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Application and evaluation of the WRF model for high-resolution forecasting of rainfall – a case study of SW Poland

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Abstract
The Weather Research and Forecasting (WRF) model is applied to provide quantitative precipitation forecasts at 10 km × 10 km and 2 km × 2 km spatial and one hour temporal resolution for the area of SW Poland. The forecasts are evaluated by comparing the WRF model precipitation with measurements gathered at a meteorological station operated by the University of Wrocław and 17 SYNOP (surface synoptic observations) sites for the period 03.03.2012–18.06.2012. The 2 km × 2 km domain is run with the Kain-Fritsch parameterization convection, and, as a separate simulation, with deep convection explicitly resolved. The results show that the model is capable of reproducing the number of observed precipitation episodes, but the performance decreases with the forecast range and rainfall intensity. The Kain-Fritsch model runs show a significantly higher area covered with rainfall when compared to the simulations with deep convection explicitly resolved, and are biased high for both 2 km and 10 km domains. The model runs with convection explicitly resolved show higher values of Success Ratio, while the Kain-Fritsch based runs, both for 10 km and 2 km, have higher Probability of Detection. None of the tested model configurations was able to resolve a highly local episode of intensive rainfall observed in the vicinity of Wrocław on 03.05.2012.

Keywords: Quantitative precipitation forecasts, Weather Research and Forecasting, model evaluation, Poland.

1 Introduction

Quantitative precipitation forecasts (QPF) are an important output of mesoscale meteorological models and are often used to support hydrological forecasts in the systems that issue flood warnings to the population (Oberto et al., 2012) and to better understand the meteorological background of floods (Davolio et al., 2009; Miglietta and Regano, 2008). Considering that a regional prediction model is able to provide a forecast of sufficient accuracy, tools such as the Weather Research and Forecasting model (WRF; Skamarock et al., 2008) can significantly improve the reliability of the hydrological forecasts (Lowrey and Yang, 2008), as well as flash-flood events (Hong and Lee, 2009).

With the large range of configuration options available for the meteorological models in terms of e.g. convection or microphysics, forecasts, both of QPF and further QPF supported hydrological predictions, can differ significantly in terms of accuracy. The convective scheme applied, together with microphysics and planetary boundary layer options are usually considered to be the most important (Jankov et al., 2007; Jankov et al., 2005). Shih et al. (2012) used the forecasted precipitation from the WRF model to calculate the hydrographs with the WASH123D model for Lanyang River, Taiwan. They found that the configuration of physics (i.e. cumulus parameterization and microphysics schemes) in the WRF model is of significant impact on the magnitude and time lag of flood peaks calculated by the WASH123D model. Similar findings were presented by Lowrey and Yang (2008) for Texas, US. Both papers proposed the same Betts-Miller-Janic cumulus parameterization scheme as an optimal approach for convective rainfall forecasts. Studies undertaken by Garcia-Ortega et al. (2012) for south-west Europe suggest that the Goddard moisture scheme and the Kain-Fritsch cumulus scheme provide the precipitation field closest to the observed one. The WRF model was also run with a Kain-Fritsch parameterisation for the rainfall simulations in the UK (Liu et al., 2012) as well as for high resolution regional model simulations for Germany (Berg et al., 2013).

Apart from the physics configuration, Westrick and Mass (2001), in studies conducted for Camano Island (south-east of Vancouver Island), showed that there is an improvement of the MM5 predicted precipitation with increasing model resolution. However, even with high spatial resolution applied, predicted rainfall was underestimated, resulting in the underestimation of the total and

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event peak flows. The importance of high spatial resolution is also supported by WEISMAN et al. (2008). The authors show that for high-resolution (4 km) forecasts there is a significant value added in representing the convective system mode (WEISMAN et al., 2008), over the 12 km operational Eta model forecasts. With high model resolution, deep convection can be explicitly resolved and does not need to be parameterized. This parameterization is considered as a source of large uncertainty for lower-resolution models (WEUSTHOFF et al. 2010; KUELL et al. 2007). Apart from the model configuration and resolution, initial conditions are also crucial for the obtained results (ARGENCE et al., 2008; PERALTA et al., 2012).

