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Numerical modeling of a downwind-developing mesoscale convective system over the Masurian Lake District

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Abstract. Meteorological data concerning the severe convective system from the 21 August 2007 are analyzed in this study. Compiled information allows to understand the reason for the storm development and to identify its fundamental convective mode. Next, the EULAG model is utilized to perform an idealized test that shows a downwind–developing storm growth in an environment comparable to the one that was observed on the 21 August 2007 in the Masurian Lake District. Finally, the COSMO numerical weather prediction model is applied to reconstruct the storm development. The experiment is carried out for various computational grids having the horizontal grid length between 7.0 and 0.55 km. It turns out that the COSMO model is capable in simulating storms of that type. Since the model is used for operational weather forecasting in Poland the evaluation of this skill contributes to the increase of public safety.

1 Introduction

Deep moist convection brings several hazards to the safety of people and property. Dangerous convective events are commonly named as severe convective storms or systems (SCS). One major mechanism of devastation is linked with precipitation and precipitation-driven downdrafts [1]. In particular, downdraft air spreading over the surface may lead to the formation of severe wind gusts. Therefore, major efforts are undertaken to improve numerical weather prediction (NWP) models capability to forecast development and evolution of severe convection.

The 21 August 2007 SCS in the Masurian Lake District (Masurian LD) distinguished itself by severe surface wind gusts up to 35 m/s that caused extensive damage and loss of life. At that time, severe weather warning informing about the approaching SCS was issued about 50 minutes before the SCS approached Mikołajki town. This short time period was insufficient to provide warning to local community about the heavy thunderstorm.

The NWP models employed in 2007 in the Institute of Meteorology and Water Management – National Research Institute had around 14 km horizontal grid length. That grid length does not allow to simulate deep convective storms. Thus, the then models could

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not forecast the storm in advance. However, the last decade brought unprecedented improvements to the NWP model dynamics, physics, and computational performance. In particular, the decrease of the horizontal grid length by nearly an order of magnitude resulted in "convection-permitting" non-hydrostatic NWP models. Nowadays, the NWP models are commonly run with horizontal grid length close to 2 km. Such a setup enables resolving basic circulations that are characteristic for deep most convection [2].

The ultimate goal of this study is to perform an assessment of the Consortium for Small-Scale Modeling (COSMO; www.cosmo-model.org) NWP model capabilities in mid-latitude deep moist convection forecasting over Poland. Such contemporary studies that are focused on Poland are not known to the author. Because during warm season severe convective systems occur regularly over Poland, the assessment may contribute to the increase of public safety. Moreover, climate-change-related increase in frequency of severe weather events over Europe is considered to be likely [3], so their skillful forecasting should be a priority. For this purpose, a reconstruction of the severe storm from the 21 August 2007 with COSMO NWP model is undertaken.

Section 2 of this report describes models and simulation strategy used in the experimental part of this study. Section 3 briefly presents meteorological observations related to the storm development. In the last section collected meteorological data are utilized to design an idealized test that models quasi-linear convective system propagation. This approach facilitates better understanding of the 21 August 2007 storm and provides guidelines for semi-realistic numerical reconstruction of the storm.

2 Tools

Two types of numerical experiments: idealized and semi-realistic are utilized in this study. The idealized experiments (Section 4.1) are carried out using the EULAG model. This model solves anelastic version of the Euler equations [4] using an accurate advection and elliptic pressure solvers i.e. MPDATA advection scheme [5] and preconditioned conjugate residuals solver [6], respectively. The framework contains one-moment moist precipitating thermodynamics [7] and turbulence scheme which is based on the turbulent kinetic energy (TKE) prognostic closure of the 1½ order [8].

The basic tool for the semi-realistic experiments is the COSMO model [9, 10] in version 5.01. Its dynamical core solves fully compressible Euler equations using the second-order Runge-Kutta time integrator [11] and the Arakawa C-grid spatial discretization. The model is capable to perform convection-permitting simulations in steep terrain for up to 1.0 km horizontal grid length simulations. Over the rather flat Masurian LD the model handles well simulations with 0.55 km grid length.

