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Aircraft measurements and WRF-FARM modeling of Ozone and Particulate Matter in the city of Naples-Caserta

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Abstract

Tropospheric ozone in urban areas is the result of complex photochemical interactions between radicals, NOx (anthropogenic emissions), VOCs (anthropogenic + biogenic emission), UV-irradiance. Moreover, actual levels of ozone, particles and other pollutants are mediated by atmospheric transport and re-circulation, leading to concentration spatial patterns that may be de-coupled from anthropogenic emission areas, leading to high concentrations in peri-urban or sea areas that may be further advected into cities. This poses a challenge of elucidating these mechanisms and assessing to which extent emission reduction policies can aim at reaching pollution reduction targets. The transport and diffusion of atmospheric pollutants depend on meteorological conditions which makes the study of meteorological conditions of prime importance to study air quality. In this study we deploy a modeling framework (WRF + FARM) and validate it on specific intensive aircraft measurements of meteorological parameters patterns (Air temperature, humidity, wind speed, wind direction), O_3 and particulate matter in the city area of Naples-Caserta (4,434,136 inhabitants on area of 2,300 km²), the largest metropolitan area in the Mediterranean where the highest population density of Europe is reached. We will show criticalities for air quality (FARM) and atmospheric modeling (WRF) in light of specialized measurements, to assess which conditions are better represented, how PBL height and scalar temporal and spatial concentration patterns are reproduced, and define an operational framework to elucidate the complex interactions between air quality and atmospheric transport in complex urban Mediterranean areas.

Keywords: Aircraft measurements, Ozone, Vertical profile, Weather and air quality

1. Introduction

Air quality is an important aspect of environmental pollution which affects living beings to a greater extent and can reduce the life expectancy for millions of people residing in the affected areas (Chen et al, 2013) and can be the cause of severe respiratory disease responsible for death of millions of people (Turner et al.,2011). It was recently argued that exposure to a high value of Particulate Matter can increase the risk of Lung cancer (Watson, 2014). The urban areas of Naples-Caserta (4,434,136 people on area of 2,300 km²) in southern Italy are recognized as the largest metropolitan area in the Mediterranean with the highest population density of Europe (Demographic Balance Data, 2014). In last few years, the urban population of Naples-Caserta is affected by high pollution episodes due to anthropogenic activities and its effect on health is a reason of concern for the scientific community and policy makers. The Naples-Caserta area is part of Campania region of Italy which have been identified to have a subset area called as "Triangle of death" (Senior and Mazza, 2004) with a higher rates for cancer mortality in region due to environmental pollution effects. The health issues related to pollution for residents in this area have been taken by researchers to help policy makers in several studies (e.g. Trinica et. al., 2001; Altavista et. al., 2004; Senior and Mazza, 2004; Comba et. al., 2006; Fazzo et. al., 2008, Martuzzi et. al., 2009; Fazzo et. al., 2011; Pirastu et. al., 2011; Triassi et. al., 2015).
Understanding and forecasting regional and local meteorological conditions are important to find out the pollution patterns in any area. The weather forecast is important for analyzing dispersion of pollutants in region of interest (Angevine et al., 2012). The pollutants transport and dispersion models takes meteorological condition as input for transport and diffusion forecast so it is very important to obtain a good meteorological dataset for evaluation of air quality predictions (Zhang et al, 2013, Kim et al., 2013). The weather forecast can be improve using high spatial and temporal grid resolution and appropriate parameterizations combined with observed meteorological parameters at any site (Arunachalam et. al., 2006; Misenis et al., 2010). To achieve this target, we also need to use the better dataset of available terrain conditions (Yver et al., 2013; Gsella et al., 2014).