According to the results provided by other authors and discussed above, the configuration of model physics and spatial resolution of the model are of importance for the QPF accuracy. There are also regional differences in forecast performance which makes the evaluation of forecasts for a specific region important. This study presents the evaluation of the Weather Research and Forecasting model rainfall forecasts for SW Poland. The model evaluation is performed for different spatial resolutions of grids of 10 km × 10 km and 2 km × 2 km. Various configurations for deep convection are applied and the results compared with the measurements. Deep convection is explicitly resolved for one set of simulations in the 2 km × 2 km model domain, and the second set of the model runs use Kain-Fritsch scheme for 10 km × 10 km and 2 km × 2 km domains. Two separate sets of rainfall measurements were used for the forecast evaluation – one set uses 1 h rainfall intensity for one site, the second uses 17 meteorological sites with rainfall data available every 6 hours. The differences in model performance due to spatial resolution and configuration of deep convection are analysed for the test period of March-June 2012 and the area of SW Poland.

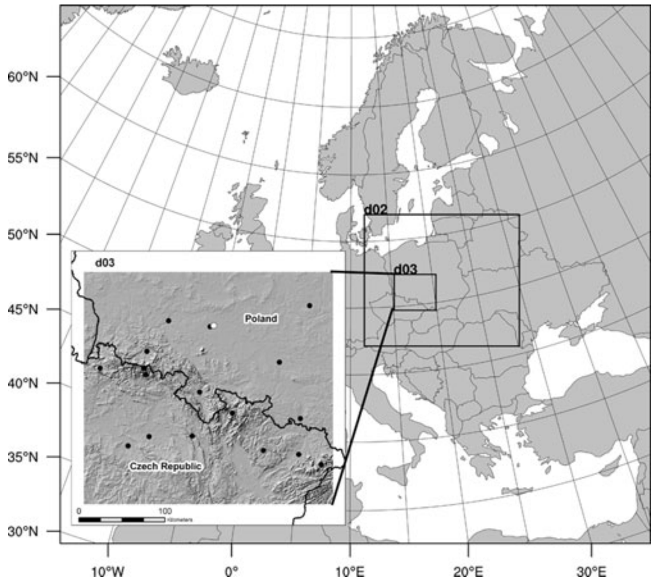

Figure 1: Study area and the WRF model domains d01 (50 km × 50 km grid mesh), d02 (10 km × 10 km) and d03 (2 km × 2 km). Terrain relief is presented for the d03 inset map, together with the location of the University of Wrocław meteorological station (white circle) and SYNOP sites used for forecast evaluation (black circles).

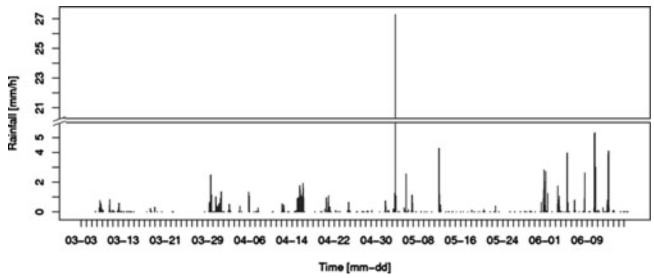

Figure 2: Rainfall measured at the University of Wrocław station during the study period (03.03-18.06.2012).

2 Data and methods

2.1 Study area and measurement data

The main focus of this study is the SW area of Poland covered by the innermost domain of the WRF model (Fig. 1). Terrain elevation of the study area varies from ca. 60 m a.s.l. in the northern part, to 1602 m a.s.l. in the mountains (main ridge along the Poland – Czech Republic border).

Two sources of meteorological data are used for evaluation of the forecasts. First, the measurements from the Wrocław University station (WUS) are used (Fig. 1). Measurements were collected every 1 minute using a Present Weather Sensor Parsivel (LOFFLER-MANG and JOSS, 2000), and aggregated to 1 hour time steps for direct comparison with WRF calculated rainfall. The second set of data used for forecast evaluation is based on the rainfall data available for 17 SYNOP meteorological sites (Fig. 1). For all these sites, 6 hourly accumulated precipitation was available. Both the University of Wrocław and SYNOP measurements were available for the period 03.03.2012–18.06.2012, and the forecasts were run and evaluated for the same period. The SYNOP sites use tipping bucket rain gauges (0.1 mm resolution, SEBA Hydrometrie GmbH & Co. KG). The uncertainty related with the measurements at SYNOP sites within the d03 study area is discussed in KOTOWSKI et al. (2011).

