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Simulation of a severe convective storm using a numerical model with explicitly incorporated aerosols

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A B S T R A C T

Despite an important role the aerosols play in all stages of cloud lifecycle, their representation in numerical weather prediction models is often rather crude. This paper investigates the effects the explicit versus implicit inclusion of aerosols in a microphysics parameterization scheme in Weather Research and Forecasting (WRF) – Advanced Research WRF (WRF-ARW) model has on cloud dynamics and microphysics. The testbed selected for this study is a severe mesoscale convective system with supercells that struck west and central parts of Serbia in the afternoon of July 21, 2014. Numerical products of two model runs, i.e. one with aerosols explicitly (WRF-AE) included and another with aerosols implicitly (WRF-AI) assumed, are compared against precipitation measurements from surface network of rain gauges, as well as against radar and satellite observations. The WRF-AE model accurately captured the transportation of dust from the north Africa over the Mediterranean and to the Balkan region. On smaller scales, both models displaced the locations of clouds situated above west and central Serbia towards southeast and under-predicted the maximum values of composite radar reflectivity. Similar to satellite images, WRF-AE shows the mesoscale convective system as a merged cluster of cumulonimbus clouds. Both models over-predicted the precipitation amounts; WRF-AE over-predictions are particularly pronounced in the zones of light rain, while WRF-AI gave larger outliers. Unlike WRF-AI, the WRF-AE approach enables the modelling of time evolution and influx of aerosols into the cloud which could be of practical importance in weather forecasting and weather modification. Several likely causes for discrepancies between models and observations are discussed and prospects for further research in this field are outlined.

1. Introduction

The overall loss from storms in Europe reached US$ 6.1 billion in the first half of 2016 (Munich Re, 2016). The central Balkan region is identified as the second most favorable area in Europe for development of significant thunderstorms (Brooks et al., 2003). The same study showed that the east parts of Bosnia and Herzegovina together with the west parts of Serbia have approximately 30 days per year with conditions favorable for development of vigorous thunderstorms. The main causes of severe weather in these regions are cumulonimbus (Cb) clouds. These convective clouds can exist isolated, but frequently, and more importantly, they form in a group. This complex cluster of thunderstorms is called a Mesoscale Convective System (MCS) and depending on the size and shape of cloud arrangements, as well as precipitation patterns, the MCSs are often subdivided into squall lines, tropical cyclones and mesoscale convective complexes (Maddox, 1980).

Although being extremely prone to severe weather and MCSs in particular, the central Balkan region seems to be left out of many studies that investigated the MCSs over Europe. For instance, Morel and Senesi (2002) excluded the Balkans from their comprehensive analysis of MCSs over continental Europe. Similarly, Tudurí and Ramis (1997) only analyzed the Western Mediterranean region. Furthermore, some of the very recent case studies on this subject were also exclusively focused on the south and southwestern parts of Europe (Cohuet et al., 2011; Romero et al., 2015; Gascón et al., 2015; Duffourg et al., 2016).

However, cloud dynamics and microphysics of cumuliform clouds are known to be highly dependent on topography and local physical characteristics of the region. This disparity can be observed by comparing the results of different case studies from around the globe (e.g. Bringi et al., 2009; Ćurić and Janc, 2010; You et al., 2016). This diversity of results between different regions shows that case studies play an important role in identifying a gap in scientific knowledge. Their findings, if the studies are carefully conducted, can contribute to deeper understanding of cloud physics and microclimate of the region.

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In addition, case studies are good source of data for validation of different numerical and analytical models. Some examples of few case studies on the severe thunderstorms in the Balkans are the one performed by Ćurić et al. (2003, 2007), Mahović et al. (2007) and Spiridonov and Curic (2015).

Numerical simulations of clouds and precipitation are sensitive to the choice of utilized microphysical scheme. Unfortunately, it is not a straightforward task to assess the accuracy of different schemes (Levin and Cotton, 2009). In this paragraph, we will discuss several relevant and recent studies on this subject from the Balkans. Ćurić and Janc (2010) investigated differences between observed and modelled amounts of precipitation in flat and mountainous regions of the central-north and eastern Serbia. Using a few different size distributions of raindrop spectrum in their cloud-resolving model, they concluded that the Khrgian-Mazin size distribution provides the best matching between numerical results and observations in both flat and rugged regions. Kovačević and Ćurić (2013) performed a comparison of two microphysical schemes, one with and the other without hailstone embryos, and they showed the scheme with the embedded hailstone embryos gives better results, such as the time occurrence of hailstone and accumulation of hail on the ground. In a very recent paper, Kovačević and Ćurić (2015) demonstrated that the unified Khrgian-Mazin distribution is more accurate at modelling rain showers than the monodisperse Marshall-Palmer distribution. Efstathiou et al. (2013a, 2013b) tested the Weather Research and Forecasting (WRF) model at simulating an intense rainfall event over Chalkidiki, Greece, using few different cloud microphysics schemes and two different boundary layer schemes. They showed that performances of each scheme depend on the type of numerical product that is analyzed. For example, the Ferrier scheme was the best option for modelling the intense hourly precipitation rates, while the Purdue-Lin scheme accurately captured the locations of maximum rainfall. None of the above studies, however, investigated the impact of modelled aerosols on cloud dynamics and microphysics. Tao et al. (2012) in a review study reported that different aerosol treatments can result in large discrepancies between simulated precipitation rates. Interestingly, they concluded that the under- or over-predictions of modelled precipitations are not a general rule, but it rather varies from study to study.

