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ARTICLE

Ensemble Cloud Model Application in Simulating the Catastrophic Heavy Rainfall Event

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ABSTRACT

An attempt has been made in the present research to simulate a deadly flash-flood event over the City of Skopje, Macedonia on 6 August 2016. A cloud model ensemble forecast method is developed to simulate a super-cell storm's initiation and evolutionary features. Sounding data are generated using an ensemble approach, that utilizes a triple-nested WRF model. A three-dimensional (3-D) convective cloud model (CCM) with a very fine horizontal grid resolution of 250-m is initialized, using the initial representative sounding data, derived from the WRF 1-km forecast outputs. CCM is configured and run with an open lateral boundary conditions LBC, allowing explicit simulation of convective scale processes. This preliminary study showed that the ensemble approach has some advantages in the generation of the initial data and the model initialization. The applied method minimizes the uncertainties and provides a more qualitative-quantitative assessment of super-cell storm initiation, cell structure, evolutionary properties, and intensity. A high-resolution 3-D run is capable to resolve detailed aspects of convection, including high-intensity convective precipitation. The results are significant not only from the aspect of the cloud model's ability to provide a qualitative-quantitative assessment of intense precipitation but also for a deeper understanding of the essence of storm development, its vortex dynamics, and the meaning of micro-physical processes for the production and release of large amounts of precipitation that were the cause of the catastrophic flood in an urban area. After a series of experiments and verification, such a system could be a reliable tool in weather services for very short-range forecasting (now-casting) and early warning of weather disasters.

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1. Introduction

Numerous studies have shown that timescale atmospheric non-hydro static models are reliable tools for forecasting severe convective systems, their initiation, and evolution, but they tend to underestimate the intensity of convective rainfall and their right location. This uncertainty mainly origins from the nonlinear atmospheric nature, small-scale convective processes as well as the initial conditions (IC), lateral boundary conditions (LBC), model configuration, horizontal grid resolution, choice of microphysics, treatment of convection, parameterize, and other factors [1,2]. Many studies have focused on the effect of horizontal grid resolution, to improve the convective precipitation, forecast [3-7]. The first numerical simulation with an explicit treatment of convection using a temporal timescale model was performed by Bernadet, et al. [6].

In addition to the approach to the better discretionary of the grid of points [8] also estimated that the forecast of convective systems also depends on surface processes such as differential heating, and soil moisture, which affects the perturbation of temperature and pressure, and affects the dynamic effect of voracity in the boundary layer, which are responsible for initiating convection. Other studies [9-11] were also conducted, which were devoted to the investigation of the physical processes of convective storms, which used the Weather Research Forecast Non-Hydrostatic Mesoscale Model WRF-NMM [12]. Further efforts were to develop an efficient and flexible system based on the Weather Research and Forecasting (WRF) model configuration [13] with the optimal 4-km resolution, with the corresponding microphysics, and the surface characterizations schemes for the treatment of the planetary boundary layer (PBL) processes, radiation schemes, including an explicit treatment of moist convection—avoiding cumulus characterization [14]. Some studies indicated that the deterministic forecasts of convective systems produced with heavy rainfall could be also improved by the increase in resolution. Weisman, et al. [15] showed an advantage in forecasting different modes of convection, using the WRF 4-km run, with an explicit treatment of the convection. However, uncertainty, when it came to the precise location and intensity of convective precipitation remained. Research has also shown, that with an increase in resolution, there may be an increase (overestimation) of convective precipitation or a delay in the onset of convection [16-20]. To adequately address the problem related to uncertainty in the initial data and to improve the forecast accuracy of convective rainfall, a new ensemble technique was initiated and applied in real-time storm forecasting [21]. A fine convective-permitted 1-km resolution has been applied in the Advanced Regional Prediction System (ARPS) [22], as part of the National Oceanic and Atmospheric Administration (NOAA) 2008 Spring Experiment. Elmore, et al. [23] developed an ensemble approach to forecasting thunderstorms. The results showed that this system has an advantage in forecasting different modes of convection, during the thunderstorm life cycle. There is no doubt that the ensemble approach is more reliable, but a computationally more expensive method, that mostly depends on computer performance. However, numerous experiments and sensitivity tests showed, that by appropriate model setup and turning to a fine grid discretionary (from 4 km to 1 km), a more reliable forecast of convective systems could be achieved. Many other studies [24-26] focused on evaluating various nested WRF model configurations in the simulation of severe convective weather and flash floods, which occurred in different geographic regions. In addition, real-time convection-allowing ensemble forecasts, are conducted in the frame of the NCAR's experiment [27]. In addition, Zittis, et al. [28] showed in their work that the WRF model configured in this way can successfully forecast extreme precipitation over the Mediterranean. Considering the importance of small-scale convective processes on the evolution of the system and the formation of intense precipitation in many centers, the development of numerical prognostic systems that use modern convective-scale data assimilation techniques and a very fine resolution of 1 km grid points in routine forecasting [29]. In doing so, the ensemble approach is also used in providing the initial data and model initialization, or they use several models with the same initial fields. The verification showed that the numerical forecast of convective scales could forecast different modes of convection but failed to accurately predict extreme cases related to the accurate forecast of location and relative intensity of heavy rainfall, which we already have mentioned. To address this problem to some extent [30] proposed a method of coupling the WRF model and the cloud model for detailed qualitative-quantitative assessments of extreme convective precipitation. The cloud model was initialized using a homogeneous horizontal field applying the standard perturbation technique and the single vertical meteorological profile based on WRF model outputs. Recently, a diagnostic tool has been developed, based on selected complex instability criteria [31], for more accurate convective-scale forecasts and severe weather alerts.

The present study is focused on a catastrophic flash-flood event that occurred on 6 August 2016 in the city of Skopje. The flash flood that happened in urban areas had catastrophic consequences because it took human lives and caused great material damage. For these reasons, it is very important to evaluate each severe weather event, especially in the era of accelerated climate changes and the increased frequency of weather extremes. In this context, the study by Milevski [32] provided an overview of natural disasters in Macedonia, with a special emphasis on the torrential flash-flooding event over Skopje. There is also a diagnostic overview of the extreme case of flooding in Skopje [33] and an overview of possible morphological, hydro-logical, and other risks for sudden flooding. The main goal of this research is to examine the possibility of the connective cloud model in the simulation of the super-cell storm evolved from a limescale convective system MCS, which produced heavy rainfall and caused a catastrophic flash flood in Skopje on August 6, 2016. The main goal of the present research was to evaluate the cloud model performances in a more realistic simulation of the super-cell storm evolution and its skill in a more accurate quantitative assessment of heavy rainfall. Section 1, in addition to the synoptic overview, provides a brief description of the urban flash flooding event, with catastrophic consequences. The next section is devoted to the description of the forecasting system, the ensemble technique, and the cloud model overview. The main results are shown and discussed in the next chapter, where the main conclusions are given about the performance of the system and its potential advantages in making quantitative forecasts and the most abundant convective precipitation.

