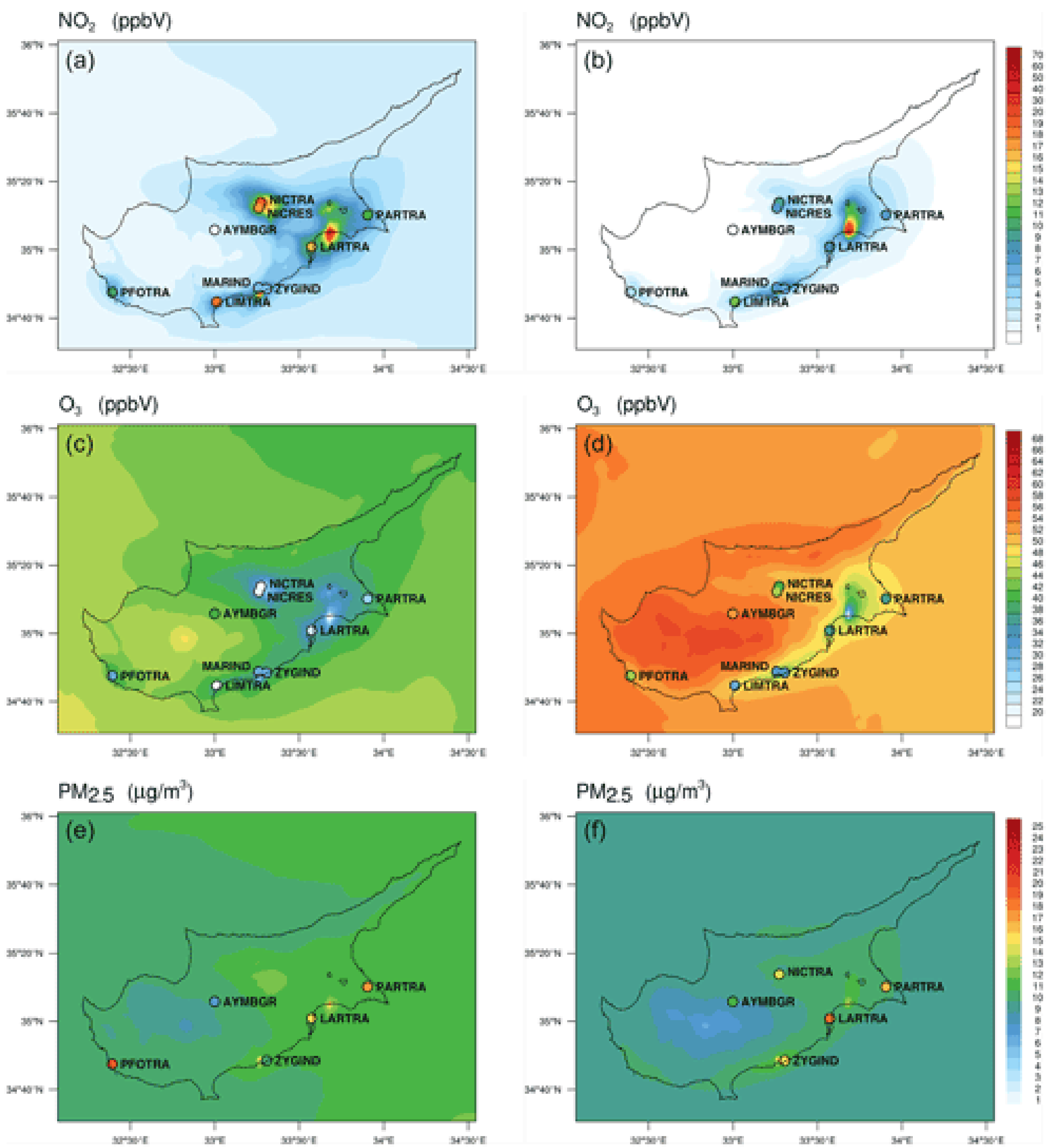

Figure 2 Pollutant seasonal mixing ratios for winter (left) and summer (right).

During both periods, the WRF-Chem model forecasts accurately the background NO_2 mixing ratios with a mean bias of less than 1 ppbv at the Agia Marina (CAO) background station. Similar performance is achieved by the CAMS model. At the Nicosia residential station, the WRF-Chem model outperforms CAMS during winter and summer. The normalized mean bias from the WRF-Chem model is found to be −7 % (about 1 ppbv) during winter and −44 % (about 3 ppbv) during summer, whereas the corresponding values from CAMS are −81 % (about 14 ppbv) and −84 % (about 6 ppbv). Underestimation by both WRF-Chem and CAMS is more evident at the traffic stations. The normalized mean bias from the WRF-Chem model is found to be −31 % (about 5 ppbv) during winter and −39 % (about 4 ppbv) during summer, whereas the corresponding values for CAMS are −86 % (about 13 ppbv) and −78 % (about 7 ppbv). These stations are located very close to traffic roads and, as a result, they often record very high concentrations of pollutants (as shown by the large number of outliers and the large standard deviation), which cannot be reproduced by the atmospheric model. At the industrial stations, the WRF-Chem model tends to overestimate the seasonal average NO_2 mixing ratios by about 4 ppbv during the winter and 7 ppbv during the summer (Figure 3).