For these reasons, the main motivation behind this paper is to build up on the previous studies and investigate the differences between the numerical model with and without explicitly incorporated aerosols. The test case is a severe MCS that occurred in the western and central Balkans on the afternoon of July 21, 2014. As discussed earlier, this geographical region is extremely prone to severe thunderstorms and therefore it would be interesting to analyze the role the aerosols play in numerical simulations of these events. Numerical model employed in this study is WRF – Advanced Research WRF (ARW), version 3.8 (Skamarock et al., 2008). The main objective of this paper is a comparison between numerical products obtained through implicitly (Thompson et al., 2008; hereafter T08) and explicitly (Thompson and Eidhammer, 2014; hereafter TE14) incorporated aerosols in WRF-ARW. In this paper, the implicit inclusion of aerosols refers to the case when aerosols are not modelled directly, but their abundant presence in the atmosphere is a priori assumed. That is, all microphysics processes are decoupled from aerosols and their physical-chemical characteristics. Both cases are validated against the observations. We seek to determine the benefits, if any, of explicitly modelled aerosols in numerical modelling of severe convective thunderstorms.

An explicit inclusion of aerosols leads to the activation of limited number of aerosols as cloud condensation nuclei (CCN) and ice nuclei (IN) (Lim and Hong, 2009; TE14). That is, cloud droplet number concentration varies in contrast to implicitly modelled aerosols where this number is fixed constant, such as in T08. This approach enables direct prediction of the concentration of cloud water droplets, as well as the concentration numbers of activated aerosols that serve as CCN and IN. In the TE14 scheme, the concentration of activated CCNs depends on the in-cloud temperature, vertical velocity, the total number of available aerosols, as well as the two prescribed constants (hygroscopicity parameter and the mean radius). The activation rules are based on the results reported in the works by Feingold and Heymsfield (1992) and Eidhammer et al. (2009), and the activation is most sensitive on the total number of available aerosols and vertical velocity. When it comes to the ice phase, the number of mineral dust aerosols dictates the number of activated INs. It has been demonstrated that mineral dust is highly active IN with moderate concentrations in the atmosphere (Hoose et al., 2010; Murray et al., 2012). TE14 tested the scheme for an idealized case of two-dimensional flow over a hill, as well as for a winter cyclone above the continental United States. They noticed the aerosols had largest impacts in the zones of light precipitation. Recently, Nugent et al. (2016) used the TE14 scheme to analyze six idealized cases of thermally driven orographic convection, but their study is limited to warm clouds. Thompson et al. (2016) coupled the TE14 scheme with the Rapid Radiative Transfer Model-Global scheme for radiation and reported small differences between the effective radii and cloud optical depth calculated in the coupled and uncoupled cases. Similarly to TE14, they also recognized that more research is needed on this subject. It seems there is a general agreement in cloud modelling community that the “cloud-aware” aerosol schemes require more testing due to the novelty of this approach and the large complexity of numerous interactions between aerosols and other methodological parameters. Hence, the motivation behind this paper is to further contribute to this subject performing detailed comparisons between the T08 and TE14 schemes for a specific case of the severe thunderstorm.

This paper is organized in the following fashion. Description of numerical model used in this study is given in Section 2, while Section 3 describes the analyzed case study. The results of numerical modelling are presented in Section 4 as follows. First, Section 4.1 will demonstrate the capability of WRF-ARW with explicitly included aerosols to reconstruct the dynamics and mesoscale footprint of the analyzed MSC. The model results will be compared against radar and satellite images of this event. Second, Section 4.2 is the verification of the modelled precipitation rates with and without explicitly included aerosols. Here, the model results will be compared against the observations from the dense network of surface weather stations in central and west Serbia. Section 4.3 contains discussion concerning the differences of these two treatments of aerosols and the possible causes of discrepancies between the reported results. Prospects for future research are outlined in Section 4.4, while the main conclusions of this study are highlighted in Section 5.

2. Model configuration and data

The non-hydrostatic numerical model used in this study is WRF-ARW (v3.8). The tests were performed embedding four one-way nested domains with horizontal grid spacing of 27, 9, 3, and 1 km on Arakawa C-grid (Fig. 1). The largest domain includes Europe and parts of the north Africa in order to simulate the transport of aerosols from the Sahara Desert to the Balkans. The recommended 3:1 nesting ratio is used and all domains had 64 vertical levels. The finest domain encompasses the MSC that is used as a test case in this study (see Section 3). The physical schemes used are T08 and TE14 for cloud microphysics (Thompson et al., 2008; Thompson and Eidhammer, 2014), the Rapid Radiative Transfer Model scheme for longwave radiation (Mlawer et al., 1997), the Dudhia scheme for shortwave radiation (Dudhia, 1989) and the Noah land surface scheme (Ek et al., 2003). Cumulus convection is parameterized in the coarse domains (27 and 9 km horizontal resolutions) utilizing the Kain-Fritsch scheme (Kain, 2004), whereas a cumulus scheme was not used for the finest two domains (3 and 1 km horizontal resolutions). In TE14, for instance, cumulus parameterization was excluded in the domains with horizontal grid-spacing below 4 km. Lastly, the planetary boundary layer scheme employed in this study is the Yonsei University scheme, which is