Impact of Data Assimilation on Short-Term Precipitation Forecasts Using WRF-ARW Model

Evgeni Vladimirov[1,2](✉), Reneta Dimitrova[1], and Ventsislav Danchovski[1]

[1] Sofia University "St. Kliment Ohridski", Sofia, Bulgaria
evgeniv@uni-sofia.bg
[2] Bulgarian Air Traffic Services Authority, Sofia, Bulgaria

Abstract. In spite of efforts made by the scientific community during the last decades on the weather forecast improving, prediction of precipitation systems and fogs is still considered to be a difficult challenge. The main reason for the difficulties in prediction of these phenomena is the complexity of their formation, such as orography dependence, spatio-temporal inhomogeneity of land use and large scale synoptic conditions. Remote sensing and in-situ data assimilation have been applied to a number of studies in recent years, demonstrating significant improvements of the model results.

The objective of this study is to evaluate the performance of Weather Research and Forecasting (WRF) model, and assess the improvement in the short-term precipitation forecast, using high-resolution data assimilation of satellite and in-situ measurements. The study case is specific weather phenomenon for the Eastern parts of Balkan Peninsula - passing winter Mediterranean cyclone causing excessive amounts of rainfall in Bulgaria. A three-dimensional variational (3D-Var) data assimilation system is used in this study. The model results obtained using or not data assimilation procedure, are compared to demonstrate the impact of this method on the start time of precipitation, rainfall spacial distribution and amount.

Keywords: WRF · 3D-VAR · Data assimilation · Weather forecast

1 Introduction

The comprehensive understanding of the physical phenomena and their interactions is of key importance for solving theoretical and practical problems that are relevant to the human safety and comfort, and is also very essential for generating weather and climate change forecasts. Terrain and land-use inhomogeneity induce meso-scale flows with thermal circulation domination under quiescent conditions, or significant modification of the large-scale synoptic flow [1].

Huge diversity of processes is presented in complex terrain, such as up/downslope and valley flows; katabatic pooling of cold air in valleys during the night and associated exclusive phenomena like entrainment into, and

The original version of this chapter was revised: an acknowledgement was added. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-41032-2_73

I. Lirkov and S. Margenov (Eds.): LSSC 2019, LNCS 11958, pp. 263–271, 2020.
https://doi.org/10.1007/978-3-030-41032-2_30

detrainment from, slope and valley flows; intermittent release of air from mountain canyons; gap flows; lee waves. The great variability in spatial and temporal scales, involved in complex terrain phenomena, makes their study very complicated as both scales, meso and micro, become significant, as does as their interaction with each other. Despite of efforts of the scientific community over the past three decades, the gap in knowledge continues to challenge the accuracy of meso and smaller scale weather predictions in complex terrains, as existing sub-grid parametrization (especially for microphysics and turbulence) fail to describe the rapid spatial and temporal variability and intricate dynamics.

Sofia city is surrounded by mountains and all effects described above affect the flow dynamics leading to difficulty in weather forecast. The prediction of the cloud formation and precipitation is a great challenge in meso-scale models. One method to improve the accuracy of short-term precipitation forecast is data assimilation. This method is attractive during the last decade due to meteorological data available from different sources and increasing power of modern supercomputers. The impact of high-resolution data assimilation on short-term mesoscale numerical weather prediction using the Weather Research and Forecasting model (WRF) and its data assimilation module (WRFDA) in a winter cyclone passing over Bulgaria was investigated. The objective of the study is to assess the impact of in-situ and remote sensing data assimilation to the forecast.

2 Model Set Up for the Sofia Region

2.1 WRF Model Set up

The WRF model, version 3.8.1 is used for the numerical experiments. High resolution numerical modelling in both directions - horizontal (500 m grid) and vertical (50 irregular stretched vertical levels with greater density in the PBL) is required for this study. Detailed representation of topography and land cover for Sofia region is very important with the fine resolution used in this study. Two datasets are implemented in WRF - for topography with 1-arc-second resolution (SRTM, NASA; https://lta.cr.usgs.gov/SRTM1Arc), and more accurate physical surface properties via CORINE 2012 landuse with 3-arc-second resolution (CLC2012, EEA; https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012) [9].