2. Observational Analysis

On August 6, 2016, the Skopje city area and its surroundings were hit by very severe convective weather which took on the dimensions of a devastating super-cell storm with intense rainfall (Figure 1a) a flash flood caused the loss of 23 human lives and caused significant material damage. However, considering that the intense development of the storm occurred over a very specific topography shown in (Figure 1b) where there is no observation, most likely more convective precipitation fell. The total estimated amount of rainfall evidenced within 2 hours reached about 100 mm. Figure 2a illustrates the consequences of a flash flood, especially in the vicinity of the ring road, the most affected area. A significant amount of rainfall was recorded in Skopje, Macedonia on 6 Aug 2016. The local maximum value of 106.3 mm was measured at the automated meteorological station AWS- "Gazi Baba", located northeast of Skopje valley in the vicinity of the most affected area. The heavy rainfall period occurred from 1530 UTC to 1640 UTC with a peak rainfall intensity evidenced at 1550 UTC (Figure 2b) recorded at AWS - "Gazi Baba" in the vicinity of the most affected flooding area.

Analysis of the observational material points to several interesting details. On 6 August 2016 at noon UTC, the cut-off low positioned over the Ionian Sea was approaching from the southwest. It is seen that there is no

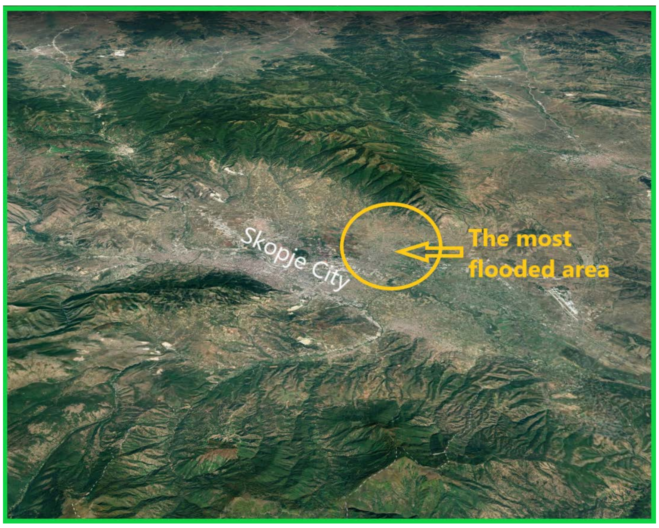

Figure. 1 (a) Geographic map of Skopje valley and the surrounding mountains. A white circle denotes a flash-flood heavy rainfall area. (b) Photo of the most affected flooding area, located northeast of Skopje, around the ring road. (Credit: WMO).

pronounced carcinogenicity or significant convection of positive voracity, which could contribute to the development of convective systems. The mean-sea level pressure distribution shown in Figure 3a and the ISO-potentiality field patterns at 500 hPa (see Figure 3b), favor a warm and moist air convection across the western part of Macedonia. Under such conditions, the individual convective cells were initiated, helped by orographic forcing, and gravity-produced waves associated with the mountain-induced timescale convective system. This long-lasting convective disturbance in the afternoon hours over Skopje valley transformed into a limescale convective vortex (a mid-level, warm-core low-pressure center) of a limescale convective system (MCS) because of favorable topographical characteristics of the area, surface wetness, differential heating, and the latent heat release over a longer period.

This implies that heavy convective precipitation is formed due to a locally forcing environment that is not the result of a synoptic-driven system. From the satellite image, two convective systems can be distinguished, one around the Ionian Sea in the high-altitude cyclone (the center of low pressure), and the other that extends NE to NW of Macedonia, due to a prefrontal disturbance. Regarding the atmospheric lighting (see Figure 3d), the atmosphere above the urban area was very unstable and active, so more than 1000 lightning were registered in a very short period.

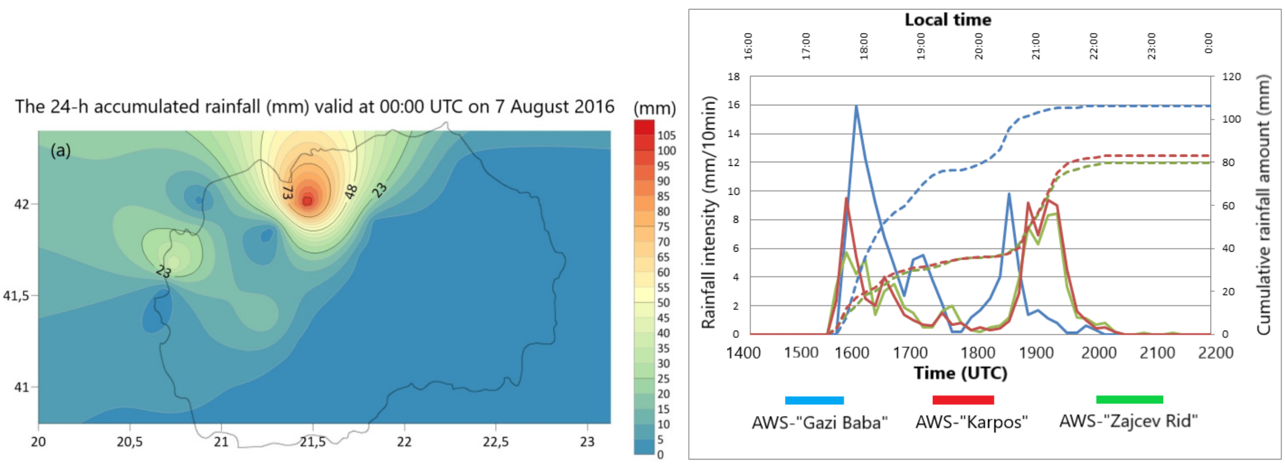

Figure 2. (a) An isohyet chart with a total 24-h accumulated rainfall (mm) in Macedonia valid at 0600 UTC on 7 Aug 2016. (b) Rainfall intensity (mm/10min) obtained at the AWS- "Gazi Baba" whose position is closer to the main target area (blue curve), AWS- "Karpos" located in the central part of Skopje City (red curve), and AWS- "Gazi Baba" located westerly from the target area at the Hydrometeorological Service of Macedonia (HSM). The dotted lines represent a cumulative rainfall amount registered for the 24 hours.

3. The Design of the System

For cloud initialization, the perturbation method is usually used, which is an approximation for the missing information about temperature deviations (deviations) when initiating the development of a convective cell, in the center of a thermal balloon with a certain radial dimension and the center is positioned above the ground. Initial vertical fields of meteorological parameters, taken from sounding or prognostic model output in the selected area, by users. horizontally homogeneous environment. In this research, the ensemble approach is used in the initialization of the cloud model, which implies the run of the model based on prognostic soundings obtained with the help of the WRF model in several network points in the selected domain of interest. In this way, a more average representative cloud development is obtained, which uses the disturbance of the basic state of the atmosphere in a smaller domain.