AriaSaNa is a project sponsored by Regione Campania and coordinated by the Institute for Agriculture and Forest Systems in the Mediterranean (ISAFOM) of the National Research Council. The main goal of AriaSaNa project is to create a regional observatory and forecasting system for air quality in the Campania region. In the present work, we analyze observed data sets and simulations obtained by project "AriaSaNa" over the Naples-Caserta region. Data of meteorological variables and pollutants have been collected using a small research aircraft "ERA-SkyArrow" (Environmental Research Aircraft, Gioli et al., 2006) over the Campania region from 07 to 09 October 2014 referred as Intensive Observation Period 2 (IOP2). To obtain the weather forecast in these days, we have used the Weather Research and Forecasting model (WRF-ARW) with nested domain at national and local scale. The model FARM (Flexible Air quality Regional Model) devoted to transport and diffusion of pollutants in the atmosphere has been coupled to WRF for air quality simulations.
In the present paper, we have evaluated the modeling set up (WRF+FARM work-flow) performance compared with the meteorological and air quality measurements over the Naples-Caserta region obtained by ERA-SkyArrow. The model domains use a grid of 1 km x 1 km resolution in inner most domain (domain 4) and 3 km x 3 km resolution in domain 3 for WRF. The FARM domain set up has a grid of 1 km x 1 km resolution in inner most domain (domain 4) and 4 km x 4 km resolution in domain 3 and hourly time step for both WRF and FARM. However, in the AriaSaNa operational setup of WRF model, every vertical profiles points (PRFs) within the inner most domain are near to domain boundary and thus to overcome the numerical boundary effect we have enlarged our innermost domain to take vertical profiles points well inside the domain. The daily air quality forecast (FARM) of AriaSaNa use an inner domain that does not cover the full flight track of IOP2 observations hence we have also prepared an enlarged domain (both WRF and FARM) to run at a resolution of 1 km for complete flight track, to check the effect of high resolution domain for the modeling performance. The new configuration domain for WRF is shown in Table 1. The daily AriaSaNa model simulations (available on website http://www.ariasana.org) are referred as “Operational” (*oper*) and the modified setup of WRF+FARM as “High Resolution” (*hrs*) simulation in the analysis. The results show the performance of modeling system with respect to Aircraft observations and the effect of high resolution run for the prediction.

2. Data sets

High frequency observed data sets for vertical profiles (Up and Down) of Wind Speed (WS), Wind Direction (WD), Air Temperature (T), Relative Humidity (RH) and Ozone (O_3), Particulate Matter (PM10 and PM2.5) and Carbon di Oxide (CO_2) are obtained from IOP2 flights (7-9 October 2014). In IOP2, we have made 5 flights with ERA-SkyArrow from 7-9 October 2014, details of which are as follows:

Flight 1: 07 October 2014, 08:39-10:58 UTC: Profiles 1Up, 2Down, 2Up, 3Down, 3Up, 4Up
Flight 2: 07 October 2014, 12:38-16:56 UTC: Profiles 1 Down, 1Up, 2Down, 2Up, 3Down, 3Up, 4Down, 4Up
Flight 3: 08 October 2014, 12:47-14:46 UTC: Profiles 1 Down, 1Up, 2Down, 2Up, 3Down, 3Up, 4Down, 4Up
Flight 4: 09 October 2014, 08:39-10:37 UTC: Profiles 1 Down, 2Down, 2Up, 3Down, 3Up, 4Up
Flight 5: 09 October 2014, 12:09-14:24 UTC: Profiles 1Up, 2Down, 2Up, 3Down, 3Up, 4Down, 4Up

The flight track of IOP2 has been shown in Figure 1 using Google Earth©. It is to be noted that Profile 1 (referred as PRF1 hereafter) and Profile 4 (referred as PRF4 hereafter) are observed over land, while Profile 2 (referred as PRF2 hereafter) and Profile 3 (referred as PRF3 hereafter) are observed over sea. Corresponding WRF+FARM both Operational and High-Resolution output for vertical profiles using same parameters have been evaluated.

Figure 1: Flight track for IOP2 (shown with sky blue colour lines). Location of 4 profiles (PRF) are outlined by red circles (Image source: Google Earth)

3. Modeling set up description

Weather Research and Forecasting model (WRF-ARW) is used to get the weather forecast and meteorology as input data for the model FARM (Flexible Air quality Regional Model), a 3-Dimensional Eulerian multiphase transport and atmospheric chemistry numerical model devoted to transport and diffusion of pollutants in the atmosphere over the region. WRF forecast are produced from NOAA/NCEP dataset at global scale. These data sets are describing the dynamics and thermodynamics of the atmosphere with a horizontal spatial resolution of 1 degree and with time resolution of 3 hours. The dynamics and physics schemes used by our WRF forecast are described in Table1.
The meteorological fields provided by WRF are spatially interpolated over FARM domains through the application interface module GAP to match different grid systems and geographic projections. After this step, the meteorological module SURFPRO is used to calculating the dispersion coefficients and the deposition velocity of pollutants (e.g. O_3, NO, NO_2, PM10, PM2.5, CO_2, SO_2, etc.). FARM model implements both one-way and two-way nesting. To obtain forecasts of air pollution for the Campania region and province of Naples, we have configured FARM to use the two-way nesting mode applied at two grids with spatial resolutions of 4 km and 1 km respectively. Detailed description and processing of modeling set up can be obtained from AriaSaNa site (http://ariasana.isafom.cnr.it).