Domains used in simulations are shown in Fig. 1. Four nested domains are used based on a Lambert Projection (Fig. 1), which essentially covered Balkan Peninsula (Domain 1, D1), Bulgaria (Domain 2, D2), Western part of Bulgaria (Domain 3, D3) and Sofia Valley (Domain 4, D4). The most inner domain has 157×129 cells with resolution of 500 m. The initial and boundary conditions are 6 h forecast from NCEP GSF 27.11.2015 06 UTC run (for the parent domain D1) and are derived from the 0.25° NCEP GFS Global Forecast Grids Historical Archive (http://rda.ucar.edu/datasets/ds084.1/) on every 6 h.

The WRF physics package includes: a Lin et al. microphysics scheme [2], the Rapid Radiative Transfer Model (RRTM) longwave radiation parameterization [3], Dudhia shortwave radiation parameterization [4], Noah land surface

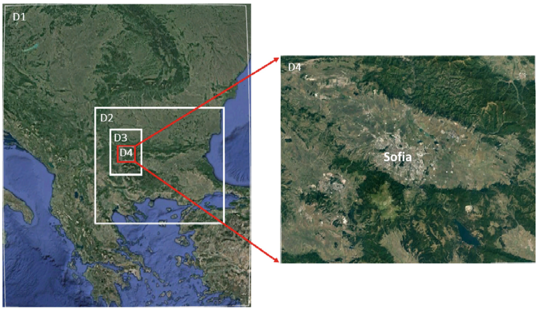

Fig. 1. Domains used in the model simulations. D1 domain includes Balkan Peninsula, D2 covers Bulgaria. D3 and D4 domains cover Sofia region.

model [5]. Simplified Arakawa - Schubert cumulus parameterization [6] is used only for D1 and D2. For high resolution domains D3 and D4 cumulus formation is resolved explicitly by the microphysics. Yonsei University - YSU [7] was selected based on previous comparison [8,9].

2.2 WRFDA 3D-var Set Up

There are a number of data assimilation techniques used in weather forecasting. One of the most prominent are the three- and four-dimensional variational data assimilation methods (3D-var and 4D-var). 3D-var incorporates meteorological data only within a time window around the initialization moment and in this method the analysis increment (an increment is introduced due to the actual observations) does not evolve in time, e.g. it has effect only at the beginning of the simulation. On the other hand 4D-var method uses tangent linear and adjoint models which model the propagation of analysis increment and more computing time is needed [12]. The 3D-var data assimilation method [11] from WRFDA [10] module version 3.8.1. is exploited with the simulations.

The 3D-var data assimilation method represents the process of combining observations and short-range forecasts to obtain initial conditions for the weather forecast simulations at set time intervals.

$$J(x) = (x - x_b)^T \mathbf{B}^{-1} (x - x_b) + (y - H[x])^T \mathbf{R}^{-1} (y - H[x]) = J_b - J_o \qquad (1)$$

In (1) J(x) is called cost function of the analysis (penalty function); J_b is the background term and J_o is the observation term. With data assimilation implementation the initial and boundary conditions at the starting time are corrected so that the cost function of the given element has minimum value.

We apply in this study the standard background error statistics **B** from generic background error data file, provided with the WRFDA module, and the standard variational bias correction. WRFDA is capable of using two radiative transfer models for retrieving meteorological data from remote sensing satellite observations - RTTOV and CRTM. The last one is exploited in this work. For the particular case a ± 1 h time interval around the initialization of the model is used for additional meteorological data assimilation. The advantage of this methodology is to provide the best estimation of the initial conditions by gathering meteorological observations.

2.3 HPC Infrastructure

The WRF model is designed to be parallel computing code along with its corresponding data assimilation module WRFDA [13]. Weather simulations and variational data assimilation in this study are carried out on a standard HPC infrastructure - the PHYSON cluster (http://physon.phys.uni-sofia.bg/hardware-en). It is a compact 216 core high performance linux cluster. The system has a 524 GiB of RAM and 6.5 TB disk space needed to store the output of the simulations that are usually large - ranging from few to several tens of gigabytes in size. Most computing nodes consist of 8-core SMP platforms. PHYSON is installed in Sofia University and dedicated to support scientific research and education.