3.1 Numerical Model Description

The numerical experiments have been performed using the Advanced Research version of the WRF triple nested model, version 4.0 [1, 13]. The parent domain (D1) with a horizontal grid resolution of 10 km covers the Southeast Europe SEE domain. The first inner nested domain (D2) with a grid spacing of 3.3-km captures the whole territory of Macedonia (Figure 4a). A 1.1-km nested domain (D3) is positioned in the northeast position of D2 in the most flooded area (Figure 4b). The initial conditions (IC) and the lateral boundary conditions (LBCs) are taken from the National Center of Environmental Prediction, Global Forecast Model (NCEP GFS) with a resolution of 0.25 deg at 3-h intervals.

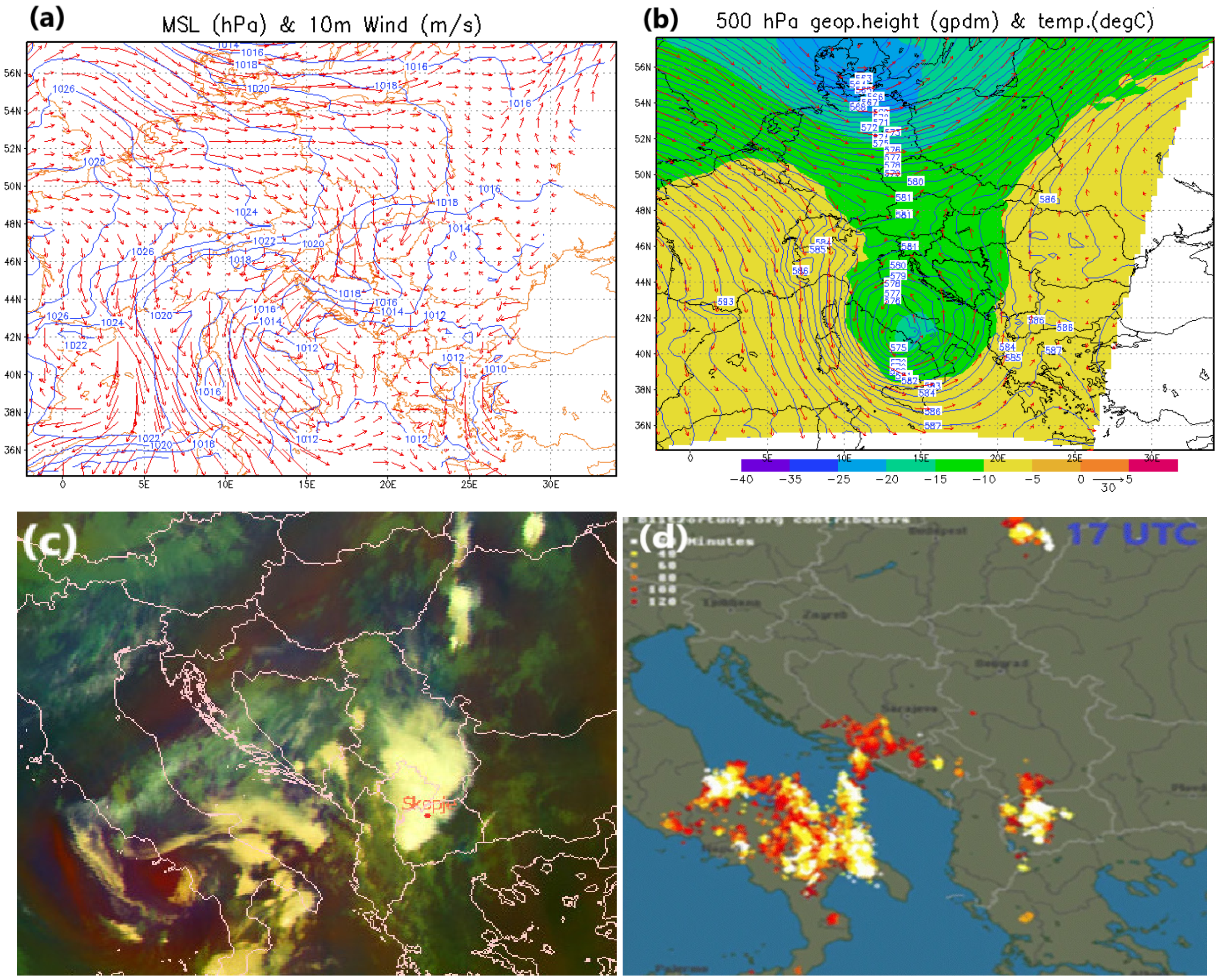

Figure 3. (a) MSL pressure chart valid on 6 Aug 2016 12:00UTC. (b) The 500 hPa geopotential height (gpdm) and the temperature (ºC), valid on 6 Aug 2016 at noon UTC. (c) Meteosat-10 Airmass RGB, valid on 6 August 19:30 UTC. (d) The real-time lightning map, valid on 6 Aug 2016 at 17:00 UTC.

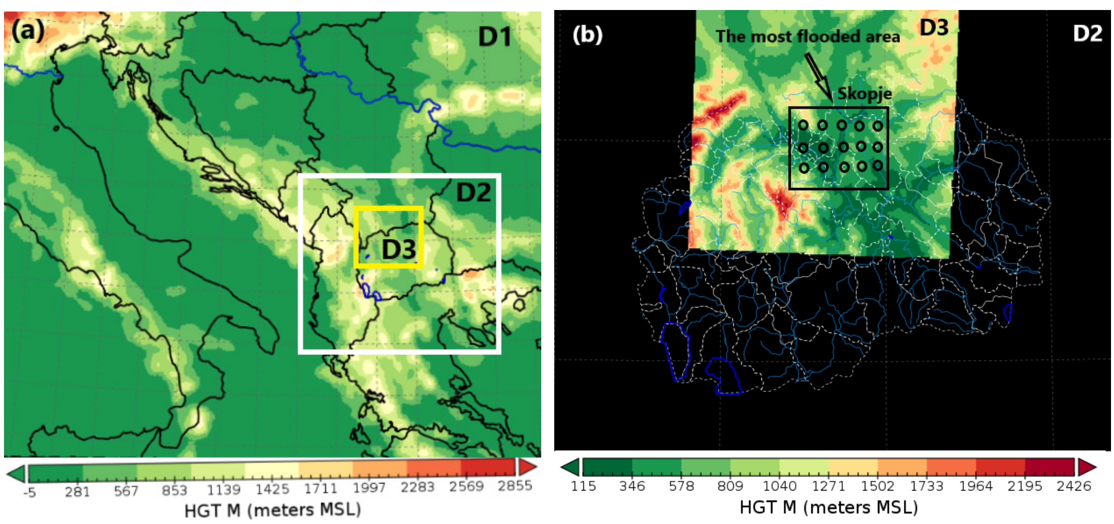

Figure 4. System design. (a) A triple-nested model configuration. (b) Schematic of ensemble generation approach. Vertical meteorological profiles are derived from the WRF 1.1-km nested run (domain 3), in three consecutive hourly outputs of the WRF model, taken during the period of intensive development of the convective system. Note: Skopje is labeled in the center of the inner plotted area which denotes the heaviest flooding area. Dotes indicate grid points from which soundings are generated.