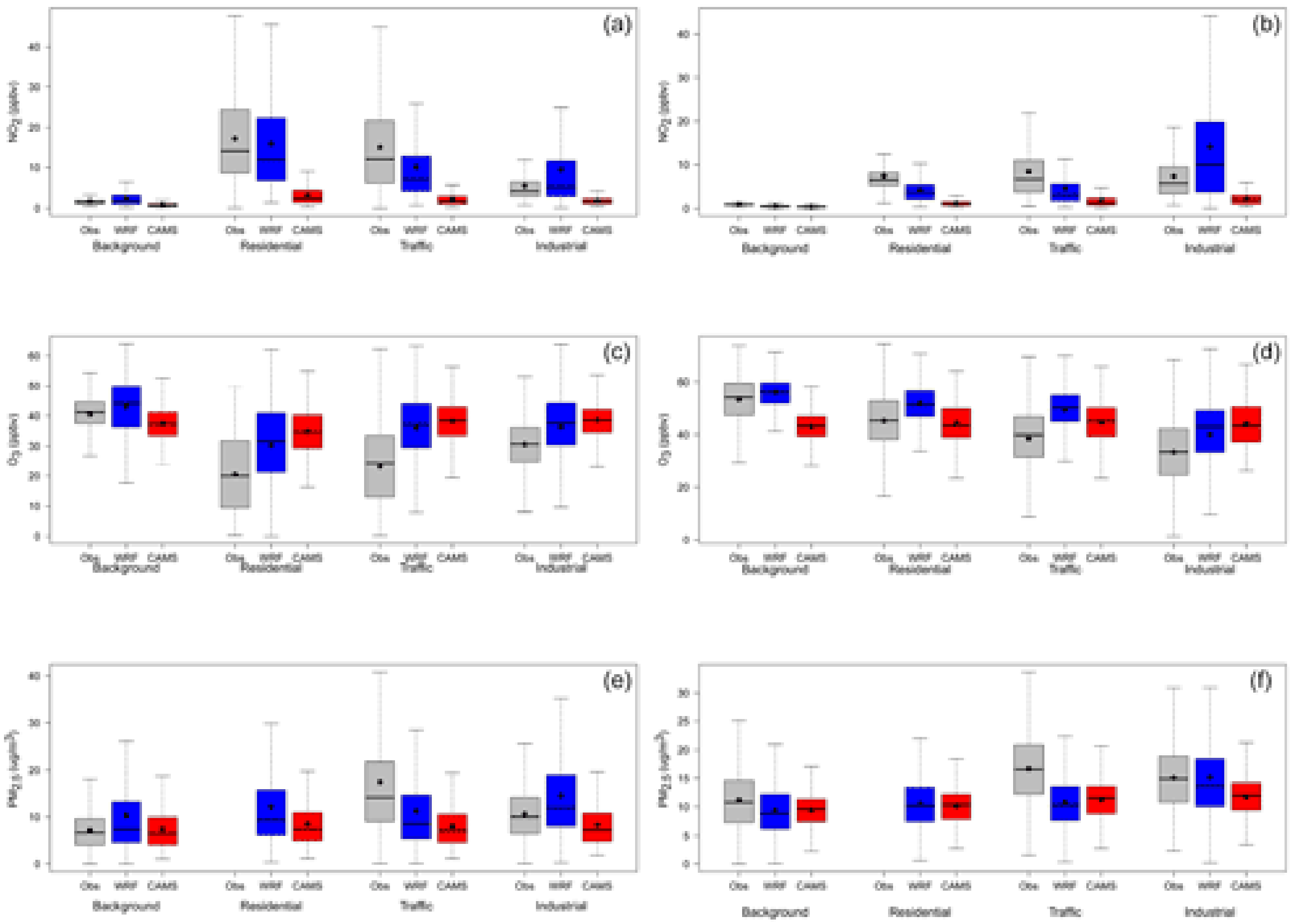

Figure 3 Intercomparison of pollutant spread at different types of stations in Cyprus for WRF-CHEM forecast system and CAMS.

II.3.2. Ozone

Observed background O_3 mixing ratios reach up to 41 ppbv during winter and 53 ppbv during summer. Using observations from 1997 to 2004, a maximum in O_3 mixing ratios (58±10 ppbv) in July and a minimum (36±7 ppbv) in December were reported over the Eastern Mediterranean. During both seasons, the lowest O_3 mixing ratios appear at the locations with intense anthropogenic activity, such as the locations of the power-generation stations and the urban centres, and the eastern part of the island (Figure 2, second row), which coincide with the highest NO_2 mixing ratios appear (Figure 2, first row). As shown in Figure 3, second row, wintertime background O_3 mixing ratios are captured by both WRF-Chem (NMB = 7 %) and CAMS (NMB = −8 %). Similar performance is shown for the 10 km WRF-Chem domain with a NMB of 4 % (Figure 4).

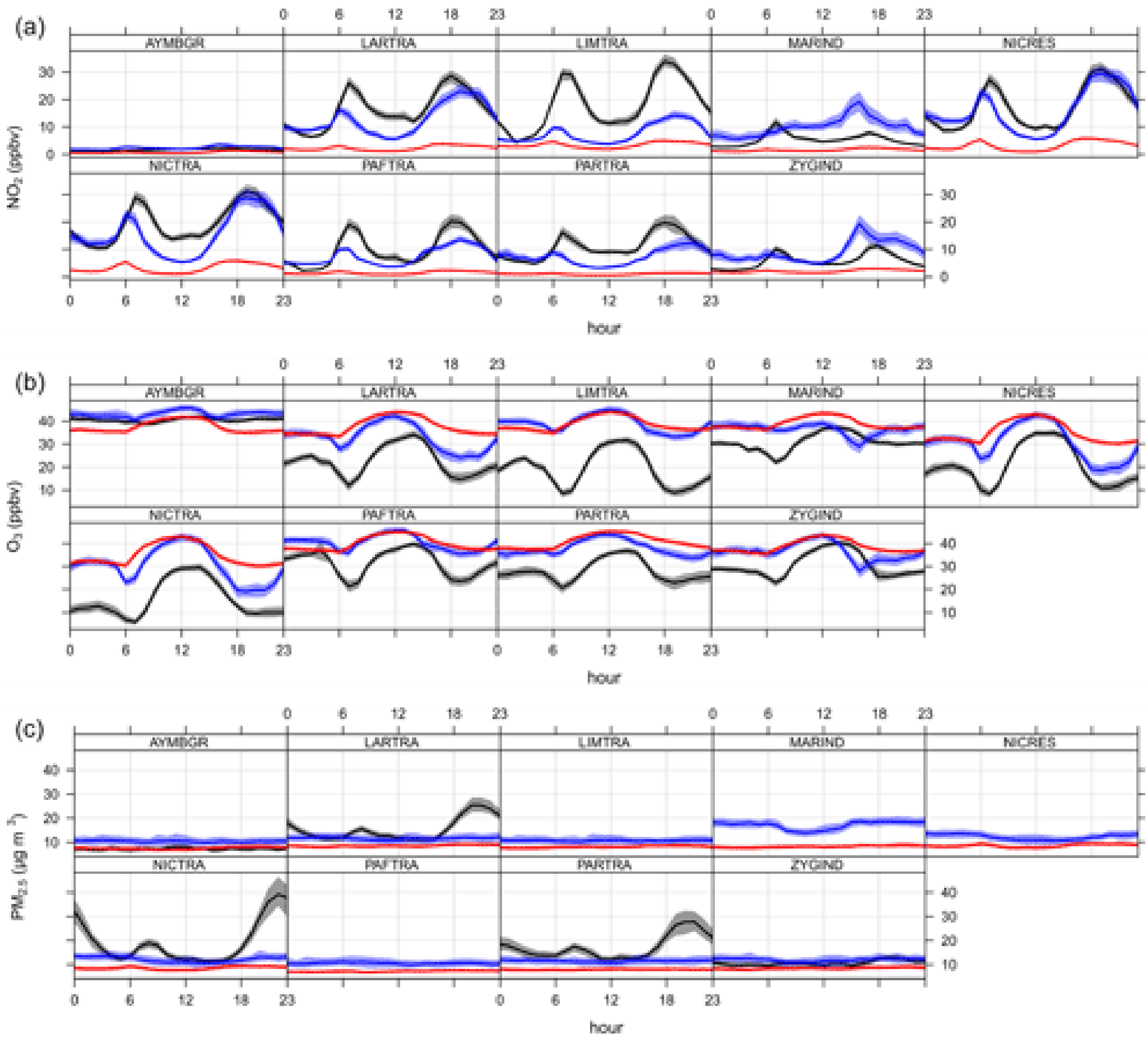

Figure 4 Intercomparison of pollutant diurnal variability at different types of stations in Cyprus for WRF-CHEM forecast system and CAMS.