A brief characterisation of the measured rainfall for the study area is presented based on the high-resolution measurements from the University of Wrocław station. For the entire period, a total number of 489 hours with precipitation was observed at WUS (Fig. 2). The first part of the study period is dominated by low intensity precipitation. Since the beginning of May, several short and intensive rainfall episodes of convective origin were measured. The highest hourly rainfall (27.3 mm h^{-1}) was measured on 03.05.2012. It was related to very local, free convection and heavy rainfall during a local thunderstorm. It should be noted that for 03.05.2012 the 24 h accumulated precipitation measured at Wrocław SYNOP station (ca 14 km to the west) is significantly lower (4.8 mm). The length of the measured rainfall episodes changes during the study period. The longer episodes of relatively low intensity are more frequent in March and April. The short episodes of intensive precipitation are more frequent in May and June. This might be of importance for evaluation of high resolution precipitation forecasts, as the shorter episodes are more likely to be missed completely or shifted in time. Such episodes, considering the high spatial and temporal resolution of the forecasts, might result in the so-called double penalty problem (Nurmi, 2003).

2.2 WRF model configuration

The Advanced Research WRF model is configured with three one-way nested domains (Skamarock et al., 2008). The outer domain (d01; 100×91 grid points) covers Europe with a horizontal resolution of $50\ \text{km} \times 50\ \text{km}$ (Fig. 1). The intermediate domain (d02, 131×111 gridpoints) covers the area of Poland and the surrounding countries with a $10\ \text{km} \times 10\ \text{km}$ grid, and the innermost domain (d03, 156×141 gridpoints), with a grid size of $2\ \text{km} \times 2\ \text{km}$, covers the area of SW Poland and N Czech Republic. Vertically, all the domains are composed of 35 terrain-following hydrostatic-pressure coordinates, with the top fixed at 10 hPa. The focus of this paper is on the d03 and the common area of the d02 and d03. The results of the d02 are included to show the role of spatial resolution on the performance of the model.

The forecasts were driven by the data from the U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), available every 3 h with $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution (ca. $36\ \text{km} \times 56\ \text{km}$ in E-W and S-N directions over the d03). The forecasts were initialized each day at 00 UTC, with a forecast lead time of 120 hours. Analysis nudging was applied (Bowden et al., 2012; Stauffer and Seaman, 1990). All the domains used the Goddard scheme (Tao et al., 1989) for microphysics and the modified Kain-Fritsch scheme for cumulus parameterization (Kain, 2004). For one set of the model runs, the modified Kain-Fritsch scheme is applied for the d01 and d02 only, and deep convection is explicitly resolved for d03 (the CuRes2 km runs). The model used the Yonsei University scheme for the boundary layer (Hong et al., 2006), the Monin-Obukhov scheme for the surface layer (Skamarock et al., 2008), RRTMG for shortwave and RRTM for longwave radiation (Mlawer et al., 1997). All the domains used the unified NOAH land-surface model, with MODIS land use data (Skamarock et al., 2008).

Table 1: Contingency table. The counts a, b, c, and d are the total number of hits, false alarms, misses and correct rejections.

	Event observed	
Event forecast	Yes	No
Yes	a	b
No	c	d

2.3 Model evaluation

The WRF precipitation forecasts were compared with the measurements gathered at the meteorological station operated by the University of Wrocław, and, separately, for 17 SYNOP sites operating within the d03 area (Fig. 1). Precipitation was regarded as a simple binary event and summarized by a 2×2 contingency table (Table 1). The table elements are hits (correct forecast and event), misses (observed but not forecasted event), false alarms (forecast but not observed event) and correct rejections (correct forecast of non-event; Wilks, 1995).

Based on the contingency table (Table 1), the performance diagrams proposed by Roebber (2009) were prepared to summarize and compare the results for various model configurations. The diagrams are especially useful for comparison of the performance of, e.g., various model simulations with different configuration. This is the case for this paper, as we compare the forecast performance for two domains of $10\ \text{km} \times 10\ \text{km}$ and $2\ \text{km} \times 2\ \text{km}$ grids and with the Kain-Fritsch cumulus convection scheme (KF10km and KF2km runs, respectively) and the $2\ \text{km} \times 2\ \text{km}$ model runs with deep convection explicitly resolved (CuRes2km runs). The performance diagrams use the following statistics (Nurmi, 2003; Roebber, 2009):

