Modelling meteorological conditions for the episode (December 2009) of measured high PM_{10} air concentrations in SW Poland – application of the WRF model

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Abstract: The weather research and forecasting model has been applied to derive information on meteorological variables for the period with high concentrations of PM_{10} (1–30 December 2009) in SW Poland. Three one-way nested domains have been used and the results for the innermost domain have been compared with surface and radiosonde meteorological measurements for pressure (PRES), air temperature (TMP), specific humidity (SPFH), wind speed (WIND) and direction (WDIR). The model results are in good agreement with the surface measurements for TMP, PRES and SPFH, with the index of agreement (IOA) above 0.9. The model underestimate the observed PRES, TMP and SPFH except for the mountainous site Śnieżka. The WIND is biased high, the overall IOA is 0.62, and range from 0.41 to 0.73 for all stations. The IOA is above 0.73 for TMP and SPFH for radiosonde measurements and the errors decrease with height.

Keywords: weather research and forecasting; WRF; meteorological modelling; air quality modelling; Poland.

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1 Introduction

Numerical weather prediction models (NWP) are used to calculate meteorological variables at various geographical and temporal scales. The models are used for both: weather forecasting and reanalysis. Meteorological models are key components of regional air pollution modelling, as the meteorological processes are important for emission, dispersion and removal of atmospheric pollutants (Seaman, 2000; Borge et al., 2008). Moreover, high concentrations of atmospheric pollutants of adverse effect on human health are often related with specific meteorological conditions, e.g., frosts or heatwaves, low wind speeds and thermal stratification within the boundary layer. This makes the modelling a challenging task of great importance for air quality management, since uncertainty in meteorological data is passed on to the air quality models (Gilliam et al., 2006; Sistla et al., 1996; Zhang et al., 2009).

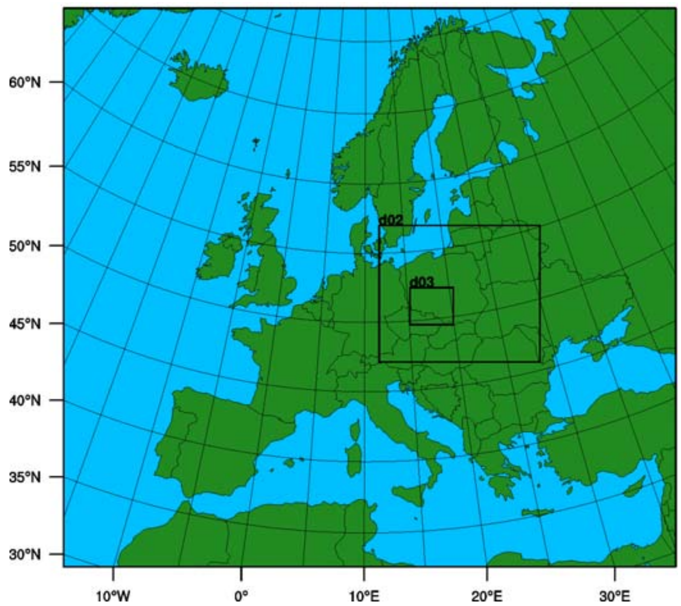
This paper presents an application and evaluation of the Weather Research and Forecasting (WRF) model for meteorological variables at relatively high spatial resolution at the regional scale. The WRF simulation was performed for the winter period with the air quality standards exceeded for particulate matter (PM_{10}) in the densely populated SW area of Poland (01-30.12.2009). The WRF model results were evaluated with both surface and radiosonde measurements collected in the innermost model domain.