Summertime background O_3 mixing ratios are also captured by the WRF-Chem (NMB = 5 % for both domains) but underestimated by CAMS by about 10 ppbv (NMB = −19 %). At the residential and traffic stations, CAMS strongly overestimates O_3 mixing ratios during winter by 70 % (∼14 ppbv) and 73% (∼15 ppbv), respectively (Figure 5). A strong overestimation is also shown by the 10 km WRF-Chem domain at these locations but better performance is achieved by the WRF-Chem high-resolution domain where the overestimation is about 48 % (∼10 ppbv) at the residential and 61 % (∼13 ppbv) at the traffic stations.

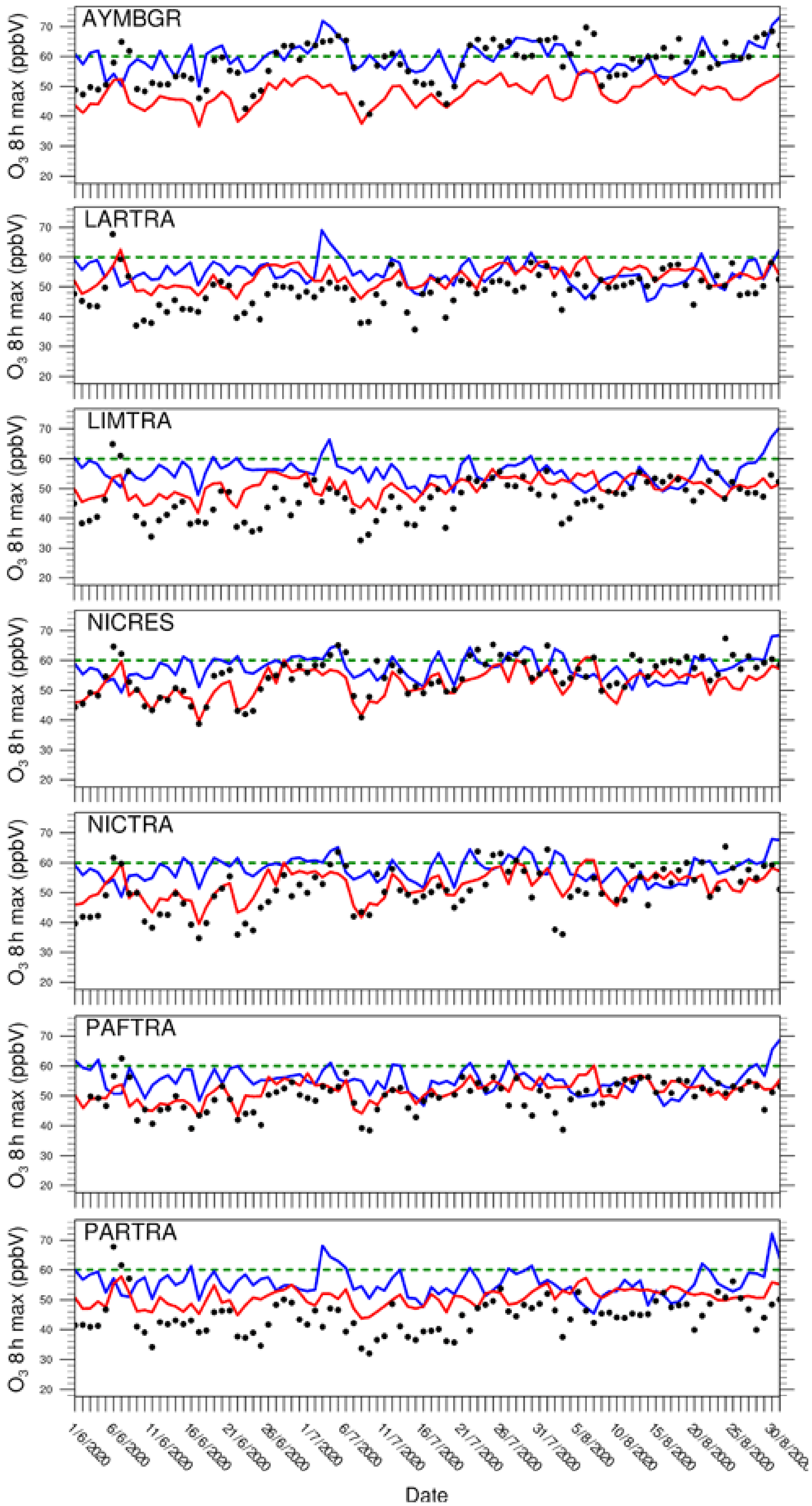

Figure 5 Modelled (red: CAMS, blue: WRF-CHEM) and observed (black) Ozone exceedances

II.3.3. Fine particulate matter ($PM_{2.5}$)

During summer, observed regional background $PM_{2.5}$ concentrations are higher (11.2 μg m^{-3}) than winter (7.2 μg m^{-3}) which can be partly attributed to the absence of precipitation and the enhanced photochemical conditions which lead to secondary aerosol formation. The WRF-Chem model overestimates background $PM_{2.5}$ concentrations during winter by about 4 μg m^{-3}, while CAMS forecasts wintertime background $PM_{2.5}$ concentrations with more accuracy (≤1 μg m^{-3}). At the traffic stations, WRF-Chem and CAMS underestimate $PM_{2.5}$ concentrations by 5 and 9 μg m^{-3}, respectively. During the summer, the two models show similar behaviour. In particular, there is an underestimation of background $PM_{2.5}$ concentrations of about 16 % (~1.8 μg m^{-3}). Underestimation is slightly higher at the industrial stations (~20 %). At the traffic stations underestimation reaches up to 5 μg m^{-3} (~33 %). The underestimation of $PM_{2.5}$ concentrations at the traffic stations can in part be attributed to the lack of road dust resuspension mechanisms in the models and the fact that these stations are located close to main roads (Figure 6).