Table1. Overview of WRF model configuration presently used at ARIASANA

Dynamics	Non hydrostatic
Data	NCEP GFS
Interval	3 hrs
Grid size and Resolution	Operational Domain1: (80×57) × 34 : 45km × 45km Operational Domain2: (95× 95) ×34 : 9km × 9km Operational Domain3: (69× 69) × 34 : 3km × 3km Operational Domain4: (69× 69) × 34 : 1km x 1km High Resolution set up Domain1: (80×67) × 41 : 45km × 45km High Resolution set up Domain2: (95× 95) ×41 : 9km × 9km High Resolution set up Domain3: (84× 69) × 41 : 3km × 3km High Resolution set up Domain4: (117× 111) × 41 : 1km x 1km
Map Projection	Lambert Conformal
Horizontal grid system	Arakawa-C grid
Integration time step	225 sec
Vertical coordinates	Terrain-following hydrostatic pressure vertical co-ordinate with 34 vertical levels
Time integration scheme	3rd order Runga-Kutta Scheme
Spatial differencing scheme	6th order center differencing
PBL Scheme	Mellor-Yamada-Janjic (Eta) TKE scheme
Surface layer Parameterization	Monin-Obukhov (Janjic Eta) Scheme
Land Surface Option	Noah Land Surface Scheme
Microphysics	WSM 6-class graupel scheme
Short wave radiation	(old) Goddard shortwave scheme
Long wave radiation	RRTM scheme
Cumulus Parameterization	Kain-Fritsch scheme in 1 and 2 domain and No scheme in 3 and 4 domain

4. Results and Discussions

4.1 Aircraft measurements and WRF simulations

Measurements of meteorological parameters (e.g. Air Temperature, Relative Humidity, Wind Speed, Wind Direction) from all flights are compared with corresponding WRF output. The WRF output has been extracted from the *oper* domain 3 and 4 (*oper-d3/d4*), and from *hrs* domain 4 (*hrs-d4*). The comparison of *oper-d3/d4*, *hrs-d4* and PRF 1Up:Flight 3 is shown in Figure 2. The Fig. 2a shows the vertical profile of WRF air temperatures follows the pattern of ERA-SkyArrow observation trend correctly. The model vertical profiles trends from oper-d3 and -d4 are close and are overlapping each other, as expected when 2-way nesting is used. The air temperature obtained by oper-d3 and -d4 are cooler than observations for the complete profile. However, the high resolution output (hrs-d4) has a temperature vertical profile which is near to observations and almost match observed values above 1000 m. The hrs-d4 performs better for relative humidity (Fig. 2b) compare to oper-d3 and -d4 as well. In WRF outputs both oper-d3 and d4 and hrs-d4, we have 9 level for vertical profile in lowest 1600 m. These points are more close to surface in hrs-d4. For relative humidity, the regional models such as WRF cannot reproduce the variation we observed from high frequency resolution aircraft measurements. The model simulations are not able to reproduce the decrease in humidity at 200 m and between 700-900 m and maxima at 550-700 m and 1000-1500 m. Moreover, shallow layers humidity variations are expected to be removed by buoyancy over timescales comparable with ensemble average model results.

However, the improvement of *hrs-d4* compared to *oper* domains are visible in complete profile. Between 200-1500 m, the *hrs* simulation results improve almost 10-15% in reproducing relative humidity profile than *oper-d3* and *d4*. The model reproduction of the vertical variation of wind is very good, showing the relevant decrease of wind speed and wind direction rotation in the shear layer observed between 500 and 900 m. As shown in Fig. 2c, the wind speed were over-predicted from surface to 500 m by oper-*d3* and *–d4*. The *hrs-d4*, however, under predicted winds in the lowest layer by almost 0.5 m/s. The trend of wind profiles near to surface is better reproduced by the *hrs-d4* setup. In case of wind direction (Fig. 2d), the *hrs-d4* simulation has not improved the results. The direction shear layer height is anyway reproduced by all the simulations and wind direction is reproduced with limited errors both near the surface and in the upper layers. The wind speed and direction estimated by *hrs-d4* however improves the near surface patterns in all the flights (not shown here) which helps model to simulate the boundary layer mixing in a better way and helps to improve the predictions. Similar behavior of these variables are observed for all other flights (Flights 1, 2, 4 and 5) of this study. The temperature and humidity are better simulated by the enlarged domain (*hrs-d4*) compare to operational setup. Though winds patterns are better in some profiles only and at other times are not improved compare to observations. We need to complete the investigation with surface variables observed at a ground station in more detail.