- Probability of detection, calculated as:

$$\mathrm{POD} = \mathrm{a}/(\mathrm{a} + \mathrm{c})$$

- Success Ratio, calculated as:

$$\mathrm{SR} = 1 - (\mathrm{b}/(\mathrm{a} + \mathrm{b}))$$

- Bias, calculated as:

$$\mathrm{BIAS} = \frac{(\mathrm{a} + \mathrm{b})}{(\mathrm{a} + \mathrm{c})}$$

- Critical Success Index (also know as the threat score), calculated as:

$$\mathrm{CSI} = \mathrm{a}/(\mathrm{a} + \mathrm{b} + \mathrm{c})$$

The bootstrap-derived error bars (number of resamples set to 1000) are marked on the performance diagrams for each point. The performance diagrams were prepared separately for the 1 h data gathered at WUS and the

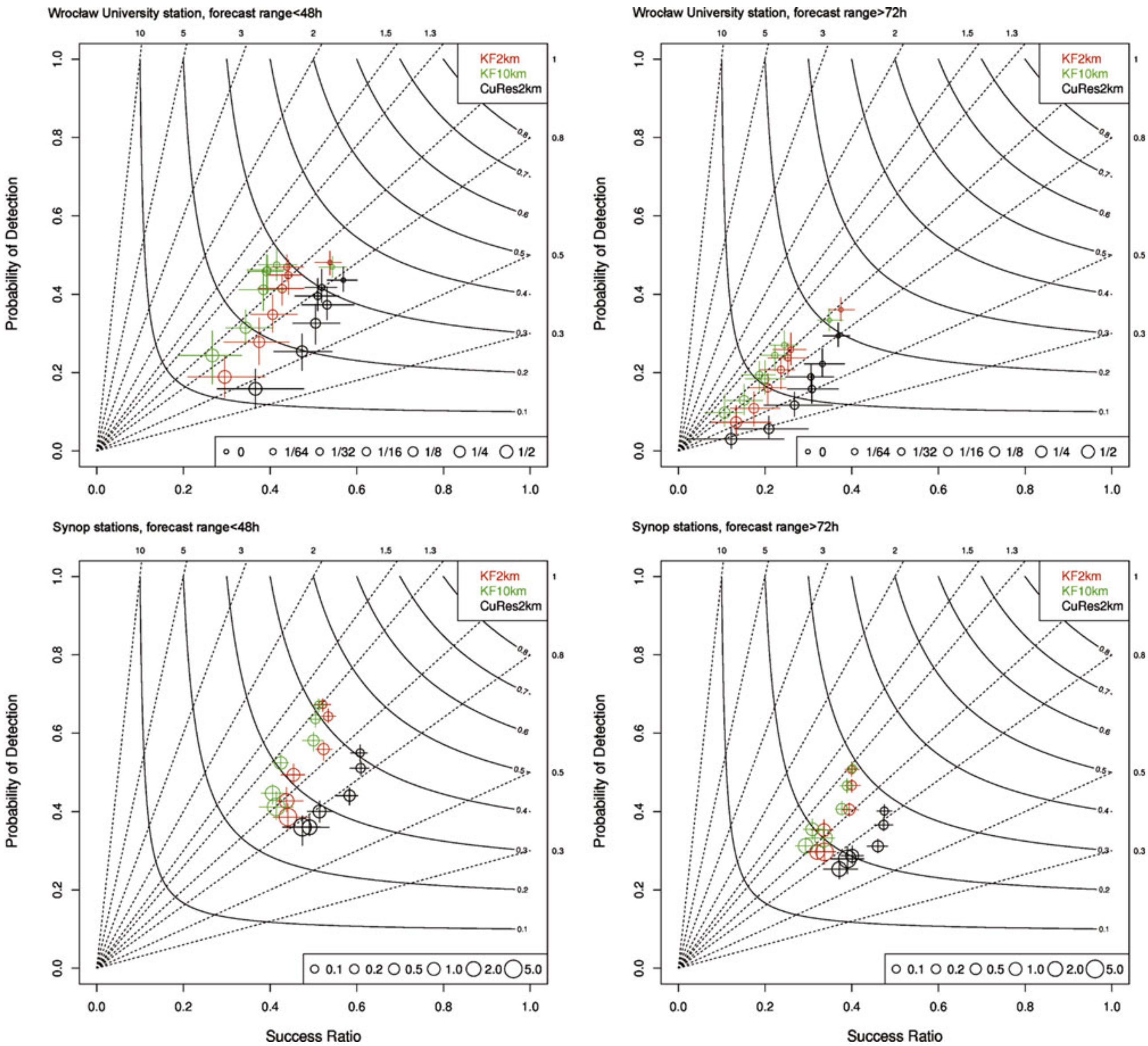

Figure 3: Performance diagrams summarizing the success ratio, probability of detection, bias (dashed lines with labels on the outward extension of the line) and critical success ratio (solid lines) for WUS (upper row) and SYNOP stations (bottom row). Bootstrap-derived error bars are given by the crosshairs. Rainfall intensity is represented by the size of the circle with the legend in the bottom-right area of the plot' – the given numbers are the lower bounds of intensity classes (units are mm 1 h^{-1} for WUS and mm 6 h^{-1} for SYNOP). Forecast ranges are below 48 h (left column) and above 72 h (right column).