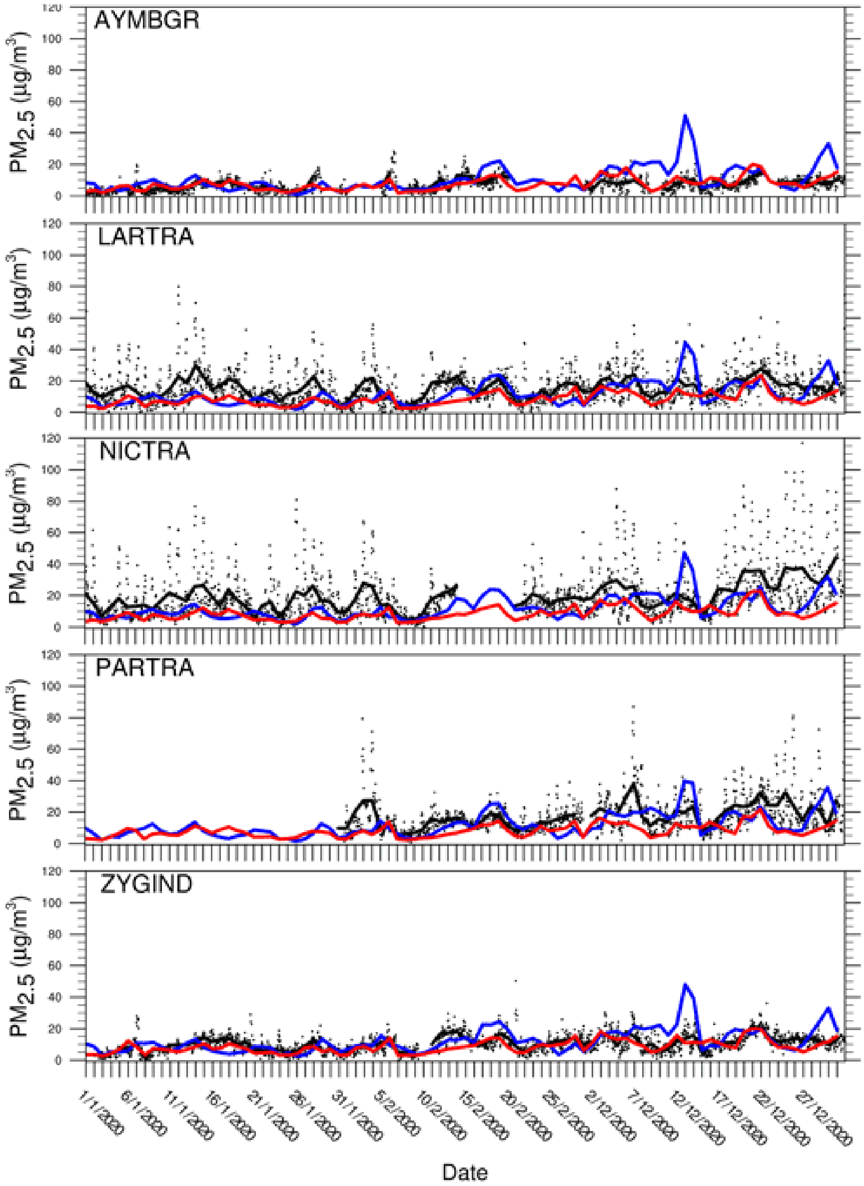

Figure 6 5 Modelled (red: CAMS, blue: WRF-CHEM) and observed (black) fine particulate matter ($PM_{2.5}$) concentrations.

II.4. Forecast Skill Metrics

The statistical metrics for NO_2, as well as O_3 and $PM_{2.5}$ at the background, residential, traffic, and industrial stations are summarized here and intercompared with the equivalent CAMS metrics.

The Pearson's correlation coefficient I, mean bias (MB), normalized mean bias (NMB), and root mean squared error (RMSE) between the modelled (by the WRF-Chem and CAMS models) and observed hourly values of nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matter ($PM_{2.5}$) averaged over the background, residential, traffic, and industrial stations during winter and summer for the first day of forecast are presented below:

		Winter								Summer							
		WRF-Chem				CAMS				WRF-Chem				CAMS			
		R	MB	NMB	RMSE	*R*	MB	NMB	RMSE	*R*	MB	NMB	RMSE	*R*	MB	NMB	RMSE
NO_2 (ppbv)	Background	0.12	0.62	0.36	2.18	0.39	−0.89	−0.52	1.25	0.03	−0.42	−0.45	0.85	−0.15	−0.57	−0.61	0.91
	Residential	0.55	−1.13	−0.07	11.11	0.59	−14.01	−0.81	17.27	0.41	−3.25	−0.44	4.98	0.16	−6.26	−0.84	7.36
	Traffic	0.36	−4.87	−0.31	12.11	0.46	−12.83	−0.86	16.22	0.16	−3.79	−0.39	8.36	0.23	−6.54	−0.78	8.71
	Industrial	0.14	4.22	0.77	12.10	0.32	−3.68	−0.67	5.46	0.19	6.96	0.95	15.42	0.21	−5.21	−0.70	7.53
O_3 (ppbv)	Background	0.16	2.66	0.07	10.18	0.44	−3.09	−0.08	6.57	0.26	2.67	0.05	9.34	0.62	−10.23	−0.19	12.15
	Residential	0.49	9.91	0.48	16.55	0.65	14.41	0.70	17.37	0.40	6.58	0.15	12.33	0.67	−0.93	−0.02	8.24
	Traffic	0.35	12.72	0.61	18.08	0.53	15.05	0.73	18.05	0.30	10.88	0.29	15.81	0.63	6.19	0.17	10.65
	Industrial	0.04	5.56	0.18	14.63	0.50	8.15	0.27	10.95	0.21	6.46	0.19	17.12	0.67	10.45	0.31	13.78
$PM_{2.5}$ ($\mu g\,m^{-3}$)	Background	0.27	3.87	0.54	10.15	0.48	0.76	0.11	4.47	−0.01	−1.85	−0.16	7.45	0.42	−1.79	−0.16	5.39
	Traffic	0.19	−5.01	−0.28	15.19	0.32	−8.76	−0.50	15.02	−0.04	−5.44	−0.32	9.51	0.59	−5.54	−0.33	7.39
	Industrial	0.29	1.82	0.17	9.69	0.48	−1.76	−0.17	5.66	−0.02	−2.96	−0.20	8.46	0.58	−3.08	−0.20	5.57

II.5. Aeolian Dust

A series of evaluation analyses of the WRF dust-related outputs has been performed by utilizing a variety of dust observations. The diversity of the reference datasets ensures a complete and comprehensive assessment of the dust numerical outputs since they provide reliable information, relying on different observing techniques, about the columnar dust load and the vertical structure of mineral particles' burden.

A sensitivity analysis was performed and the model was calibrated for the GOCART online dust emission scheme and secondly for the overall emissions of the enhancements by the Air Force Weather Agency (AFWA) developed after some shortcomings of the GOCART became apparent such as the need to tune it depending on the location and the event modelled.

II.5.1. AOD from AERONET

Aerosol observations acquired from the AERONET Robotic Network have been utilized in numerous studies dealing with the evaluation of satellite retrievals and model outputs. This extensive use is attributed to their high accuracy as well as to the provision of spectrally resolved optical properties of aerosol load (i.e., AOD), nature (i.e., single scattering albedo) and size (i.e., Angstrom exponent) along with microphysical properties (e.g., volume size distribution).

Relying on the synergistic implementation of the available information, it is feasible to identify cases where aerosol load is dominated by mineral particles. Nevertheless, the optimum scenario of extracting pure dust conditions cannot be realized (with few exceptions for stations situated at desert areas) since AERONET retrievals are representative for the whole atmospheric column and the removal of other aerosol species "contamination" cannot be easily achieved. Despite this inherent limitation, there are some approaches where dust conditions can be identified, at a large degree of acceptance, from the ground-based AERONET sunphotometric measurements. Considering that the coarse-size dust aerosols are mainly recorded at considerable concentrations, their dominant presence in the atmosphere is associated with coincident moderate-to-high AODs and low Angstrom exponent levels (Figure 7).