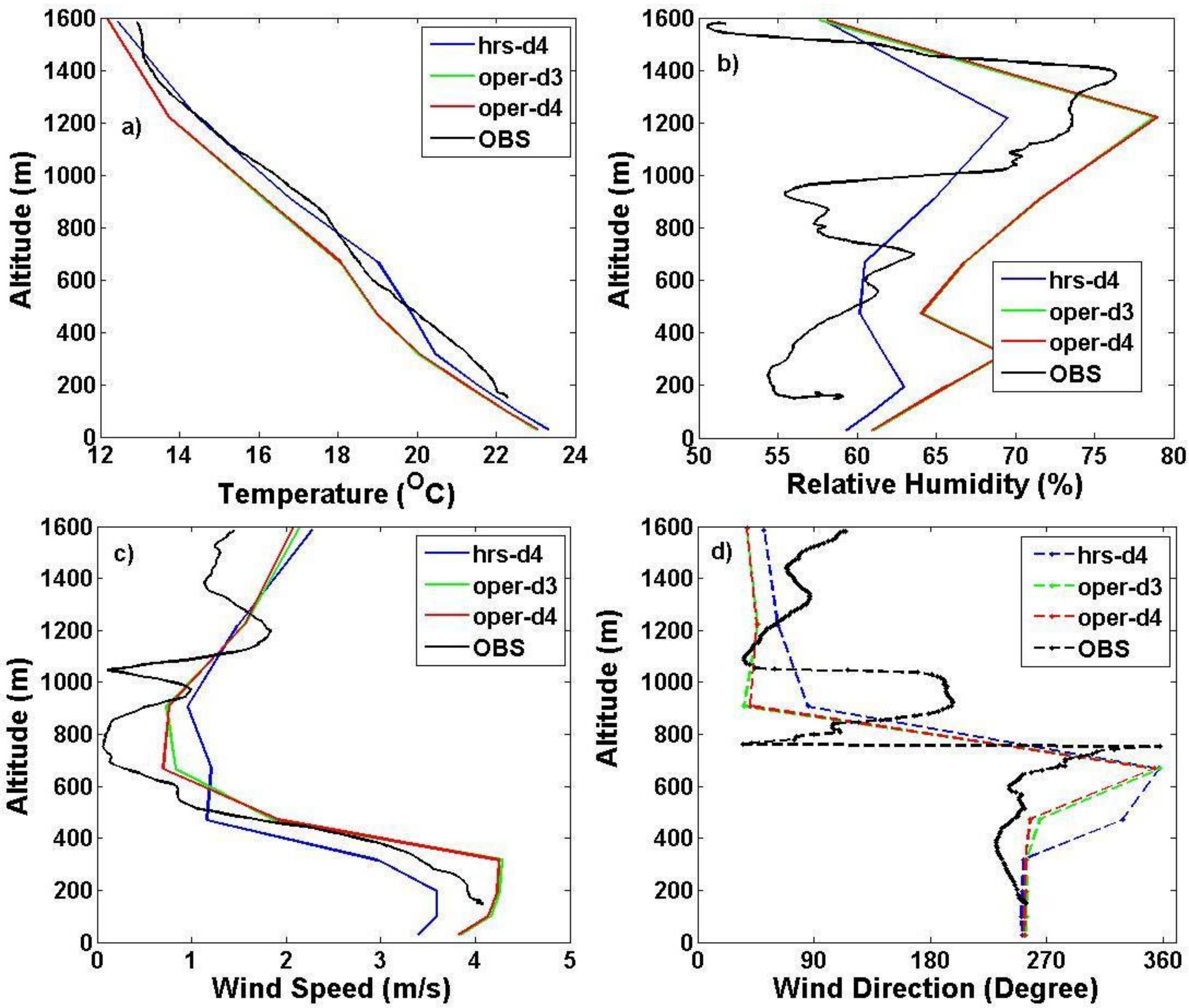

Figure 2: Comparison of (a) Air Temperature, (b) Relative Humidity, (c) Wind Speed and (d) Wind Direction from WRF Model output and Observations for PRF 1-Up Flight 3 (08 October 2014) IOP2. In Legends, hrs-d4 = High Resolution run domain 4, oper-d3 = Operational set up Domain3, oper-d4 = Operational set up Domain4 and OBS = Observational data as measured by Aircraft.