2 Data and methods

2.1 Episode selection and synoptic conditions

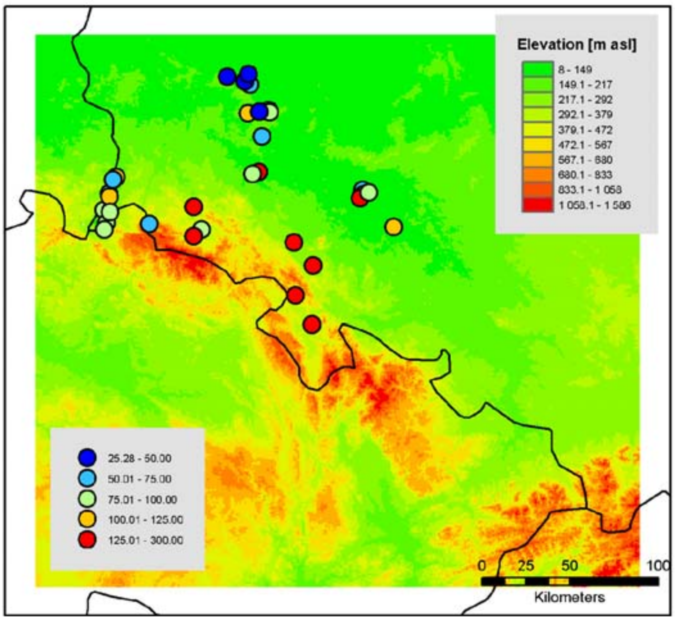
The selection of the period for the WRF simulation is based on the 2009 air quality measurements performed on the air quality network of the Voivodship Inspectorate for environmental protection in Wrocław, SW Poland. The air quality standards for PM_{10} were exceeded in the period from 1 to 30 December. The highest values of daily average PM_{10} concentrations are presented in Figure 1. For all 41 sites, except for four located in N part of the area, the 50 μg m^{-3} threshold (24 h average) was exceeded at least once, and for five stations, the exceedences were measured for more than 15 days, with the daily average maximum at Jelenia Góra reaching 284.7 μg m^{-3} (03.12.2009).

Figure 1 (a) Configuration of the WRF model domains and (b) the highest daily average PM_{10} air concentrations measured over the domain d03 during the period 1–30 December 2009 (see online version for colours)



(a)

Figure 1 (a) Configuration of the WRF model domains and (b) the highest daily average PM_{10} air concentrations measured over the domain d03 during the period 1–30 December 2009 (continued) (see online version for colours)



(b)

In December 2009, stable high pressure system was present over the SW area of Poland for almost an entire month. The weather was misty and cloudy, with generally low wind conditions. This encouraged stagnation and systematic transformation of the air masses, and led to an accumulation of locally emitted pollutants. In the middle of December, a cold air outbreak of Arctic origin took place in Central Europe. This resulted in decrease of average daily air temperatures (TMP) below –15°C for several consecutive days. As a results of these low temperatures, emissions of atmospheric pollutants were enhanced, mainly from domestic combustion (Juda-Rezler et al., 2011). The meteorological conditions were also favourable for pollutants to accumulate in the boundary layer, resulted in extremely high PM_{10} concentrations over the study period.

2.2 WRF model configuration

The WRF model is configured with three one way nested domains (Skamarock et al., 2008). The outer domain (d01; 100 × 91 grids) covers Europe with a horizontal resolution of 50 km × 50 km (Figure 1). The intermediate domain (d02; 131 × 111 grids) covers the area of Poland and surrounding countries with 10 km × 10 km grid. The innermost domain (d03; 156 × 141 grids) covers the SW area of Poland with a grid size of 2 km × 2 km. Vertically, the domain is composed of 35 terrain-following hydrostatic-pressure vertical coordinate, with the top fix at 10 hPa. The model setup is detailed in Table 1. The simulation was driven by the NCEP final analysis, available every 6 h with 1° × 1° spatial resolution, and the analysis nudging was not applied.

Table 1 Setup for the WRF model simulation

Category	*Setup*
Shortwave radiation	Dudhia scheme (Dudhia, 1989)
Longwave radiation	Rapid radiative transfer model (Mlawer et al., 1997)
Microphysics	New Thompson scheme (Thompson et al., 2004)
Cumulus parameterisation	Kain-Fritsch (Kain, 2004) scheme for d01 and d02, no parameterisation for d03
Land surface processes	Noah land surface model (Chen and Dudhia, 2001)
Planetary boundary layer	Asymmetric convective model version 2 (Pleim, 2007)
Horizontal resolution	d01: Δx = Δy = 50 km; d02: Δx = Δy = 10 km; d03: Δx = Δy = 2km
Vertical levels	35 levels