The framework of COSMO is equipped with large set of physical parameterizations that contain: radiation, turbulence, cloud microphysics, land-surface model, and surface flux scheme. The operational turbulence scheme [12] is based on the 2nd order turbulence closure with the prognostic equation for TKE. An additional fully three dimensional Smagorinsky-Lilly turbulence scheme is also available in the model [13]. The essential one-moment microphysics parameterization is based on the Kessler warm-rain scheme. Its operational extensions allow to treat basic forms if ice condensate: cloud ice, snow and graupel.

Semi-realistic experiment in Section 4.2 is carried out using a few inclusive computational domains that are depicted in Figure 1. The most coarse domain grid length equals to 7.0 km. The grid lengths of finer domains are equal to 2.2, 1.1 and 0.55 km, respectively. Technical data related to each of the simulations are provided in Table 1.

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3 Weather observations

During the early hours of 21 Augusts 2007 weather in Poland was influenced by two synoptic pressure systems: a polar maritime low with the center over Germany and a polar continental high with the center over northern Russia. The cold front, associated with the low, was entering Poland from the south-western direction gradually replacing warm air with colder and drier air. The high and the low were driving upper-air circulation over Poland, creating a favorable condition for the inflow of a sub-tropical air mass from the south and south-eastern directions to the central Poland.

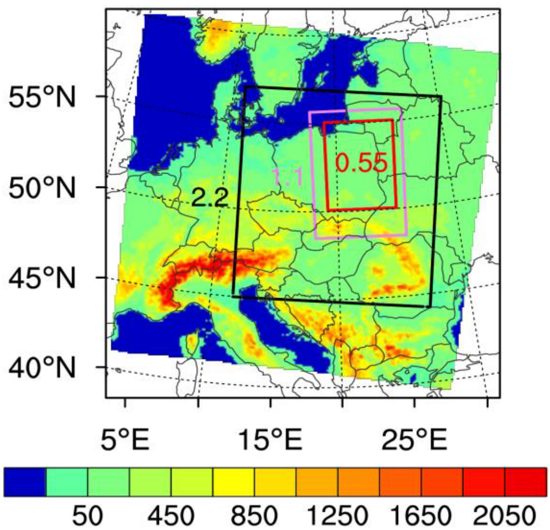

Fig. 1. Computational domains for semi-realistic simulations. The orographic map depicts 7.0 km domain. The 2.2, 1.1 and 0.55 km domains are marked using black, violet and red frames, respectively.

Table 1. Configuration of semi-realistic simulations.

	7.0 km	2.2 km	1.1 km	0.55 km
Domain width x height	310x310	540x600	500x720	750x1000
Simulation start time	0:00 UTC 20.08.2007	18:00 UTC 20.08.2007	03:00 UTC 21.08.2007	07:00 UTC 21.08.2007
Boundary update frequency	3 hours	1 hour	15 minutes	15 minutes
Turbulence scheme	2nd order closure with prognostic TKE			Smag.-Lilly

The Masurian LD was free of deep convective activity between 0:00 and 6:00 UTC. Because of that and owing to the weak south-eastern wind close to the surface, the atmospheric boundary layer (ABL) within the Masurian LD remained quite warm and moist during the night. Shallow fogs were observed in Mikołajki (3:00 UTC) and in Olsztyn (6:00 UTC). At 6:00 UTC, the measured 2-m dew point temperature in Mikołajki was equal to 19.3°C and the 2-m temperature was equal to 21.4°C (relative humidity of 88%). Later, during the day, the ABL air was further heated and moistened till the moment of deep convection development. In other words, the ABL over Masurian LD supported extreme weather formation.

The 12:00 UTC sounding from Legionowo provided basic information about the upper-air conditions in the warm sector of the low. This sounding, depicted in the form of a Skew-T diagram in Fig. 2, shows ABL spanning between the surface, i.e. 96 m above sea level (ASL), and around 800 m ASL which is capped by around 4ºC inversion layer with about 18% drop in relative humidity. Above the inversion, an elevated mixed layer extends from 1250 to approximately 2620 m ASL. This elevated mixed layer, in combination with warm and humid ABL air over Masurian LD, could foster the build-up of convection available potential energy (CAPE) rich environment over Masurian LD [14].