3 Conventional and Nonconventional Observations for Data Assimilation

There are two types of data typically assimilated - conventional and nonconventional. The difference is that conventional are provided in GTS (Global Telecommunication System) and nonconvenitonal could be local, for example satellite, radar, rain gauges, automated weather stations and other. Due to large spatial coverage satellite data from a number of space based sensors are chosen to be assimilated in this particular study. The conventional data from GTS (included in Table 1) and observations from instruments on sun-synchronous orbiting satellites (included in Table 2), available in the time interval around noon (from 11:00 UTC to 13:00 UTC) and thereafter, have been assimilated. The observations used in this work are presented in Tables 1 and 2.

4 Case Study

27.11.2015 (Synoptic analysis)
The case study is well-defined low pressure system above Ionian sea, with center situated west of Bulgaria (see Fig. 2). The south-western flow transported moist and warm air over western Balkans. A warm front and a cold front has consecutively passed over Bulgaria during the next few days followed by an occlusion. The system has provoked intensive precipitation over the Sofia region, started as rain from occasional thunderstorms, and turned into snow with the temperature decrease. Bad weather conditions have caused difficulties in traffic and electricity provision.

Table 1. Number of conventional observations assimilated in each domain

Conventional observations	D1	D2	D3	D4
Sounding reports	9	1	1	1
Synoptic reports	359	58	4	2
Geostationary satellite atmospheric motion vectors	480	90	3	0
GPS Refractivities	300	0	0	0
METAR reports	99	15	1	1
Ship reports	7	0	0	0

Table 2. Data source for nonconventional observations assimilated in each domain

D1	D2	D3	D4
noaa19-amsua	noaa19-amsua	noaa19-amsua	noaa19-amsua
eos2-airs	eos2-airs	-	-
eos2-amsua	eos2-amsua	eos2-amsua	eos2-amsua
jpss0-atms	jpss0-atms	jpss0-atms	jpss0-atms
noaa19-mhs	noaa19-mhs	noaa19-mhs	-

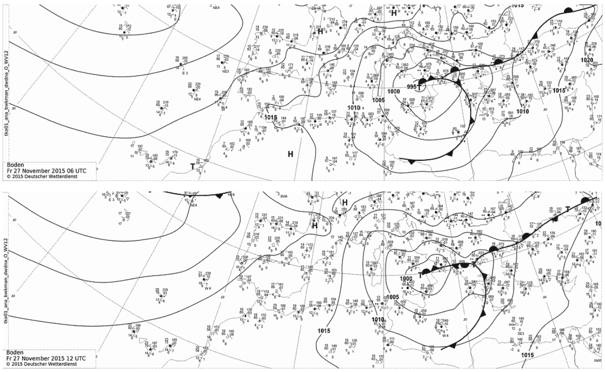

Fig. 2. Analysis from DWD (taken from wetter3.de) for 27.11.2015 of surface pressure (hPa) and frontal systems. The upper is for 06 UTC and the lower - 12UTC

5 Results and Discussion

5.1 Numerical Experiments

Several sources of observations are used in this study - surface observations (Synoptic, METAR and Ship reports, Table 1), upper air observations (Sounding reports, Table 1) and satellite data (Geostationary satellite atmospheric motion vectors and GPS Refractivities, Table 1 and all instruments, Table 2). Observational data are named satellite and non-satellite (surface and upper air observations) for further convenience. Four different numerical experiments are performed – (1) simulation without data assimilation; (2) simulation with only satellite data assimilated; (3) simulation with only non-satellite data assimilated; (4) simulation with satellite and non-satellite data assimilated. The effect on different type data assimilation on short-term local forecast is estimated by plotting differences in fields of temperature and water vapor mixing ratio.