2.3 *Evaluation of the model results*

Because the main focus of this study is on the SW area of Poland, only Polish meteorological stations operating in the d03 were used for model evaluation. Surface meteorological measurements were available from nine synoptic stations. Five meteorological variables were used for comparison of surface data: atmospheric pressure (PRES), TMP at 2 m, SPFH at 2 m, wind speed (WIND) and wind direction (WDIR) at 10 m. The measurements were available at frequency of 1 h (Wrocław station) to 3 h (all other stations). The ravisonde measurements were performed at Wrocław station every day at 12:00 UTC, and TMP and SPFH data up to the 750 hPa level was used for vertical model – measurements comparison.

The model vs. measurement comparison was calculated for each meteorological variable and summarised using three commonly used statistics: mean bias (MB), mean absolute gross error (MAGE) and index of agreement (IOA) for PRES, TMP, SPFH and WIND (Willmott, 1982; Yu et al., 2006). For WDIR, MB and MAGE were calculated, as recommended by Emery et al. (2001). MB, MAGE and IOA were calculated with the following equations (M_i – modelled value, O_i – observed value):

$$MB = \frac{1}{N}\sum_i (M_i - O_i) \tag{1}$$

$$MAGE = \frac{1}{N}\sum_i |M_i - O_i| \tag{2}$$

$$IOA = \frac{N * \sum_{i=1}^{N} (M_i - O_i)^2}{\sum_{i=1}^{N} \left(|M_i - \overline{O}| + |O_i - \overline{O}|\right)^2} \tag{3}$$

3 Results

The evaluation results show that the model is able to correctly resolve spatial and temporal changes of surface PRES, TMP and SPFH, with the IOA calculated for all measurements > 0.9 (Table 2). Overall, there is a general tendency of the model to underestimate the observed TMP (Figure 2) and SPFH for the selected period, described by the negative MB values for the majority of the stations. The meteorological variables are overestimated for Śnieżka station, and in case of PRES, for Kłodzko. For Śnieżka, the overestimation can be attributed to the specific location of the station – at the isolated mountain top. The model grid height at Śnieżka station is 1,293 m, while the real station elevation is 1,602 m asl. This can explain the overestimation of PRES and TMP for Śnieżka, and suggest insufficient spatial resolution of the model for the areas of complex terrain. The terrain features are smoothed with the 2 km × 2 km model grid, and the actual deformation of air streamlines produced by topography is more significant than that estimated by the model.

The IOA calculated for WIND is lower than for the remaining meteorological variables used for comparison. The worst results, in terms of IOA, are calculated for Rudniki station, which is difficult to explain in terms of, e.g., topographic position of the measuring post (Figure 2). The low values of IOA and the large negative bias for Śnieżka station can be attributed to the same reasons as provided above for PRES and TMP. The model has a general tendency for overestimation of the measured WIND for most WDIRs (see Figure 3 for Wrocław station used as an example). There are also large discrepancies in observed and modelled WDIR (Table 3). The errors for WDIR are especially large for the periods of observed low wind speeds and for sites with specific topographical position: Jelenia Góra, Kłodzko and Racibórz. All these sites are located in concave landforms (Figure 2), and observed WDIR depends on local topography, which is not resolved sufficiently at 2 km grid size.

Table 2 Error statistics for PRES, TMP and SPFH for surface and ravisonde measurements

Site	*N*	*PRES*			*TMP*			*SPFH*		
		MB [hPa]	*MAGE [hPa]*	*IOA*	*MB [K]*	*MAGE [K]*	*IOA*	*MB [g/kg]*	*MAGE [g/kg]*	*IOA*
All	2,020	0.46	6.46	0.98	–1.49	2.71	0.92	–0.15	0.58	0.91
Wrocław	600	–2.75	3.72	0.92	–1.63	2.74	0.91	–0.12	0.57	0.91
Legnica	180	–1.48	3.31	0.94	–1.59	2.77	0.89	–0.24	0.58	0.91
Wieluń	179	–2.20	3.53	0.92	–1.45	2.40	0.93	–0.19	0.55	0.93
Jelenia Góra	179	–6.72	6.87	0.84	–0.88	2.76	0.91	–0.10	0.57	0.92
Śnieżka	178	33.92	33.92	0.34	1.02	2.36	0.93	0.25	0.65	0.86
Kłodzko	179	2.32	3.74	0.93	–1.55	2.47	0.92	–0.11	0.47	0.94
Racibórz	166	–3.82	4.46	0.89	–2.51	3.02	0.90	–0.30	0.62	0.92
Rudniki	179	–0.67	3.32	0.93	–2.43	2.99	0.91	–0.31	0.66	0.91
Opole	180	–4.17	4.69	0.89	–2.04	2.79	0.92	–0.36	0.64	0.92
Wrocław ravisonde	265	-	-	-	–0.02	2.31	0.95	0.11	0.77	0.85