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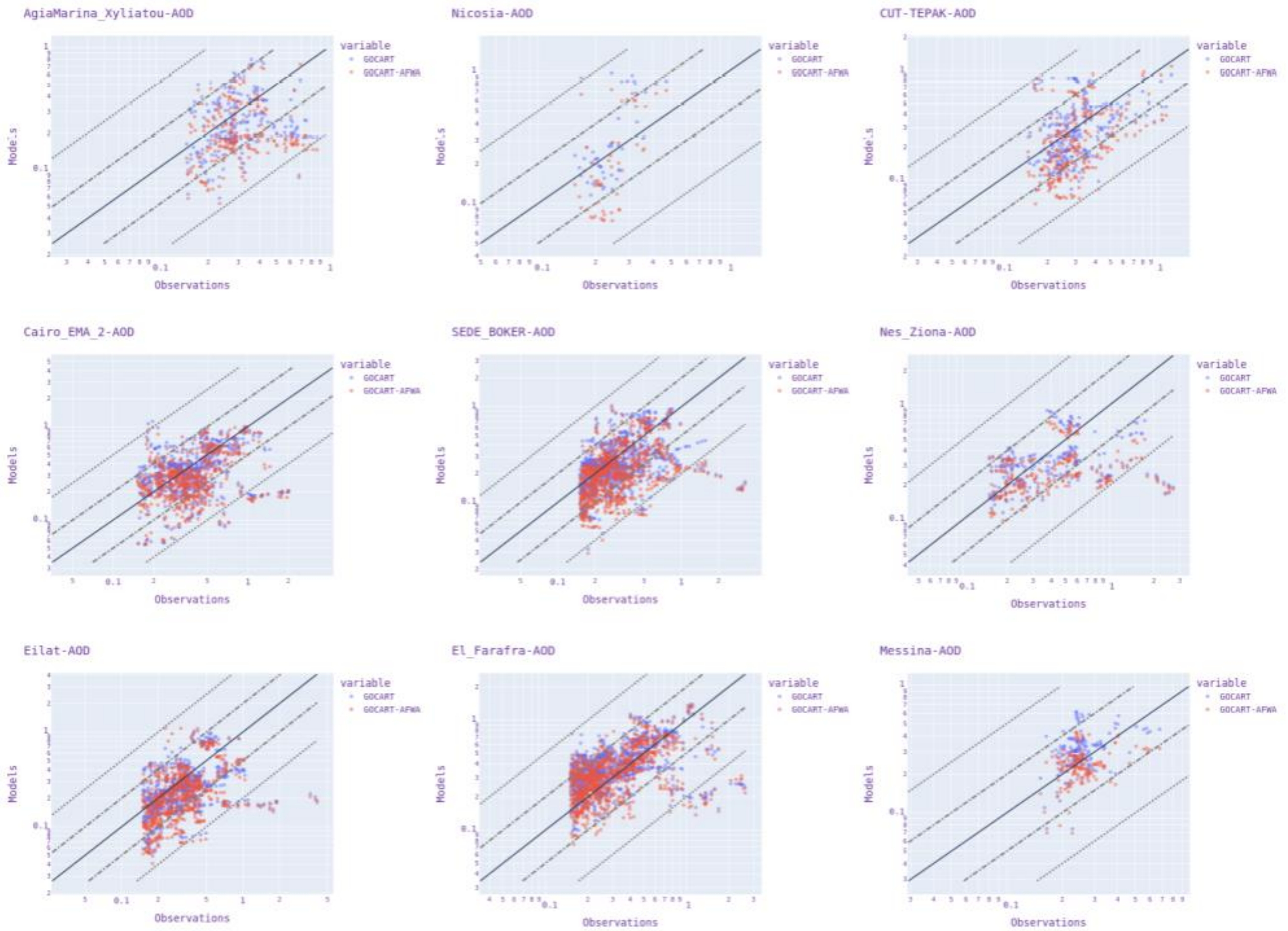

Figure 7 WRF-CHEM forecast of AOD with the different emisions schemes at stations in Cyprus and the Mediterranean.

II.5.2. PM_{10} from Station Measurement Networks

Following the Convention on Long-range Transboundary Air Pollution in 1979, legally binding protocols were introduced for the reduction of the impact of air pollution. The European Monitoring and Evaluation Programme (EMEP) was then established, consisting of five Centres and four Task Forces that support its implementation by providing guidelines to governmental and subsidiary bodies responsible for monitoring local air pollutants.

The bodies involved are required to report on a variety of air pollutants including ground level ozone, heavy metals, persistent organic pollutants and particulate matter. These reports are then stored in EMEP's open-access database which are mapped using a 0.1º x 0.1º longitude-latitude grid. We have sourced hourly profiles for Coarse Particulate Matter (PM_{10}) for the EMEP stations to compare simulated results to observations. In addition, we include all station measurements by the Dept of Labour Inspection in Cyprus, as well as the measurements performed in the context of the ACCEPT project.

The quality indicators are well within the target values and comparable to the state-of-the-art forecast models such as CAMS, giving confidence in the model capacity to capture dust events in the longer-term, and allowing its use for assessment of climate change effects on the emission and transport of aeolian dust (Figure 8).