3.2 Ensemble Approach

The initial conditions for running the cloud model are obtained from the WRF 1.1-km forecast outputs in a period of intense convective activity and heavy rainfall. The fifteen soundings are extracted from a grid spacing of 0.05 º E-W × 0.05 º N-S on the area of interest. The soundings are derived from the 00:00 UTC WRF run (+24 hours) that verify at three successive times at 1500, 1600, and 1700 UTC, which coincides with a period of intense convection. Thus, the system contains 15 sounding at every three times, or 45 -ensemble members. Such design using forecast soundings over the spatial domain of interest, to the extent level minimizes the effect of uncertainty in the initial conditions and cloud model initialization [23]. Such design of the system, illustrated in Figure 4b is applicable across the entire cloud model domain, as the result of implicit recognition of spatial and temporal uncertainty in the forecast sounding. In this way, the perturbation technique could be avoided, as the cloud model initialization is less dependent on the modeler. This advanced approach is more suitable for the initiation of the convection, and it is a highly unstable atmosphere to trigger a severe convective storm.

3.3 A Three-dimensional Cloud Model Setup

A cloud-resolving model (CRM) is a three-dimensional (3-D), non-hydrostatic, time-dependent system, with dynamics, thermodynamics, and cloud microphysics [34-36]. The present version of the model contains ten prognostic equations: three momentum equations, the pressure, and thermodynamic equations, four continuity equations for the water substances, and a sub-grid kinetic energy equation.

Three-dimensional simulations are performed within a small model integration domain, with a size of 50×50×15 km^3 that covers the most flooded area and suburbs of Skopje city. The horizontal grid resolution is 500-m while the vertical discretionary is 250-m, respectively. The refined vertical grid resolution of 50 m grid length near the surface layer resolves boundary layer structures. The total number of grid points in a 3-D simulation is 201×201×66. The time step of the model is 5 s and the smaller one is 0.5 s for solving the sound waves. The cloud model is integrated for a 2-hour simulation to capture the life cycle of this very severe convective case. Model equations are solved on a semi-staggered grid. Since the model equations are compressible, a time-splitting procedure with a second-order leapfrog scheme is used for the portions that do not involve sound waves to achieve numerical efficiency. The lateral boundaries are open and time-dependent, so disturbances can pass through with minimal reflection. Crucially, the cloud model's open lateral boundary conditions allow it to freely evolve and produce strong net ascent/convergence/divergence across its domain, without being constrained by LBCs from the WRF model. Initial conditions are taken by soundings derived from the WRF triple-nested (10 km × 3.3 km × 1.1 km) forecast outputs for the inner domain of WRF (D3). One forecast sounding, with a vertical profile of meteorological parameters (e.g., potential temperature, specific humidity, and horizontal wind components) represents an individual ensemble member (Figure 5). More detailed information about the WRF nested model configuration and the convective cloud model parameters could be found in Table 1.

Table 1. The list of WRF and Cloud Model Parameters

Parameter/Run	**WRF triple nested forecast**	**Cloud Resolving Model 3-D simulation**
Domain used and size	Domain 1 (parent) 10 km hor. grid res. Domain 2 (nested) 3.3 km Domain 3 (nested) 1.1 km	Covers domain 3
Model dynamics and thermodynamics	WRF-non-hydrostatic mesoscale model [13]	Klemp and Wilhelmson [34-35]
Microphysics	Thomson microphysics [37], Thompson microphysics scheme with aerosol climatology [38]	Orville and Kopp [36]
PBL scheme	Yonsei University YSU PBL Scheme [39]	Turbulent kinetic energy equation TKE with first-order closure
Land surface scheme	Noah's land-surface scheme [40]	Homogeneous field
Cumulus parameterization	Domain 1-scale and aerosol aware scheme NCEP GFS Cumulus Convection Scheme with scale and aerosol awareness [41, 42] Domain 2 and 3 Explicit treatments	Explicit treatment convection
Long wave radiation	Mlawer and Taubman [43]	

Table 1 continued

Parameter/Run	WRF triple nested forecast	Cloud Resolving Model 3-D simulation
Short wave radiation	Dudhia Scheme: Simple downward integration allowing for efficient cloud and clear-sky absorption and scattering. [44]	
Hor. grid resolution	10 km; 3.3 km; 1.1 km	0.5 km
Vertical discretization	50	0.250 km
Time step (DT)	60, 20, and 6.6 sec., respectively	5 sec
Time step for solving the sound waves (DTAU)		1 sec
Simulation time	24 hours	90 min
Total grid points (x,y,z) direction	120×120 91×121 121×121	100×100×66
Radial dimensions of thermal bubble		15 × 15 ×3.5 km^3
The maximum temperature perturbation		Ensemble approach
Lateral boundary conditions (LBC)	LBC at each 3-hrs	Opened LBC
Initial conditions/initial meteorological fields	NCEP GDAS/FNL GFS 0.25 deg LBC at every 3 hours	WRF output-derived soundings
Computing Processing Unit	26 CPU hours	90 CPU hours

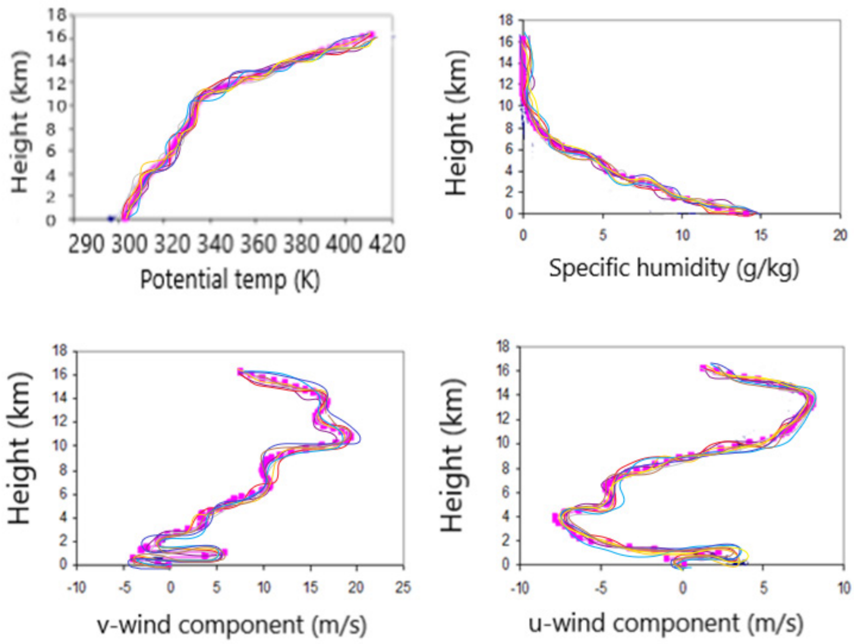

Figure 5. Initial vertical profiles of the equivalent potential temperature (θ_e), mixing ratio (q), horizontal (u) and (v) wind components, extracted from WRF 1.1 km scale forecast outputs

4. Results

The obtained results indicate that a 3-D run with an ensemble initialization demonstrated a high model skill and potential in the realistic simulation of a flash-flooding produced supercell storm that passed through a different phase of evolution and convective modes. The first part of this section deals with storm dynamics and the main triggering factors for convective cell initiation and evolution, during the life cycle. Then, the key micro-physical processes responsible for the formation of large water content and heavy rainfall are examined. Finally, the results are discussed in light of the comparative analysis with the available observations.