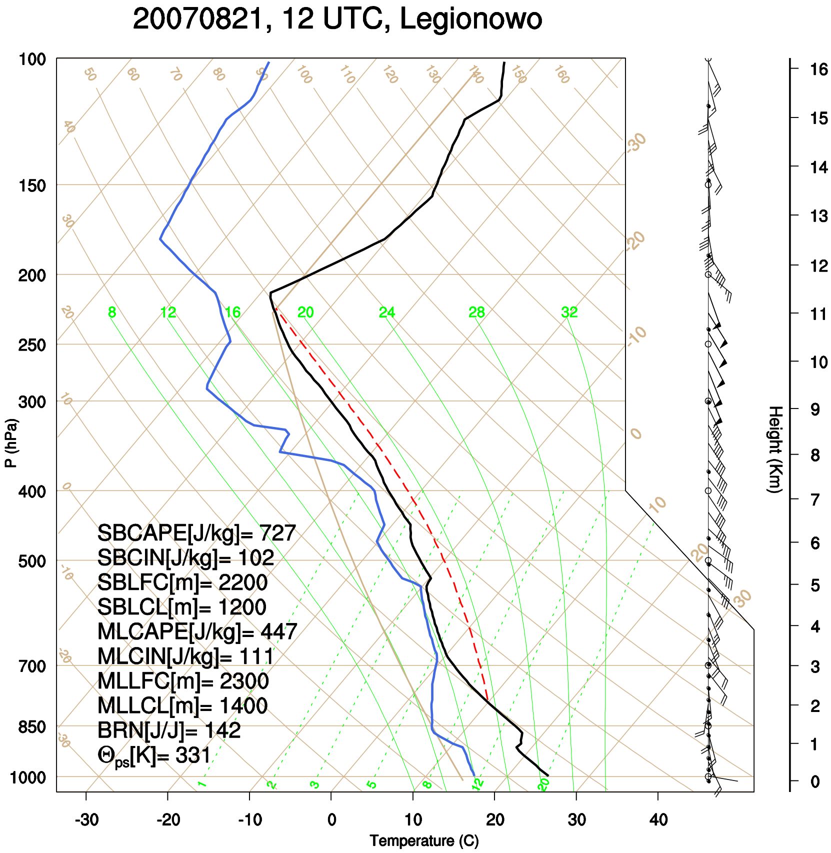

Fig. 2. Skew-T diagram acquired from radiosonde measurement in Legionowo (21 August 2007 12:00 UTC). Blue solid line denotes the vertical profile of dew point temperature. Black solid line denotes the vertical profile of temperature. Red dashed line denotes possible CAPE release. In the bottom left part of the diagram values of several standard convective indices are shown.