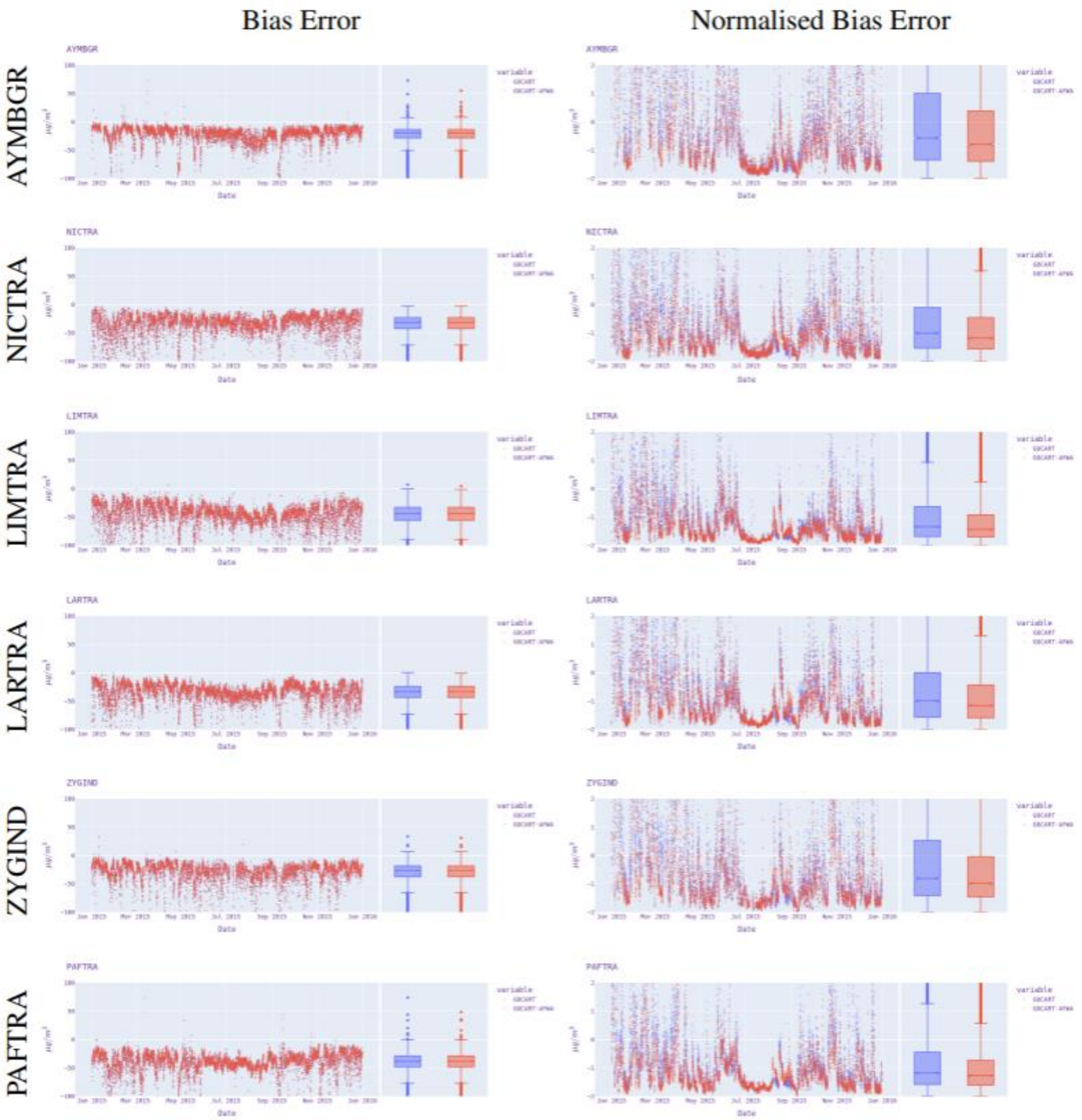

Figure 8 WRF-CHEM forecast model skill metrics with the different emisions schemes at stations in Cyprus.

II.6. Remote Sensing Observations

We aim to improve the accuracy of physical processes and land–atmosphere interactions that govern dust emission and transport in numerical weather prediction models for enhanced spatial and temporal model skill regarding dust burden and the characterisation of source and recipient areas.

The ECMWF-IFS (European Centre for Medium-Range Weather Forecast – Integrated Forecasting System) outputs, produced with and without the assimilation of Aeolus quality-assured Rayleigh–clear and Mie–cloudy horizontal line-of-sight wind profiles, are used as initial and boundary conditions in the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) to simulate 2-month periods in the spring and autumn of 2020, focusing on a case study of dust episodes over the domain.

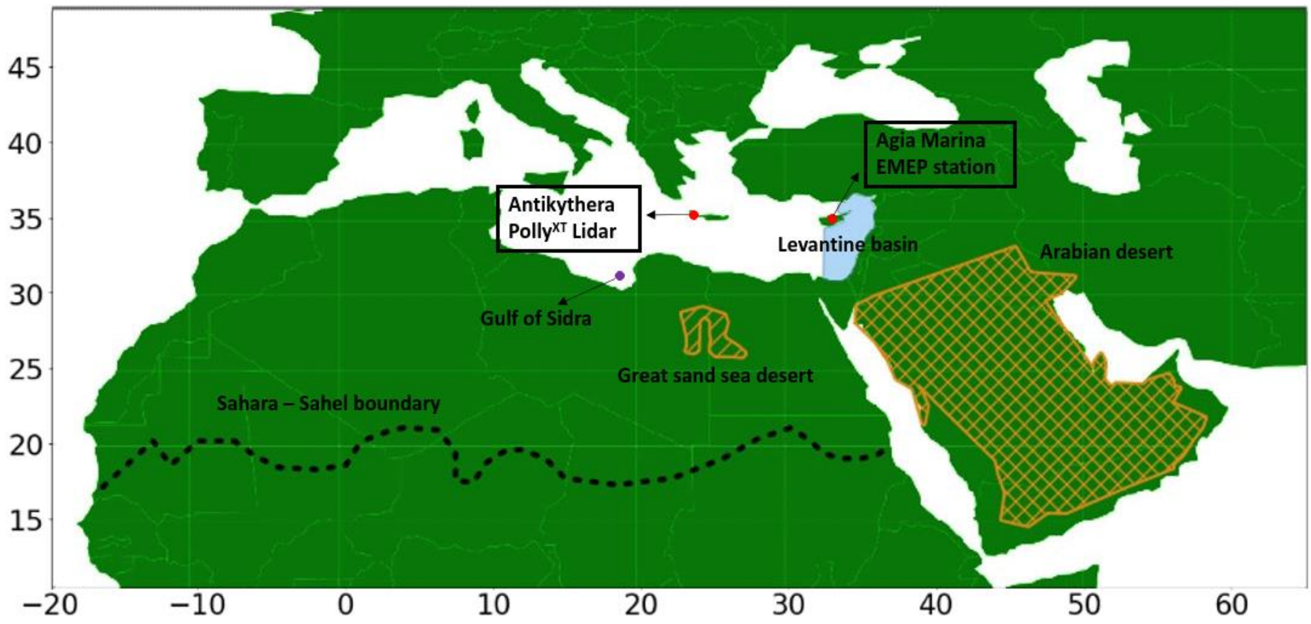

Figure 9 Model domain used in the WRF-Chem simulations alongside some locations and observation stations mentioned in the text.

Our experiments have been performed over the broader eastern Mediterranean and Middle East (EMME) region, which is frequently subjected to dust transport, as it encompasses some of the most active erodible dust sources. Aerosol- and dust-related model outputs (extinction coefficient, optical depth and concentrations) are qualitatively and quantitatively evaluated against ground- and satellite-based observations. Ground-based columnar and vertically resolved aerosol optical properties are acquired through AERONET sun photometers and Polly^{XT} lidar, while near-surface concentrations are taken from EMEP. Satellite-derived vertical dust and columnar aerosol optical properties are acquired through LIVAS (LIdar climatology of Vertical Aerosol Structure) and MIDAS (ModIs Dust AeroSol), respectively.