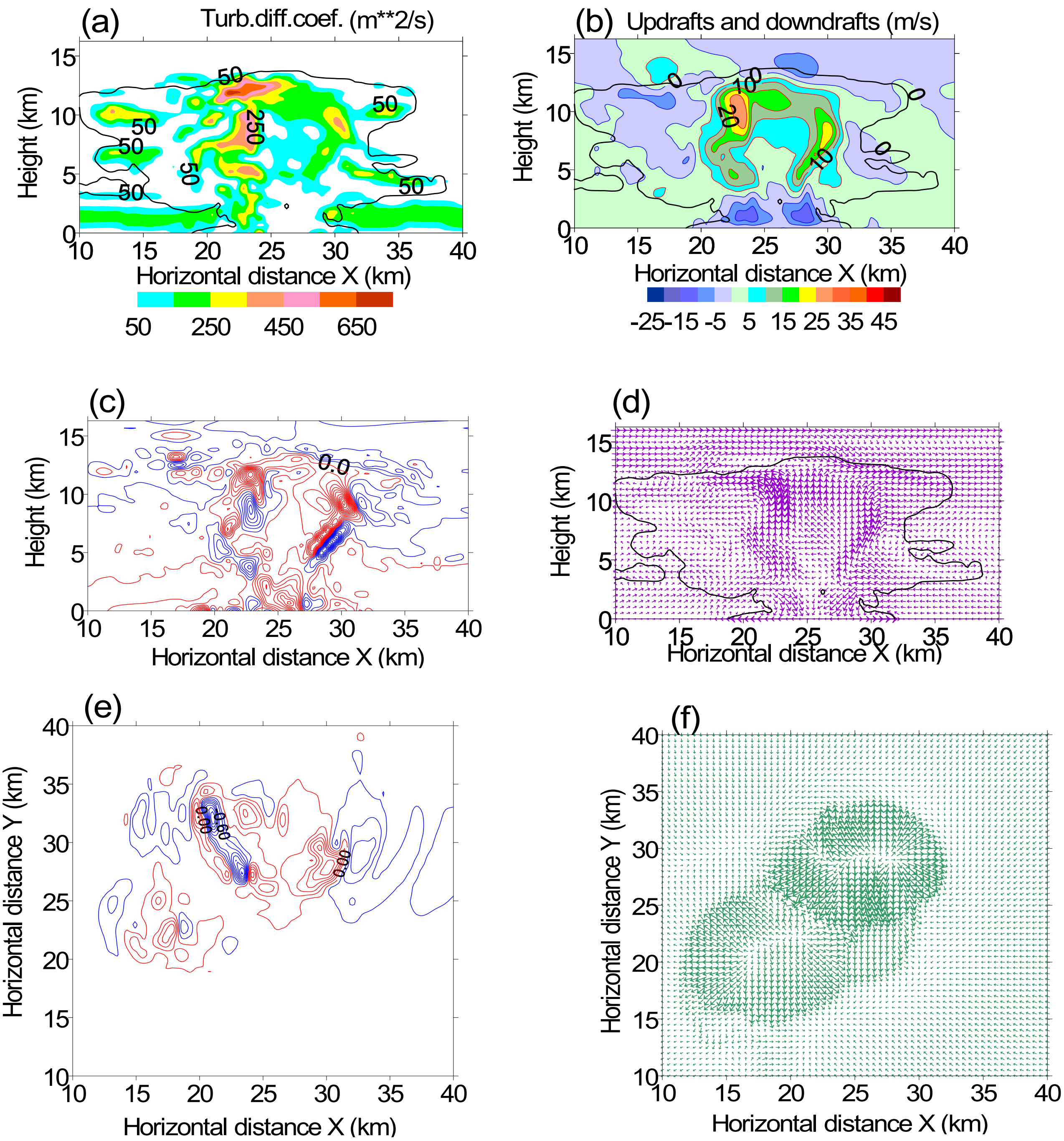

Figure 6. Dynamic characteristics of a super-cell storm in the most intense phase of development. (a) Vertical section of the turbulent diffusion coefficient. (b) Same as Fig. 6a, but for updrafts and downdrafts. (c) Same as Fig. 6a, but for the vertical component of relative voracity. (d) x-z cross-section of the vertical wind profile. (e) horizontal x-y cross-section of the vertical component of voracity at 2 km height. (f) Horizontal wind profile at ground level.

4.1 Super-cell Storm Dynamics

Turbulence plays a key role in convection, primarily through a process of turbulent mixing of updrafts with the surrounding air, which often has a low equivalent potential temperature. This reduces both the buoyancy force and the vertical velocity. Figure 6a shows the vertical profile of a turbulent diffusion coefficient derived from a turbulent kinetic energy equation. Weak to moderate turbulence occurs in the updraft portion of the simulated storm in the middle and upper troposphere. But what is indicative, is that the maximum turbulence coefficient value is evidenced in the forward flank core in the region of upward motions, on the edge of the updraft, which contributes to the significant hail growth. In the initial phase of cloud evolution, directional wind shear in the lower portions of the atmosphere, allows the horizontal component of voracity to transfer into a vertical component of voracity (ζ). At the place of intense convection, the vortex column of air ascends, maintaining the direction of rotation. This process is responsible for the formation of a pair of vertices with quasi-vertical axes, rotating in opposite directions. Such vertices are produced by linear effects. When precipitation and a downdraft form in such a storm, the vortex tube descends, and an additional pair of vertices is generated. This pair of vertices form as the result of non-linear effects, which later separate the single cloud mass into two separate cells. The disturbance of the voracity occurs due to the vertical wind shear-twisting term of the vortex tube. As it is shown in Figure 6c, a pair of vertices, with a positive disturbance of ($\zeta_t^{'}$), (left portion of updrafts) relative to the storm motion and a negative voracity disturbance (right portion of updrafts). The area with large values of vertical velocity is located near the top and bottom of the updraft, where maximum disturbance of voracity occurs (Figure 6b, d). In addition to the tilting term, the stretching term ($\zeta^{'} w_z$) becomes significant. The cloud model run was able to simulate a persistent rotating updraft with a lonesomeness, as typical for the development of a tornado super-cell. A divergence signature shown in Figure 6f, with two distinct cores occurs as the result of downdrafts (vertical columns of sinking air), observed in the mature phase of storm evolution at the onset of precipitation.