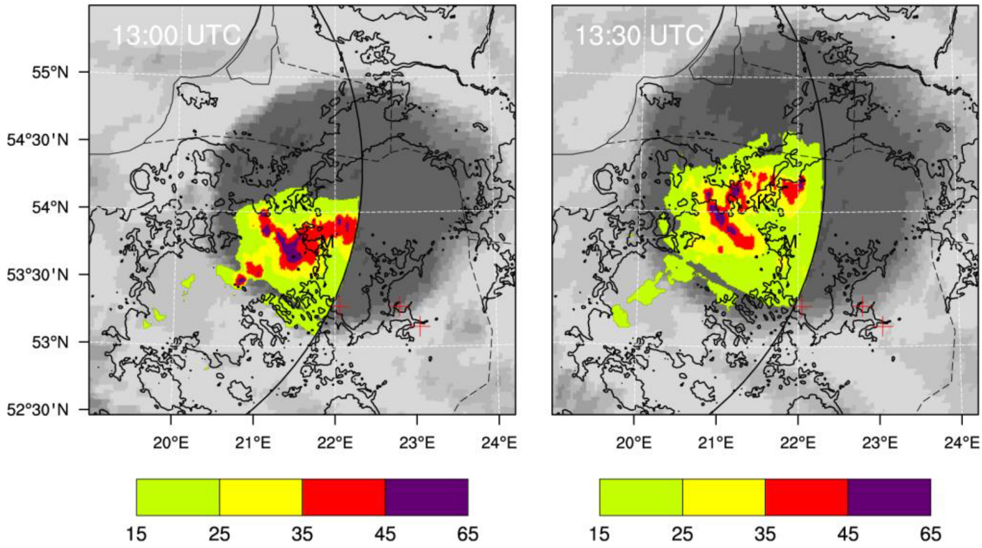

Fig. 3. Radar reflectivity at 6 km height ASL measured by the weather radar in Gdańsk (colors; 21 August 2007) overlaid over satellite image in 7.3 µm wavelength (grayscale). Gray lines mark orography isolines at 40 m and 116 m (the isoline of Śniardwy Lake) height ASL. Black circle marks the radar coverage boundary. The red crosses mark the locations of towering cumulus growth around 11:15 UTC. The capital letters "K" and "M" and the respective black markers denote location of Kętrzyn and Mikołajki towns.

Convection initiation of the severe convective system took place around 11:15 UTC in the northern part of Podlasie Region (see red crosses in Figure 3). The initiation was related to the approach of a moderate convective system from the south. It is worth to notice that according to the satellite images three deep cumulonimbus clouds grew at the windward side of local mesoregion uplands.

The severe convective system represented the class of downwind-developing mesoscale convective systems (MCS) [15] and, to some extent, resembled the squall line convective system [16]. It hosted one bow echo [17] that moved across Masurian LD between 12:45 and 13:50 UTC (Fig. 3). The estimated propagation speed of the bow echo did not exceed 27 m/s. The peak surface wind gusts measured at local WMO-compliant synoptic station in Mikołajki during the storm achieved 35 m/s, however, the average wind speed measured at this station was equal to 16 m/s.

4 Numerical results

4.1 Idealized test

The initial and boundary conditions for this test are based on the sounding from Legionowo (Fig. 2) which is modified within ABL to adjust it to the surface temperature (27.6°C) and dew point temperature (20.2°C) observations from 12:00 UTC from the Mikołajki synoptic station. The adjustment within ABL significantly increases surface-based CAPE value from around 700 J/kg to around 3400 J/kg. The boundary condition for the wind is based on the sounding from Legionowo.

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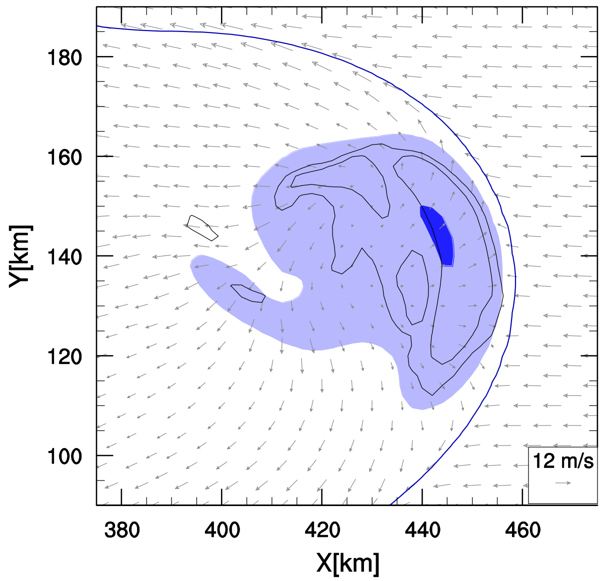

Fig.4. Quasi-linear storm development in 2 km grid length simulation without the Coriolis force for the wind profile as measured in Legionowo (21 August 2007 12:00 UTC). Intermediate storm-relative wind field 160 m above ground level (AGL) at T = 8 hours is shown. Blue line depicts meso-cold front position 160 m AGL. Light and dark blue shading denote rain mixing ratio exceeding 0.1 and 2 g/kg at 160 m AGL. Black contours depict isolines of the vertical velocity field 4108 m AGL: the solid lines mark 1, 2, 5 and 10 m/s values and the dashed lines mark negative values.