17 SYNOP sites operating in the d03, with rainfall information available every 6 h. The forecast performance is stratified by precipitation intensity thresholds and forecast ranges.

3 Results

The performance of the WRF forecasts for selected forecast ranges and rainfall intensities is summarized in Fig. 3, separately for the WUS and SYNOP sites and for KF10km, KF2km and CuRes2km runs. The forecast performance drops with increasing rainfall intensity and forecast range for both subsets of rainfall measurements and all model configurations applied. The decrease in the forecast performance is especially large for 1 h rainfall observed at WUS. The simulations with the deep convection explicitly resolved are described with higher SR values, if compared to KF2km and KF10km runs for both WUS and SYNOP sites. The KF2km runs show similar POD values if compared to KF10km, but also the bias is above 1.0 and higher if compared to KF10km model runs. The CuRes2km simulations underestimate rainfall episodes, with the bias below the reference value of 1. For the KF2km and KF10km, the bias is above 1 for the SYNOP sites. The simulations with the modified Kain-Fritsch parameterization of the convection show

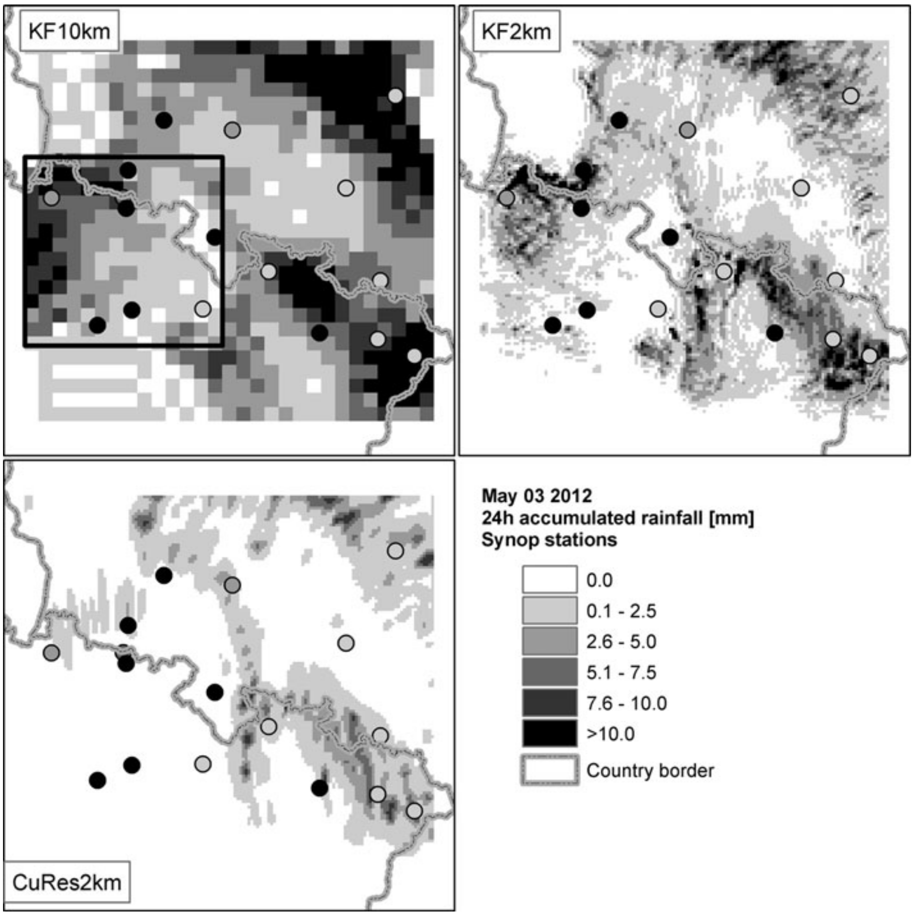

Figure 4: 24 h accumulated rainfall for 3 May 2012, modelled for KF10km, KF2km and CuRes2km model configurations (d03 area). The location of the SYNOP sites with 24 h accumulated rainfall is presented by filled circles. The black square area is discussed in text.

higher POD values, if compared with CuRes2km runs. This might be related with the larger area covered by rainfall for Kain-Fritsch runs, for both 2 km and 10 km domains, which is presented for the selected case of 03.05.2012 (Fig. 4).