4.2 Evaluation of the Micro-physical Processes

Figure 7 shows the radar reflectivity fields for this specific case associated with a flood over an urban area due to a large amount of precipitation, with a strong intensity over a smaller area and for a very short period. In the first two columns, vertical and horizontal radar reflectivity profiles are shown in the most developed phase of the super-cell storm, at 1530 UTC; 1545 UTC; and 1600 UTC. The 3rd column in Figure 7, displays the horizontal transects of composite radar reflectivity patterns at 2 km altitude (Constant Altitude Plan Position Indicator-CAPPI). The strong convective cells that passed over the Skopje area, oriented in the SW-NE direction are captured well with the cloud model simulation. There is a large similarity in the simulated relative to the observed reflectivity patterns. The maximum radar reflectivity value of 70 db Z recorded at 1545 UTC, was successfully simulated with a cloud model. In addition, the bow-echo signature that is visible on the vertical transects of the reflectivity field (1545 UTC) along the NW-SE direction, as well as the specific hook shape of the radar reflection on the horizontal view, clearly indicate the formation of a super-cell storm.

Micro-physical processes play a crucial role in the internal storm structure and distribution of hydrometers during the storm life cycle. The simulation in Figure 8 indicates a rapid super-cell storm evolution, micro physical transfer, and transformations among different phase transitions, associated with large water production and heavy rainfall occurrence. The simulation gives a clear micro physical picture of the dominant processes and nucleation phases that are initiated by the dynamics of the storm (rotating updrafts and lonesomeness, and strong ascent that keeps the ice structure at higher altitudes, as well as downdrafts in the heavy rainfall phase.

The simulation gives a clear micro physical picture of the dominant processes and nucleation phases that are initiated by the dynamics of the storm (rotating updrafts and lonesomeness, and strong ascent that keeps the ice structure at higher altitudes, as well as downdrafts in the heavy rainfall phase. It is seen that in a very short time the simulation period of 20-32.5 min, which corresponds to the time from 1545 UTC to 1600 UTC, intense processes of formation of cloud elements, and ice structures take place, snow, and cloud ice in the upper part of the cloud, hail along two ascending areas of updrafts in the central inflow region, and raindrops in the lower part of the atmosphere. At about 22.5 min simulation time, a new cell develops in the front right wing, which gradually strengthens and contains only super cooled water and snow and ice crystals and gradually merges with the leading cloud.

A few minutes later (25 min.) downdrafts begin with updrafts, so that the core of the city gradually descends, intensifying the process of rain formation through accretion and ice melting so that the first precipitation on the surface is also registered. 27.5 min is the most intense development with two formed channels and heavy rain

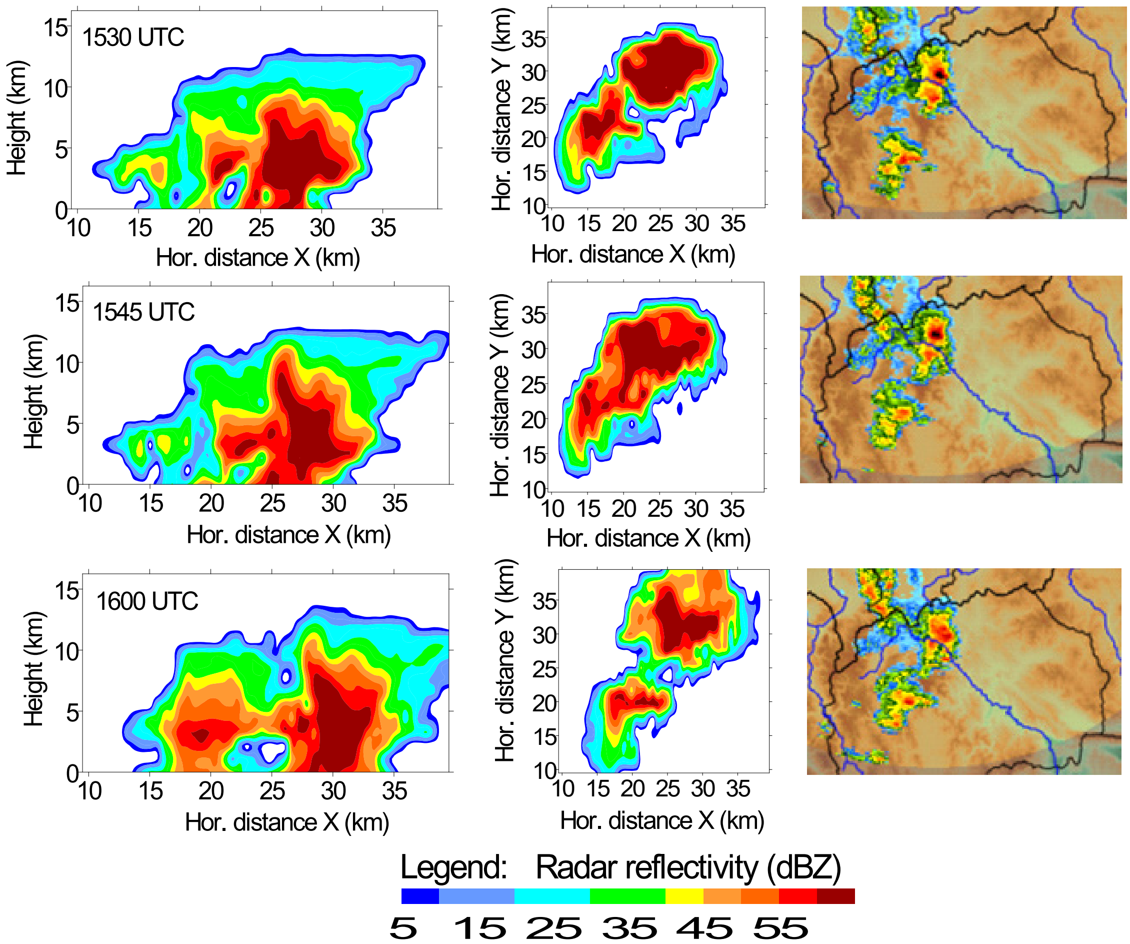

Figure 7. (1st column) Vertical cross-sections of simulated radar reflectivity (dBZ) at 1530 UTC, 1545 UTC, and 1600 UTC, respectively. (2nd column) Same as Figure 7a, but for the horizontal transects at 2.0 km height along NW-SE. (3rd -column) Same as Figure 7a, but with 2.0 km height -CAPPI composite radar image (dBZ). Source: Republic Hydrometeorological Institute of Serbia (RHIS)

fluxes. The anvil in the upper part of the cloud is visible. The intensity of a supercell storm.