Note: N – number of measurements.

Figure 2 Mean bias for TMP and WIND for the meteorological stations operating in d03 (see online version for colours)

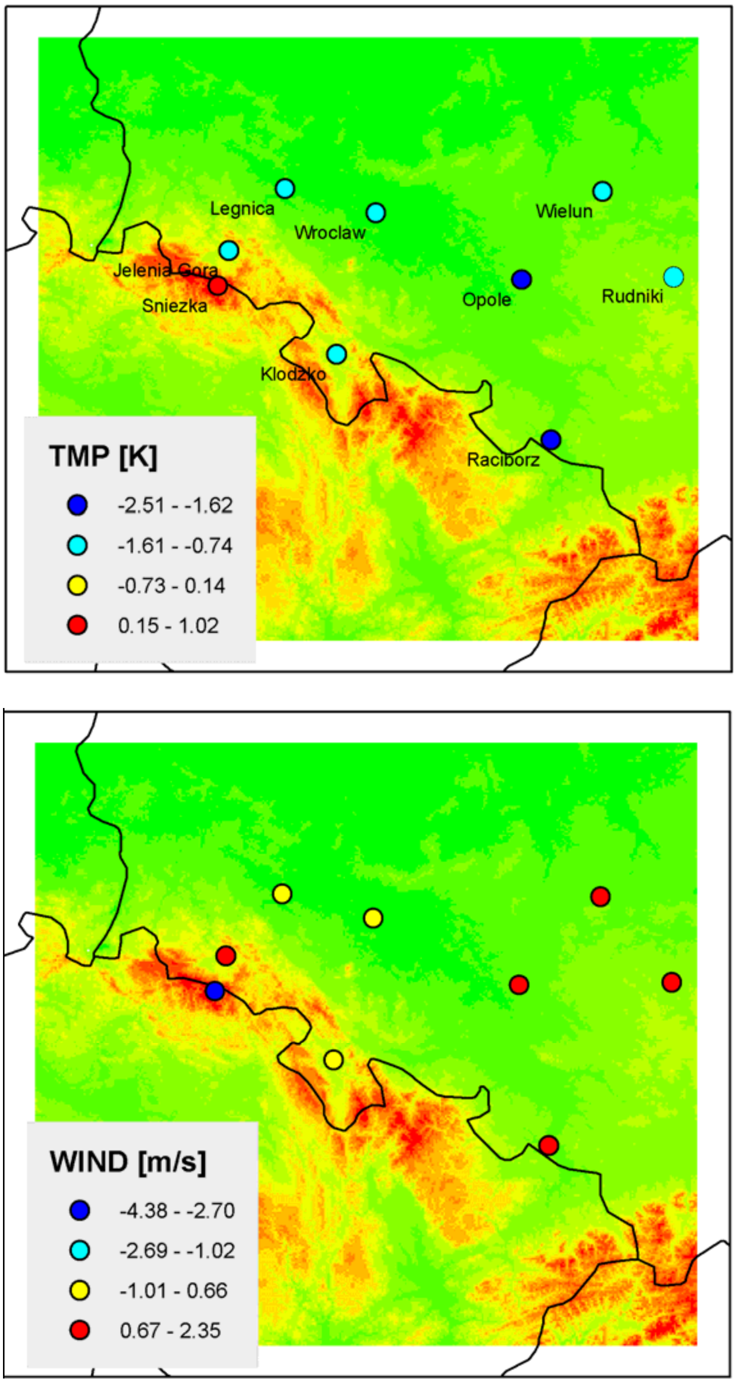
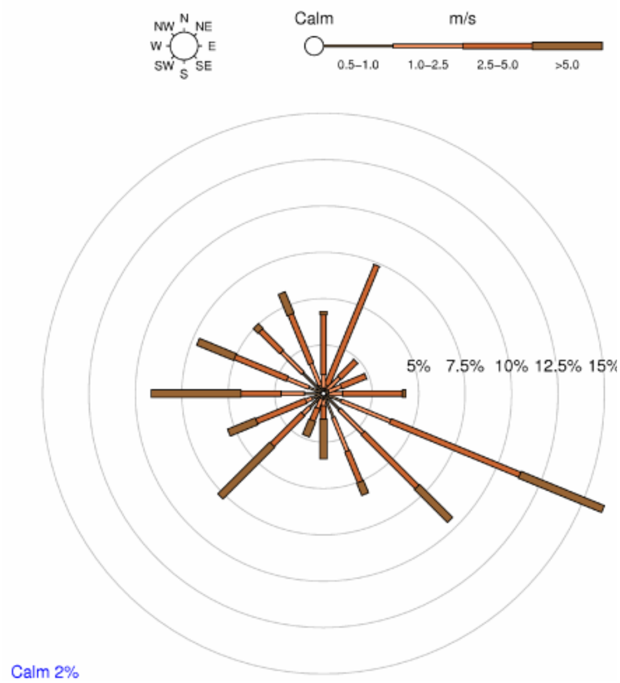
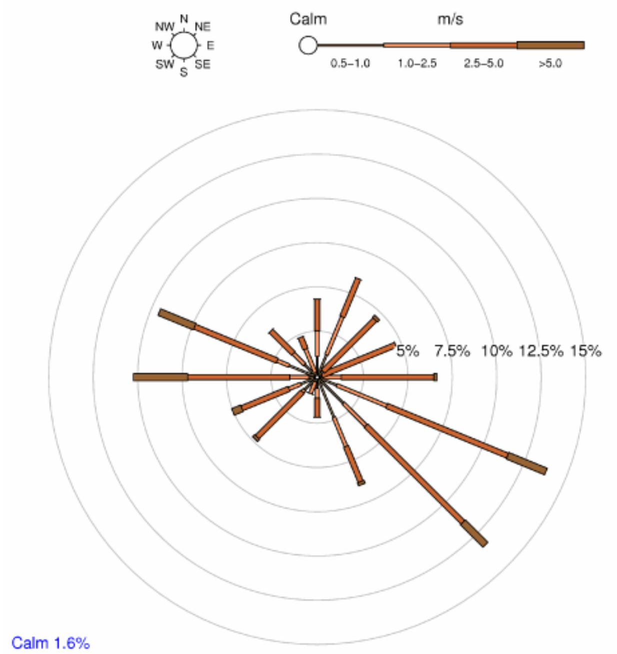