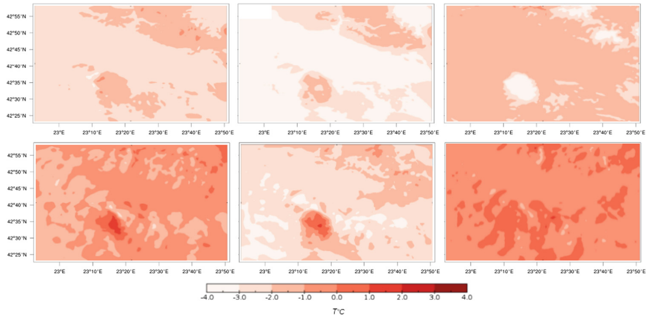

Fig. 3. Temperature (T) field differences at first sigma model level (∼10 m) - (a), (b), (c); and at the 30-th sigma model level (∼1500 m) - (d), (e), (f). T field difference between the case with all data assimilation and the field without assimilation (a, d); between satellite observations assimilation and the field without assimilation (b, e); between non-satellite data assimilation and the field without assimilation

5.2 Temperature

The correct analyses of the temperature fields near the surface and aloft is important, especially for assessment of the type of precipitation. Differences between results from described above experiments are shown in Fig. 3. The assimilation of non-satellite data is less significant (Fig. 3c, f), providing cooling effect ∼1 °C at first model level (∼10 m) and do not affect the upper levels (the main reason is that only 1 measurement per day at one location is available from the sounding reports in this area). Satellite data assimilation has meaningful effect at all levels, leading to cooling effect near the ground (∼3–4 °C) which is extended in PBL above the valley floor, but in opposite show warming effect at the higher levels above the Vitosha mountain.

5.3 Water Vapor Mixing Ratio

Water vapor mixing ratio (WVMR) is used in synoptic analysis to provide information on the air mass moisture content above the area of interest. High WVMR and low temperatures are a sign for a possible precipitation. Differences between results from described above experiments are shown in Fig. 4. Again the effect of

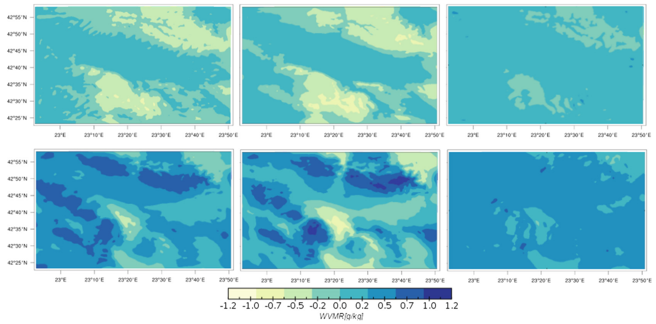

Fig. 4. WVMR field differences at first sigma model level (~10 m) - (a), (b), (c); and at the 30-th sigma model level (~1500 m) - (d), (e), (f). WVMR difference between assimilated all data and without assimilated data (a, d); between satellite observations assimilation and without assimilation (b, e); between non-satellite data assimilation and without assimilation (c, f)

satellite data assimilation is more significant. The model output with assimilation provide higher moisture inside the valley and drier air above the mountains at the near surface level (Fig. 4a, b). The moisture augmentation due to satellite assimilation is more significant at higher level (Fig. 4d, e).

6 Vertical Profiles of Temperature and Relative Humidity

A comparison between vertical profiles of temperature and relative humidity extracted from simulations with and without data assimilation is shown in Fig. 5. The effect of satellite data assimilation is very significant for the relative humidity. Only surface data assimilation is not enough to correct deficit in model