A significant amount of rainfall with the torrential flash flood was evidenced on 6 August 2016 in the city of Skopje, and northeast in the surrounding rural parts in the vicinity of the mountain complex "Skopska Crna Gora" (SCG). From the isohyet chart (Figure 2a) it is evident that most of the accumulated precipitation is recorded in Skopje at the Automated Weather Station (AWS)- "Gazi Baba" with a total amount of 106.0 mm/24 hours and the maximum rainfall intensity of 36.0 mm/hour at 1545 UTC. Details about the rainfall intensity were discussed in the observational section. However, is well to mention that over the area of Skopje about 100 mm of rainfall has been evidenced, within two hours, which is twice the average amount of rain for all month of August, according to climate statistics. The WRF-10 km run (domain 1) produced rainfall close to the target area (Figure 9a), while the total amount was underestimated. The simulation with a finer resolution of 3.3 km (nested domain 2) showed better results in terms of not only the total amount of precipitation, but also in the detection of two precipitation zones, the first one positioned southwest of Skopje with a total amount of about 80 mm, which is a slight deviation from the measured values, and another heavy rainfall area shifted to the NE, from the location of the flash flood with a total rainfall of about 90 mm. Finally, the WRF 1.1-km run quite successfully simulates a convective system and cores with intense precipitation, one positioned SW from the Skopje valley. The heavy rainfall zone of about 90-100 mm/24 hrs. is positioned northeast in the vicinity of the border with Serbia.

WRF 1.1-km nested run with explicit microphysics and without parameterization of convection, produced a more total accumulated rainfall closer to the most affected flood area but underestimated the observed amount (Figure 9c). The cloud model simulation using the ensemble method (Figure 9b) indicates two distinct rainfall zones. The first

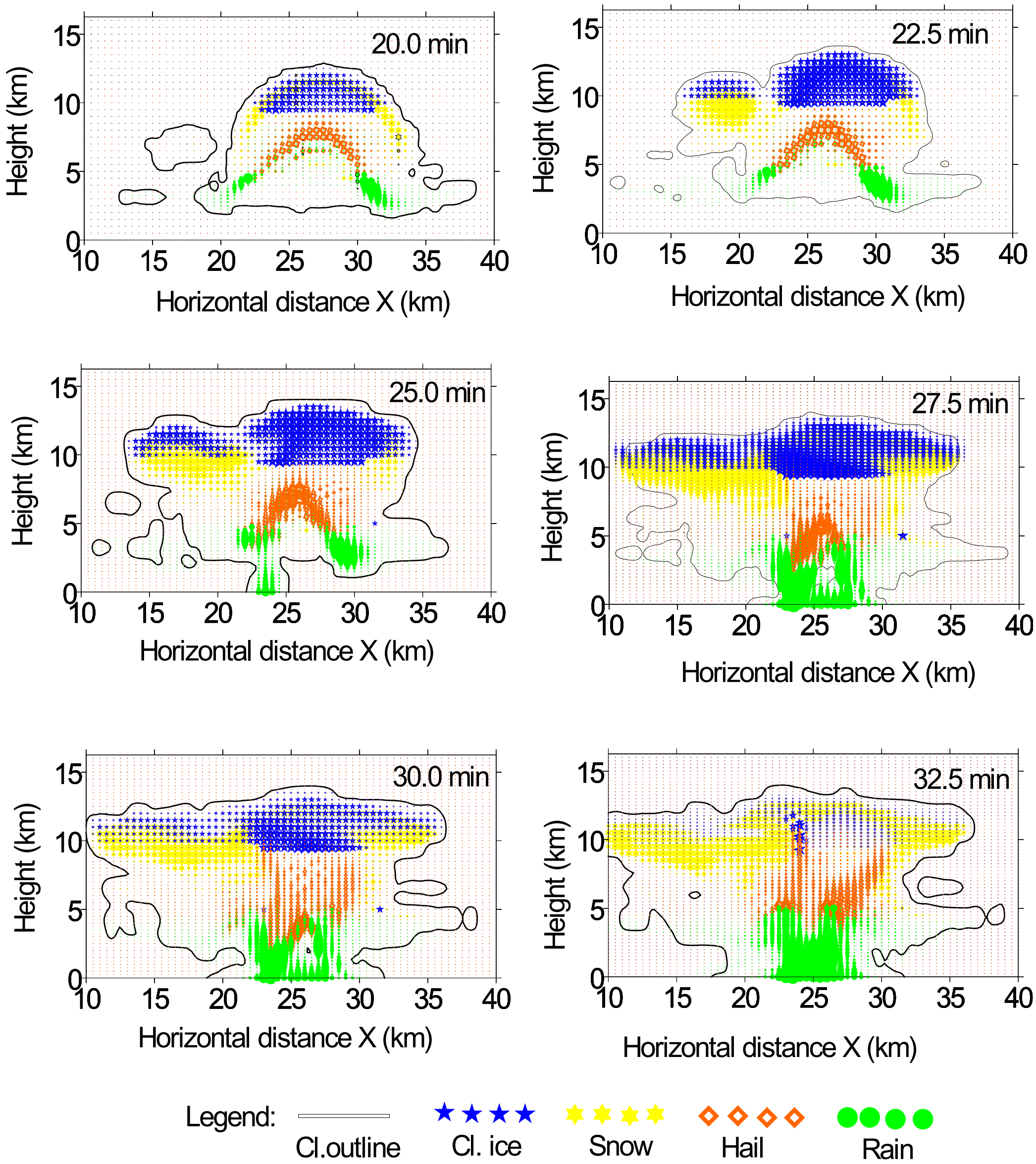

Figure 8. Vertical cross sections of micro-physical structure of the simulated super-cell storm during simulation time starting from 20.0 to 32.5 min at 2.5 min time intervals. Hydro-meteors (cloud water, cloud ice, snow, graupel or hail, and rain) are expressed through their corresponding mixing ratios (g/kg).

is distributed over the mountain "Vodno", located in the southeast part of Skopje, spreading towards the municipalities, "Gazi Baba" and "Butel". The heaviest rainfall and flash-flood occurred in the municipality of "Stajkovci", which belongs to the rural part of Skopje. The total accumulated rain averaged over the cloud model domain of about 100 mm precipitation is in good agreement with the observed pattern of heavy rainfall. The peak rainfall amount exceeds 120 mm and largely overestimates the observed peak rainfall of 106 mm at the AWS- "G.Baba". However, considering the catastrophic consequences of the flash-flood, there is a high probability that in the rural part of Skopje City and in the vicinity towards the mountainous part of SCG, where there is no coverage with meteorological observation stations, the total precipitation will be even higher.

The three-dimensional view gives a more realistic view of the structure, evolution, and strength of the super-cell storm. Cloud elements and dynamics with characteristic rotating vertical velocities are observed. The cloud hydrometeors, expressed through their mixing ratios are displayed in Figure 10 with the cloud outline mixing ratio of 0.1 g/kg. The light grey fields denote cloud water, dark gray-cloud ice, yellow snow, red hail, and green rainwater mixing ratio, respectively.