There are large differences when the spatial patterns of 24 h accumulated rainfall is compared, which is shown with the example of 3 May 2012 (Fig. 4). For this day, the highest 24 h accumulated rainfall was measured at WUS (35.1 mm measured by the Parsivel sensor and 25.3 mm measured with the manually operated rainfall gauge). Neither of the three model runs compared was able to reproduce the very local episode of high rainfall observed at WUS. The CuRes2km run shows very close agreement with the measurements from Wrocław SYNOP site (4.8 mm measured and 5.0 mm modelled). The differences in spatial patterns of the daily rainfall sum are both due to spatial resolution of the domain and the applied convection parameterisation. The model runs with the modified Kain-Fritsch scheme applied show substantially larger areas covered with rainfall (90%, 76% and 56% of the d03 area covered with rainfall for KF10km, KF2km and CuRes2km, respectively). The 24 h sums of precipitations are also locally higher for KF2km and especially KF10km runs, if compared to CuRes2km. None of the three model configurations was able to reproduce the high 24 h rainfall sums observed in the mountainous region at the Polish-Czech Republic border and over the SW area of the d03 (black rectangle in Fig. 4). The CuRes2km simulation shows almost no rainfall for this area. The 10 km model run shows the best agreement with the measurements for this area, but the simulated precipitation is underestimated. For the eastern and NE part of the domain, the CuRes2km run is in close agreement with the measurements gathered at SYNOP sites.

4 Summary and conclusions

In our study the Weather Research and Forecasting model was used to forecast precipitation for the next 120 h using the GFS data as an input. The WRF forecasts were performed for two domains with spatial resolution of 10 km × 10 km and 2 km × 2 km grid, and temporal resolution of 1 hour. The results were compared with two sets of ground measurements gathered at the University of Wrocław meteorological station (1 h temporal resolution) and 17 SYNOP sites (6 h temporal resolution).

To the authors' knowledge, this is the first simulation over this geographical region that uses the WRF model at high spatial and temporal resolution for weather forecasting. The results are intended to support the HydroProg system of ensemble hydrological forecasts for the same area of SW Poland (www.hydro.uni.wroc.pl).

The general conclusions that can be draw from this study are:

1. The forecasts show reasonable skills for low intensity and long lasting rainfall episodes. The rare episodes of intensive precipitation of convective origin are often missed or the observed value of rainfall intensity is underestimated by the model. This is where the forecasts should be improved, e.g., by application of a different model parameterisation (Droegemaier et al., 2000) or through data assimilation techniques (Courtier et al., 1998; Fritsch and Carbone, 2004; Schwitalla et al., 2011).
2. The forecast performance drops with forecast lead time and rainfall intensity. The decrease in forecast performance is especially large if high temporal resolution measurements are used for evaluation.
3. The simulations with deep convection explicitly resolved show higher values of Success Ratio, if compared with the Kain-Fritsch runs, but also the simulated rainfall is underestimated if compared with the measurements. This might be due to the microphysics scheme applied (Schwartz et al., 2010). Further tests for model sensitivity to various parameterizations of microphysics are recommended.
4. The model runs with the modified Kain-Fritsch convection scheme show higher values of Probability of Detection statistics, if compared to the simulations with the convection explicitly resolved, but are also biased high. The high values of POD statistics may be related to the significantly larger area covered with rainfall, if the Kain-Fritsch based simulations are compared with the runs for which convection is explicitly resolved.
5. The local episodes of intensive precipitation, as presented with the example of 03.05.2012, are not resolved properly by either of the three model configurations. High spatial resolution leads to more small scale features, but forecast are still affected by biases and displacements errors, which was earlier reported by Mass et al. (2002).

There is a further need for more complex evaluation of the forecasts for this study area. Future forecast evaluation should also include a spatial approach with radar and satellite data. Checking other model configurations, especially convective and microphysics schemes will be important to determine the reasons for, e.g., underestimation of the observed rainfall amount.

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