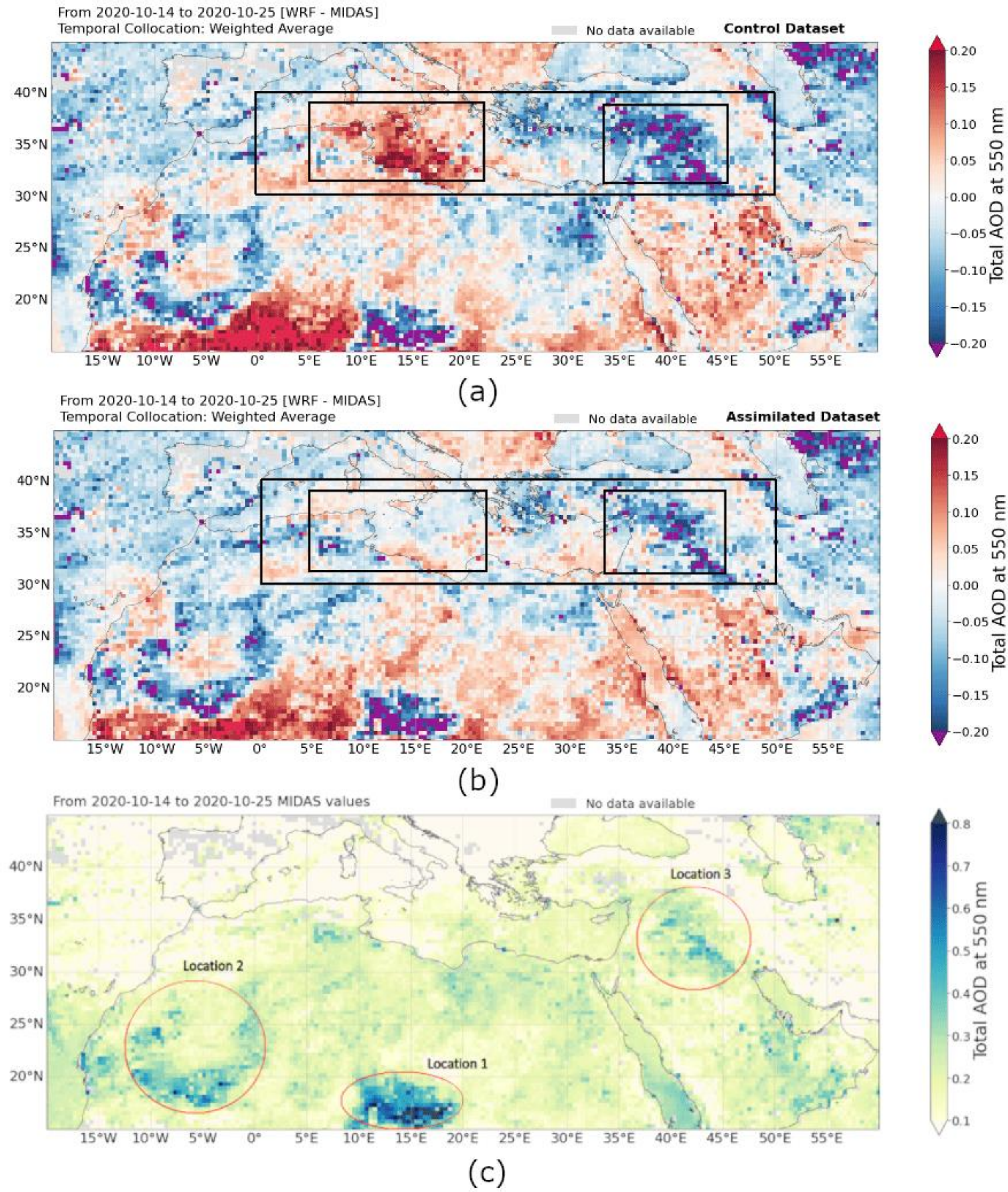

Figure 10 Time-averaged differences in AOD (WRF-observations analysis MIDAS) for the control run (a) and the assimilated run (b), where the black rectangles indicate regions of significant improvement when simulating conditions using the assimilated run. Additionally, (c) represents the observed AOD values for the time-averaged period of 14–25 October 2020, where the highlighted red circles indicate locations where both runs underestimate AOD

Comparison of the model results to both ground- and satellite-based observations, including EMEP, AERONET, Polly^{XT}, MIDAS and LIVAS, allowed for a thorough investigation of numerical dust outputs both horizontally and vertically. In all cases, using the assimilated Aeolus wind products improved the model predictive ability with increases in correlation coefficient and index of agreement and decreases in positive and negative biases. The most significant improvements were observed when the statistical analyses were performed over the EMME region, while comparisons with the whole simulated domain decreased the improvements. Specifically, for the period where a second anticyclone forms in the control run, the use of Aeolus resulted in a reduction of positive bias atop the anticyclone by 44 % and an improvement in the correlation coefficient by 0.19. Through backwards-trajectory analysis with the FLEXPART model, the source regions of aerosols were analysed. It was revealed that the control run had an influx of aerosols from continental Europe, while the assimilated run had an influx of aerosols from the Saharan region. The benefits attained from the incorporation of the assimilated IFS Aeolus data solely relate to the period of 14 to 25 October 2020, where anticyclonic conditions prevail in the EMME and central Mediterranean regions. Even though the period of improvement is statistically negligible compared to longer timescales, the strong reductions in positive bias and underestimates highlight the importance of Aeolus in further dust research.

Overall, in cases of either high or low aerosol loadings, the model predictive skill is improved when WRF-Chem simulations are initialised with the meteorological fields of Aeolus wind profiles assimilated by the IFS. The improvement varies in space and time, with the most significant impact observed during the autumn months in the study region. Comparison with observation datasets saw a remarkable improvement in columnar aerosol optical depths, vertically resolved dust mass concentrations and near-surface particulate concentrations in the assimilated run against the control run. Reductions in model biases, either positive or negative, and an increase in the correlation between simulated and observed values was achieved for October 2020.

This case study can serve as a benchmark for future relevant studies with emphasis on long-term periods and other natural aerosol species. Our results contributed to the European Space Agency Aeolus+ Innovation initiative motivation to maximize the potential of the first-ever satellite to directly observe wind profiles from space by making use of its Doppler shift information on atmospheric dynamics and particles advected by wind and its UV lidar signal. (grant no. NEWTON, 4000133130/20/IBG//Aeolus+ Innovation (Aeolus+I), in close collaboration with patterns at the National Observatory of Athens (NOA).

III. Hazard Risk Assessments (Task 6.5.c)

CARE-C and The Qatar Environment & Energy Research Institute (QEERI) are pursuing joint research collaboration to estimate and predict the contamination risks from the atmospheric dispersion of pollution, including radionuclides released by nuclear power plants, in the Middle East and the associated impacts.

The purpose of the collaboration is to develop a methodology for risk and vulnerability assessment in the Middle East, and to test this methodology through estimation of a nuclear risk to population in the state of Qatar in case of a severe accident at the nuclear risk sites. The main objectives are the following:

- Establishment of preliminary radioactivity risk maps regarding atmospheric deposition of – and the population exposure to radionuclides, following potential nuclear accidents in the Middle East.
- Risk assessment of atmospheric deposition and population exposure to radioactivity and other toxic substances, following potential accidents at nuclear power plants and other major industrial facilities.
- Establishment of an early warning system for radioactive and other toxic spills in the atmosphere in the Middle East Region, using numerical forecasting tools.