4.2 Aircraft measurements of Ozone, Particles, Pollutants and comparison with FARM simulations

The ERA-SkyArrow measures Ozone (O_3), Carbon di Oxide (CO_2) and Particulate matter (PM) for Flight 3, 4 and 5. These profiles of O_3 and PM are compared with the model simulations of FARM. However, we do not obtain CO_2 as an output variable from FARM. In Figure 3, we have compared domain 3 (oper-d3) and hrs-d4 profiles obtained from FARM simulations with observations. As shown in Figure 3, the comparison of O_3 for PRF 1-UP: Flight3, the hrs-d4 has a little improvement respect to oper-d3 profile in lowest 1 km. These improvements are also visible for all other profiles generated by all flights of IOP2. Also in FARM, we have 9 vertical levels to simulate pollutants profiles trend in lowest 1600 m. It is to be noted that the forecast of pollutants distribution is due to meteorological dataset and resolution of emission inventory data. The initial and boundary conditions are supplied from the Italian model QualeAria. Thus to improve the prediction for air quality, only model resolution seems incomplete and we need to check and analyze the other conditions along with resolution of model. Moreover, the model space resolution is expected to have limited impact on ozone concentration out of the emission source area due to the large scale that characterize photochemical phenomena.

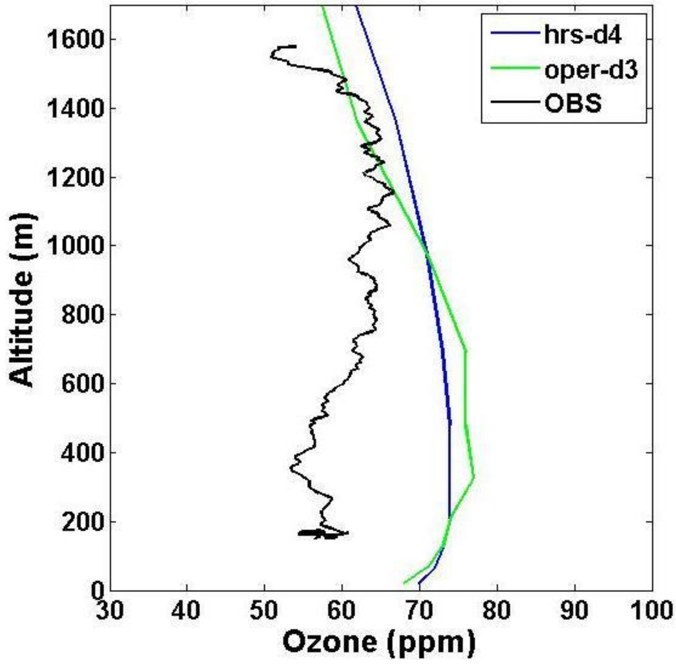

Figure 3: Comparison of Ozone Concentrations, from FARM Model output and Observations for PRF 1-Up: Flight 3 (08 October 2014) IOP2. In Legends, hrs-d4 = High Resolution run domain 4, oper-d3 = Operational set up Domain3, and OBS = Observational data as measured by Aircraft.

5. Conclusions

We have presented the comparison of model simulations (WRF+FARM) with observed profiles obtained by ERA-SkyArrow during the IOP2 campaign over Napoli-Caserta area in Campania region in southern Italy made from 07 to 09 October 2014. In this work, we have compared the meteorological variables such as air temperature, relative humidity, wind speed, wind direction and atmospheric pollutants. To improve the model simulation results, the operational domains of WRF+FARM modeling workflow setup of AriaSaNa project has been enlarged to take in account complete flight track of IOP2. This new setup of WRF+FARM (*hrs*) seems to improve the agreement of simulations compared to ERA-SkyArrow measurements. The results will be tested for all the flights profiles and the improvement by high resolution simulations will be analyzed in all the observed profiles. The complete analysis of results will be presented at ICUC9.

Acknowledgements

Authors want to acknowledge Regione Campania. Authors are also grateful to Team Arianet, Milano, for their valuable support during the present work.

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