Convection initiation utilizes five warm thermals that are released concurrently within the ABL [18]. The initial storms cause the development of a few small cold pools that subsequently merge into a larger one. The presence of the large cold pool subsequently facilitates quasi-linear storm development (Fig. 4). The detailed structure of convective flows depends on the horizontal grid length and the mixing length parameter in the turbulence scheme. In some of the simulations, fast storm propagation is observed and the maximum surface wind speed reaches 30 m/s. Rear-inflow-jet [17] is observed as well.

4.2 Semi-realistic weather simulations

Semi-realistic weather simulations are configured as detailed in Section 2. Initial and boundary data for the most coarse 7.0 km grid length simulations originate from the global model GME [19] with 40.0 km horizontal grid length that was ran by Deutscher Wetterdienst at that time. Simulations utilize nudging (surface and upper-air observations) which is applied until 6:00 UTC of 21 August 2007. It turns out that severe deep convection is not simulated when the basic setup is applied.

In order to improve weather forecasts, the experience gained from Section 4.1 is utilized. In the default COSMO NWP simulations: (i) the elevated mixed layer is not present, and (ii) the surface temperature and dew point temperature over Masurian LD do not reach the observed values. Therefore, these biases are reduced by a nudging-based inclusion of additional meteorological information to the model. This additional nudging includes: (i) nudging of soil temperature (turned on till 2:00 UTC of 21 August 2007), (ii) nudging-based generation of a well-mixed elevated layer (turned on till 6:00 UTC), and

(iii) inhibition of precipitation for areas where available radar reflectivity data do not confirm it (turned on till 12.00 UTC).

The new setup allows to observe the squall line development in 1.1 and 0.55 km horizontal grid length simulations (Figure 5). The squall line has correct timing but is shifted around 30 km to the east. In 2.2 km and 7.0 km horizontal grid length runs the squall line is not simulated.

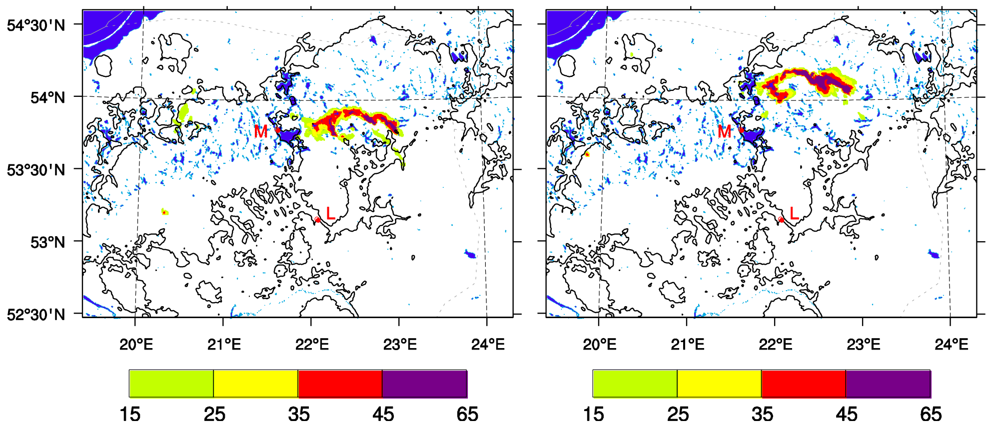

Fig.5. Model-simulated radar reflectivity values at the 850 hPa level height at 13:00 UTC (left) and 13:30 UTC (right). The simulation was performed with COSMO model with horizontal grid length equal to 0.55 km. Black line marks orography isoline at 116 m ASL. Letters "M" and "L" denote an approximate location of Mikołajki and Łomża towns. Lakes and the Baltic Sea are colored in blue.

5 Conclusions

Presented results suggest that COSMO model with 1.1 km and smaller horizontal grid lengths is capable in simulating downwind-developing MCS. Obtained results also confirm that a successful forecast of deep convection requires an accurate information about the initial state of the atmosphere (especially at low levels) and underlying Earth surface (e.g., soil moisture and temperature). Contemporary simulations in the convection-permitting regime provide improved weather forecasts than those available in 2007.

The results of simulations show that the severe convective storm from the 21 August 2007 could not be forecasted using the models available at that time. Nowadays, the probability of a successful numerical forecast of a comparable storm is higher. The quality of such forecasts noticeably depends on the quality of simulation's initial state.

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