Figure 3 (a) Modelled and (b) measured WIND and wind frequency for Wrocław station at 10 m (see online version for colours)



(a)



(b)

Table 3 Error statistics for WIND and WDIR for surface measurements

Site	*N*	*WIND*			*WDIR*	
		MB [m/s]	*MAGE [m/s]*	*IOA*	*MB [deg]*	*MAGE [deg]*
All	2,020	0.53	2.22	0.62	5.80	32.46
Wrocław	600	0.84	1.88	0.50	0.09	28.28
Legnica	180	0.35	1.61	0.73	–0.03	31.34
Wieluń	179	1.67	2.05	0.62	15.71	33.14
Jelenia Góra	179	0.96	1.87	0.57	0.22	46.67
Śnieżka	178	–4.38	5.46	0.54	21.69	32.15
Kłodzko	179	0.42	2.32	0.70	6.45	38.84
Racibórz	166	0.85	1.89	0.58	–1.01	44.68
Rudniki	179	2.35	2.55	0.41	14.23	28.33
Opole	180	0.95	1.55	0.66	11.36	35.73

Note: N – number of measurements.

From the perspective of air pollution dispersion, it is important to know how accurately the meteorological model is able to resolve the low wind speeds, as these conditions are favourable for high concentrations of atmospheric pollutants. The total number of measurements in the selected period with the wind speed below 1 m s^{-1} was 163 (all stations). WRF calculated the wind speed below this threshold 139 times at the location of the meteorological stations. However, only for 15% out of 163 cases of the observed low wind speed, the WRF estimate was also below 1 m s^{-1}. The MB for the WIND observation below 1 m s^{-1} is 2.3 m s^{-1}. If the threshold was increased to 2.0 m s^{-1}, the model was able to reproduce 35% of the observed cases, with the MB = 1.8 m s^{-1}.

The modelled TMP and SPFH are in good agreement with radiosonde measurements collected in Wrocław. The IOA is higher and the MB lower than calculated for surface measurements for all stations and for Wroclaw only (except for SPFH). However, the MAE suggests larger absolute errors than for surface data for SPFH. The largest errors are found for the lowest model layers. Also, for the specific days of temperature inversions, the model is not able to reproduce the vertical profile of TMP (results not presented here).

4 Summary and conclusions

In this paper the WRF model was applied to estimate meteorological parameters in SW Poland for a selected period of high concentrations of PM_{10}. The results were evaluated by comparison with surface meteorological measurements gathered at nine stations and one site providing the ravisonde data, for TMP, SPFH, WIND, direction and PRES.

The model is capable of reproducing the temporal changes of PRES, surface temperature and SPFH for the majority of the stations. The error values are similar to those reported from other areas and periods (Prabha and Hoogenboom, 2008). For PRES, SPFH, TMP and WIND (for majority of the stations), the IOA meets the benchmark values proposed by Emery et al. (2001) and Borge et al. (2008). The benchmark thresholds are not met for MAGE and MB for TMP and for MAGE statistic for WDIR.

The sites for which the model performed worse are located in the mountainous area of the domain, and insufficient spatial resolution is expected to be the reason for this. The model constantly underestimates the measured air temperature at 2 m and overestimates the wind speed. This can be attributed to the insufficient vertical resolution of the model to reproduce 2 m air temperature, and the predominant land use class approach used by the WRF model to calculate air temperature. Overestimation of the WRF modelled wind speed was also reported by other authors. Chen and Steenburgh (2005) reported overestimation of the observed wind speed at 0.5 m s^{-1} for the Western United States. Shimada et al. (2011) found that the WRF modelled wind speed for the lower boundary layer is overestimated by 1.0 to 2.7 m s^{-1} for the model domain covering Japan. However, for the August 2003 heat-wave in the UK (related to high ozone concentrations), the underestimation of the measured wind speeds, on average by 1.3 m s^{-1}, were reported by Vieno et al. (2010). Further tests are necessary to address this issue, focused mainly on initial meteorological data used to run the model, boundary and surface layer parameterisation and vertical configuration of the domain. The tests will be performed also for other cases with high PM_{10} concentrations measured in SW Poland, which are relatively frequent in cold seasons over the recent years.

The success of the model in reproducing observed wind speed below 1m s^{-1} threshold were limited (15% of successful cases). For several cases, the model also failed to reproduce the vertical profile of air temperature, especially when a strong inversion layer was measured near the ground. Similar results were reported by Zhang et al. (2009), who concluded that the WRF model applied at 3 km spatial resolution in Mexico City was unable to resolve weak winds realistically, which was important for the air-quality model results.

The results presented in this paper show that during severe air-quality episodes related to low air temperature, wind speed and strong inversions, the modelled meteorological data may introduce significant uncertainty to air-quality models, which should be considered by, e.g., environmental managers and policymakers. More systematic comparison of model prediction versus measurements is needed to further quantify the uncertainty related to meteorological information. This study has identified, using an example from SW Poland, a number of important issues, including persistent underestimation of air temperature and overestimation of wind speed, both important for atmospheric chemistry and transport. However, further studies are recommended to explain the differences between the modelled and observed meteorology, improve the state of the meteorological data available for air quality modelling within the area, and finally define the optimal WRF model configuration for the cases of severe air-quality in the area.

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