We studied the diurnal and seasonal changes in the dispersion of radionuclides using a four-member ensemble based on FLEXPART and FLEXPAR-WRF. We found that simulations are affected by the spatio-temporal resolution of meteorological inputs, the seasonal and diurnal changes in meteorological conditions, and the simulation code of choice. The preparedness programs for potential nuclear accidents, the FLEXPART community, and radionuclide dispersion modelers may benefit from our findings.

We investigate the spatiotemporal distribution of radionuclides including Iodine-131 (^{131}I) and Cesium-137 (^{137}Cs), transported from fictitious accidents at Nuclear Power Plants. To model the dispersion of radionuclides, we use the Lagrangian particle/air parcel dispersion model FLEXible PARTicle (FLEXPART) and and FLEXPART coupled with the Weather Research and Forecasting model (FLEXPART-WRF).

A four-member mini-ensemble of meteorological inputs is used to investigate the impact of meteorological inputs on the radionuclide dispersion modelling. The mini-ensemble includes one forecast dataset (GFS) and three (re)analysis datasets (native resolution and downscaled FNL, and downscaled ERA5). Additionally, we explored the sensitivity of the radionuclide dispersion simulations to variations in the turbulence schemes, as well as the temporal and vertical emission profiles, and the location of emission sources.

Towards developing capacity, the collaboration has used numerical models to simulate the atmospheric transport of pollution originating from the explosion of 4 August 2020 at Beirut, Lebanon (Figure 11). The Environmental Predictions Department of the Cyprus Institute Climate and Atmosphere Research Center has used the HYSPLIT Langrangian model to track and forecast the potential atmospheric transport of pollution. In the HYSPLIT particle model, a fixed number of particles are advected about the model domain by the mean wind field and spread by a turbulent component. The model calculates a 3-dimensional particle distribution. After the first 48 hours, the modelled concentrations are estimated to be diluted by a factor of 1000× lower compared to the initial release.

Figure 11 Time of arrival contours of particulate matter (PM2.5) plume formed after the explosion (left) and forward trajectories, starting at the accident site with ellipses showing the spatial spread of Langrangian particles over time.

For dispersion modelling, the state-of-the-art Lagrangian particle/air parcel dispersion model FLEXPART coupled with the Weather Research and Forecasting model (WRF) were used (Nabavi et al., 2022). Carbon monoxide CO and black carbon BC are modelled as proxy for gaseous and aerosol pollutants to facilitate the performance analysis of the models. FLEXPART/FLEXPART-WRF model the atmospheric transport of pollutants in both forward (source-oriented) and backward (receptor-oriented) approaches.

IV. Projects and Future Plans related to Task 6.5

The air quality forecasting activity in EMME-CARE has been instrumental in attracting additional funding through competitive processes to facilitate complementary and synergistic activities, and to establishing EPD as a regional centre of excellence in atmospheric composition modelling. In particular, **the following projects directly benefit from and contribute to the air quality and dust forecasting activity (Task 6.5)**:

- **LIFE-SIRIUS**: A System for Integrated Environmental Information in Urban areaS - LIFE Programme European Union project LIFE21-GIE-EL-LIFE-SIRIUS/10107436:

The LIFE SIRIUS implementation takes place in three EU urban metropolitan areas (Thessaloniki in Central Macedonia, Greece, Rome in Lazio, Italy, and Nicosia in Cyprus), involving directly in the Consortium the responsible authorities for air quality management in these regions towards updating Air Quality Management Plans (Deliverable D7.3).

- **ACCEPT**: Assessment of Climate Change Effects on Pollution Transport in Cyprus project, EEA AND NORWAY GRANTS

ACCEPT aims to provide new scientific knowledge on air pollution that is not currently available in Cyprus, with the expected positive impact of implementing efficient abatement strategies, improving air quality, and reducing human exposure. This will be done through the studies that will contribute to a better understanding of the local versus transported (e.g. transboundary) air pollution and provide air quality forecasts as well as testing of new technologies.

- **AQ-SERVE**: Air Quality Services for cleaner air in Cyprus. Integrated Project, The Research Promotion Foundation Programmes for Research, Technological Development and Innovation, RESTART

Combines innovative technical developments with new scientific knowledge on the characterization and prediction of air quality in order to provide an evaluation of the health impact and risk assessment of air pollution in Cyprus. Different scenarios (abatement measures) are tested in a coupled Air Quality/Health & Risk model with the objective to define efficient mitigation measures which can be translated to the public authorities (National Air Quality Action Plan, additional information in Deliverable D7.3).

- **FAIRMODE:** Forum for Air Quality Modelling in Europe.

FAIRMODE aims to provide a harmonized approach of model evaluation for regulatory purposes. We are testing the proposed methodology by assessing the performance of the Weather Research and Forecasting model coupled with chemistry (WRF-Chem) against ground-based air quality observations over Cyprus, a member state of the European Union.

- **Edu4ClimAte:** European Higher Education Institutions Network for Climate and Atmospheric Sciences (HORIZON-WIDERA-2021-ACCESS-05 — European Excellence Initiative)

Edu4ClimAte will not only facilitate the above process but will also establish a “hub of knowledge, innovation, and cooperation”, specifically aimed at addressing challenges relating to climate change and air pollution for the EMME region. As part of an international joint Research Strategy, two a new impact-oriented “Flagship Research Infrastructure” will be co-developed: the EMME “Atmospheric Modelling Platform” (EMME-AMP) will develop new digital services for a better prediction of severe air pollution and dust episodes.

V. Publications related to Deliverable D6.4 (Task 6.5)

1. Georgiou, G. K., Kushta, J., Christoudias, T., Proestos, Y., and Lelieveld, J.: Air quality modelling over the Eastern Mediterranean: Seasonal sensitivity to anthropogenic emissions, Atmospheric Environment, 222, 117 119, https://doi:10.1016/j.atmosenv.2019.117119, 2020.
2. Georgiou, G. K., Christoudias, T., Proestos, Y., Kushta, J., Pikridas, M., Sciare, J., Savvides, C., and Lelieveld, J.: Evaluation of WRF-Chem model (v3.9.1.1) real-time air quality forecasts over the Eastern Mediterranean, Geosci. Model Dev., 15, 4129–4146, https://doi.org/10.5194/gmd-15-4129-2022, 2022.
3. Kiriakidis, P., Gkikas, A., Papangelis, G., Christoudias, T., Kushta, J., Proestakis, E., Kampouri, A., Marinou, E., Drakaki, E., Benedetti, A., Rennie, M., Retscher, C., Straume, A. G., Dandocsi, A., Sciare, J., and Amiridis, V.: The impact of using assimilated Aeolus wind data on regional WRF-Chem dust simulations, Atmos. Chem. Phys., 23, 4391–4417, https://doi.org/10.5194/acp-23-4391-2023, 2023.