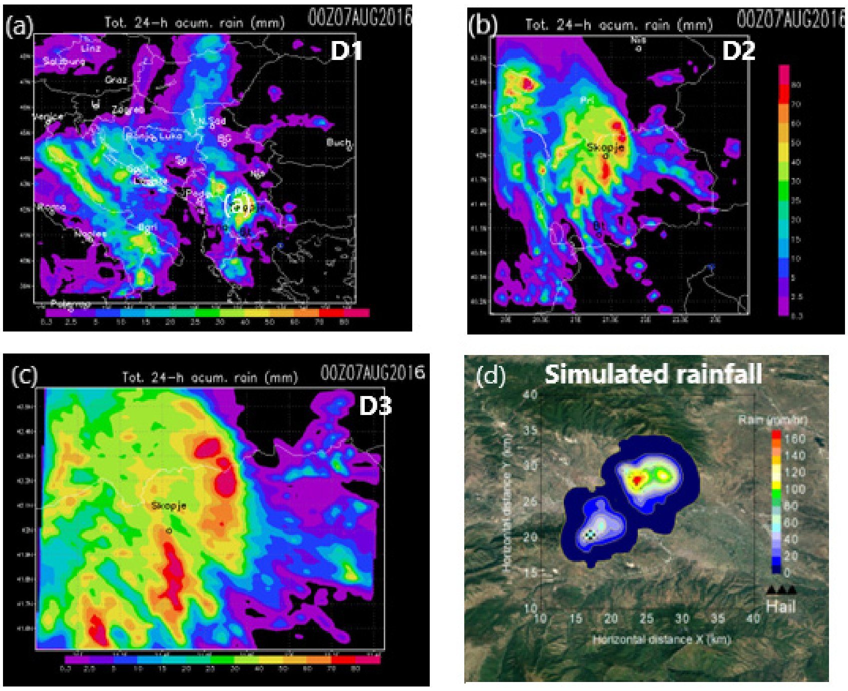

Figure 9. (a) WRF 10-km total 24 h-acc. rainfall (mm) ending at 0000 UTC 7 Aug 2016, (b) Same as 9a, but for the simulation of domain 2 (3.3-km grid) (c). WRF 1.1-km (domain 3). (d) Total simulated rainfall from 1500-1630 UTC on 6 August 2016, obtained from the cloud model simulation. The topography of the Skopje basin in 3-D is shown as a basis in the picture.

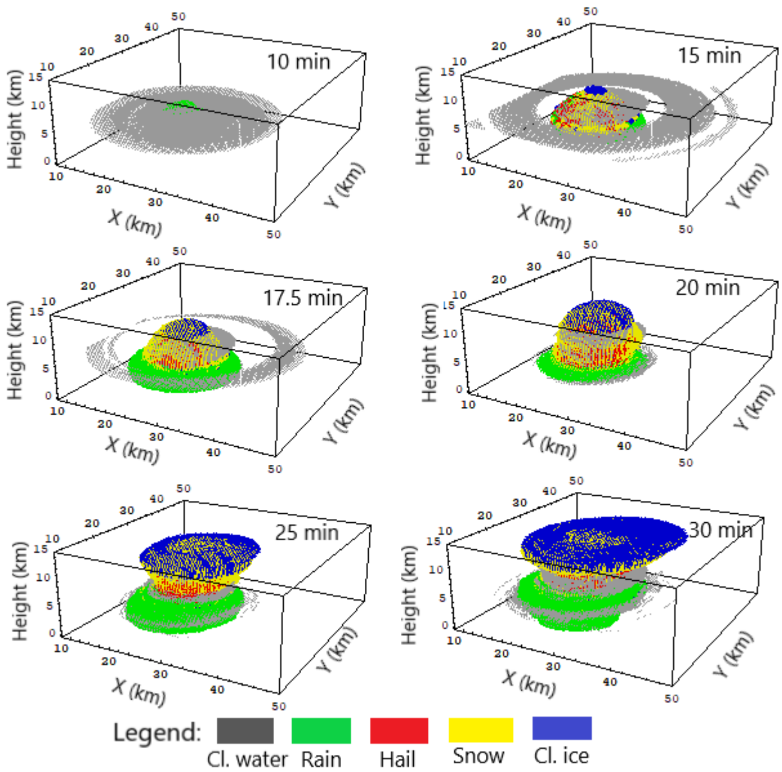

Figure 10. A three-dimensional cloud sequence of simulated storm micro-physics fields, viewed from NW-SE direction at the most intense phase of evolution, starting from 10 min simulation on 2.5 min time intervals. Hydrometeors are expressed through their mixing ratios (g/kg). The light gray fields denote cloud water, dark grey-cloud ice, yellow snow, red hail, and green rainwater. The cloud outline is 0.1 g/kg.

5. Conclusions and Discussions

The present research study is focused on the evaluation of the cloud model performances in the simulation of a deadly super-cell storm, which caused an urban flash-flooding in the Skopje valley on August 6, 2016. A new ensemble method of cloud initialization has been implemented, using WRF triple-nested model run, with hourly forecast outputs in a period of severe convection. Then the initial vertical meteorological profiles are extracted in the corresponding grid points of the selected target area (domain 3). Thus, the cloud model is run in ensemble mode with 45 members, avoiding the standard perturbation method, and minimizing the uncertainties in the initial conditions.

The WRF model reasonably simulated the initial formation of a cluster of convective clouds or Mesoscale Convective System (MCS) and its successive transition to a Mesoscale Convective Vortex (MCV), evolution over the urban area in the city of Skopje. WRF 1.1-km scale nested run showed an advantage in the simulation of a more detailed aspect of convection over the smaller domain, in a local-scale area where a flash-flood occurred. However, it failed to predict the accurate location of heavy rainfall and the relative intensity of rainfall.

A three-dimensional cloud model (3-D) simulation using the ensemble method, showed the ability to simulate the initiation of individual convective cells, persistent rotating updrafts, downdrafts, and formation of the mesocyclone. The cloud micro-physics associated with the production of large water content, cloud ice structure, transfer, and transformation processes responsible for intense rainfall fluxes and heavy torrential downpours are reproduced well. The simulated horizontal cross-section of the radar reflectivity fields, indicated a hook echo while the vertical transects of reflectivity showed a bow echo region as typical signatures for the development of a super-cell storm. As a summary of this research, it can be pointed out that the cloud model with a fine resolution successfully solves small-scale convective processes, which are significant not only from the aspect of dynamics and the initiation of a super-cell storm but also for micro-physics, which was crucial for the occurrence of extreme rainfall in a smaller urban area caused a catastrophic local-scale urban flooding. The initialization of the model using the ensemble approach enabled the development of the storm in perturbed atmospheric conditions, which gave an improvement to a far more realistic simulation of the storm, which was also shown by radar measurements, as well as data on extreme precipitation in the Skopje area. We believe that the first experiment with this ensemble approach showed certain advantages compared to the standard method, but we are not yet able to give a subjective assessment of the success of this method because more cases are needed to verify the real-time ensemble Cloud Resolving Model (CRM) applications to forecasting severe thunderstorms and to improve the reliability of this tool and use it in the context of very short-range forecasting (now-casting) and severe convective weather warning.

Conflict of Interest

There is no conflict of interest.

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