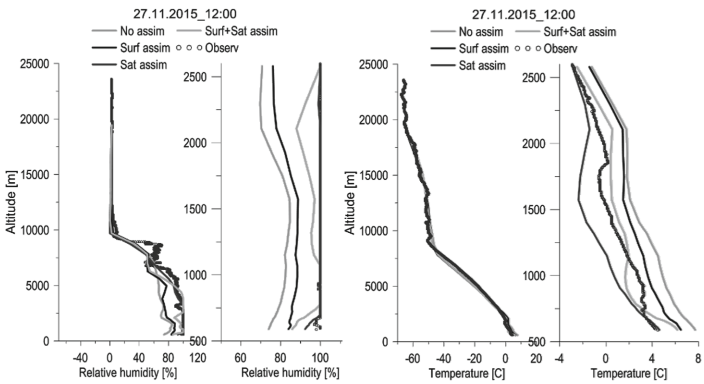

Fig. 5. Vertical profiles of relative humidity (left) and temperature (right). Different altitudes are shown, the right parts of both plots are zoomed to the 2500 m to emphasize on the differences in the PBL

results. Better agreement with observations is registered in both vertical profiles inside PBL. Using satellite data assimilation increase the relative humidity with ∼10% and reduce temperature with ∼4 °C.

7 Conclusions

Conventional and nonconventional meteorological data had been assimilated in this case study. Satellite data assimilation showed improved prediction of temperature and relative humidity for Sofia region, especially at lower altitudes. Meteorological characteristics were simulated better with only satellite data assimilation, moreover including non-satellite observations in assimilation process diverted results from the actual observations. The case study showed that 3D-var data assimilation in WRF could be used for improving prediction of temperatures and humidity, that are crucial for the precipitation forecasts in Sofia region.

Acknowledgements. This work has been supported by Research Fund at the Bulgarian Ministry of Education and Science, grant number DN4/7 (Study of the PBL structure and dynamics over complex terrain and urban area). We acknowledge also the provided access to the e-infrastructure of the NCDSC - part of the Bulgarian National Roadmap on RIs, with the financial support by the Grant No D01-221/03.12.2018.

References

1. Bodine, D., Klein, P.M., Arms, S.C., Shapiro, A.: Variability of surface air temperature over gently sloped terrain. Appl. Meteorol. Climatol. **48**, 1117–1141 (2009)
2. Lin, Y.L., Farley, R.D., Orville, H.D.: Bulk parametrization of the snow field in a cloud model. J. Appl. Meteorol. **22**, 1065–1092 (1983)
3. Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J., Clough, S.A.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. J. Geophys. Res. Atmos. **102**(4), 16,663–16,682 (1997)
4. Dudhia, J.: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. J. Atmos. Sci. **46**, 3077–3107 (1989)
5. Arakawa, A., Schubert, W.H.: Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. J. Atmos. Sci. **31**, 674–701 (1974)
6. Hong, S., Noh, Y., Dudhia, J.: A new vertical diffusion package with an explicit treatment of entrainment processes. Mon. Weather Rev. **134**(9), 2318–2341 (2006)
7. Arnold, D., Schicker, I., Seibert, P.: High-resolution atmospheric modelling in complex terrain for future climate simulations (HiRmod). VSC report (2010)
8. Egova, E., Dimitrova, R., Danchovski, V.: Numerical study of meso-scale circulation specifics in the Sofia region under different large-scale conditions. Bul. J. Meteorol. Hydrol. **22**(3–4), 54–72 (2017)
9. Vladimirov, E., Dimitrova, R., Danchovski, V.: Sensitivity of the WRF model results to topography and land cover: study for the Sofia region, Annuaire de l'Université de Sofia "St. Kliment Ohridski", Faculté de Physique **111**, 87–101

10. Barker, D., et al.: The weather research and forecasting model's community variational/ensemble data assimilation system: WRFDA. Bull. Am. Meteorol. Soc. **93**, 831–843 (2012)
11. Barker, D.M., Huang, W., Guo, Y.-R., Bourgeois, A.J., Xiao, Q.N.: A three-dimensional (3DVAR) data assimilation system for use with MM5: implementation and initial results. Mon. Weather Rev. **132**, 897–914 (2004)
12. Mazzarella, V., Maiello, I., Capozzi, V., Budillon, G., Ferretti, R.: Comparison between 3D-Var and 4D-Var data assimilation methods for the simulation of a heavy rainfall case in central Italy. Adv. Sci. Res. **14**, 271–278 (2017)
13. Shainer G., et al.: Weather research and forecast (WRF) model performance and profiling analysis on advanced multi-core HPC clusters. Conference. linuxclusterinstitute.org (2017)