H14-115
MODELLING METEOROLOGICAL CONDITIONS FOR THE EPISODE OF MEASURED HIGH PM_{10} AIR CONCENTRATIONS – APPLICATION OF THE WRF MODEL

Maciej Kryza[1], Małgorzata Werner[1], Anthony J. Dore[2], Marek Błaś[1], Anetta Drzeniecka – Osiadacz[1], Paweł Netzel[1]

[1]Wrocław University, Department of Climatology and Atmosphere Protection, Poland
[2]Centre for Ecology and Hydrology, Edinburgh, United Kingdom

Abstract: The Weather Research and Forecasting (WRF) model was applied to derive spatial and temporal information on meteorological variables for the period with exceeded limit values of particulate matter (PM_{10}; 1 – 30 Dec 2009) in SW Poland. The WRF model was configured for three one-way nested domains, covering Europe (50km x 50km grid), central Europe (10km x 10km) and SW Poland (2km x 2km), all with 35 vertical levels. The model was initialized with MODIS landuse and land-water mask, and the simulation was driven by the NCEP FNL data. The results for the innermost domain were evaluated by comparison with surface and ravisonde (up to the 750 hPa level) meteorological measurements for atmospheric pressure (PRES), air temperature (TMP), specific humidity (SPFH) and wind speed (WIND).
The model results were found to be in good agreement with the surface measurements for TMP, PRES and SPFH, with the index of agreement (IOA) for air and dew point temperatures above 0.9. The model underestimated the observed PRES, TMP and SPFH for all sites except Śnieżka, located on the mountain top. For 10m wind speed, the overall IOA for all stations was 0.62, and the range from 0.41 to 0.73. The model overestimated the measured wind speed. If the model is compared with the ravisonde measurements, there is a good overall agreement, with IOA above 0.73 for TMP, SPFH and WIND, and the errors decrease with height. However, in several cases the model was not able to describe the vertical structure of the boundary layer correctly, which is important for air pollution dispersion modelling.

Key words: *Weather Research and Forecasting, meteorological modelling, air quality modelling, Poland.*

INTRODUCTION
Mesoscale meteorological models are widely used to derive spatially continuous meteorological parameters at various temporal scales. The models are used for both: weather forecasting and reanalysis. The output of the meteorological models is also a key component for 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, thermal stratification within the boundary layer or type and mobility of the atmospheric air mass.

This paper presents the results of application and evaluation of the Weather Research and Forecasting (WRF) model for calculation of meteorological parameters 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 in SW area of Poland (PM_{10}; 01-30.12.2009). The WRF model results were evaluated with both surface and ravisonde measurements collected in the innermost model domain.

DATA AND METHODS
Episode selection
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 24h average PM_{10} concentrations are presented in Fig. 1. The air quality standards for PM_{10} (24h average concentration below 50µg m^{-3}) were not exceeded in this period only at four sites located in N part of the domain. For all the remaining sites, the 50µg m^{-3} threshold was exceeded at least once, and for five stations (out of 41), the exceedences were measured for more than 15 days, with the daily average maximum at Jelenia Gora reaching 284.7 µg m^{-3} (03.12.2009).

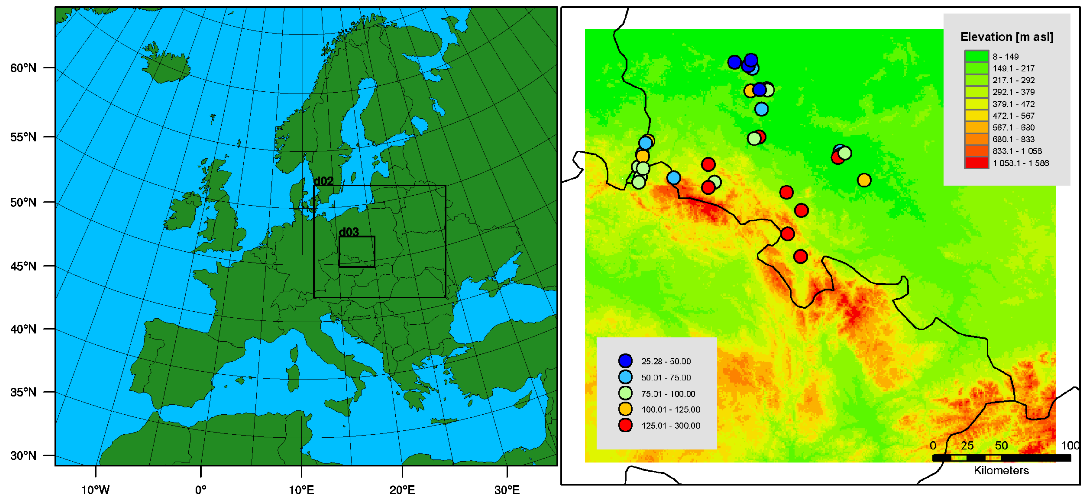

Figure 1. Configuration of the WRF model domains (left) and the highest daily average PM_{10} air concentrations measured over the domain d03 during the period 1 – 30 Dec 2009 (right)

WRF model configuration

The WRF model is configured with three one way nested domains (Fig. 1; Skamarock et al., 2008). The coarse domain (d01) has a size of 100 x 91 grids and covers Europe with horizontal resolution of 50km x 50km. The intermediate domain (d02) mesh size is 131 x 111 grids and covers the area of Poland and surrounding central European countries with 10km x 10km grid. The innermost domain (d03; 156 x 141 grids) covers the SW area of Poland with the grid size of 2km x 2km. Vertically, the domain is composed of 35 full sigma levels, with the top at 10hPa. The model setup is detailed in Table 1. The model was initialized with MODIS landuse and land-water mask. The simulation was driven by the National Centres for Environmental Prediction FNL Global Tropospheric Analysis, available every 6h with 1^o x 1^o spatial resolution.

Table 6 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 parameterization	Kain-Fritsch (Kain, 2004) scheme for d01 and d02, no parameterization for d03
Land surface processes	Noah Land Surface Model (Chen and Dudhia, 2001)
Planetary boundary layer	Asymmetrtic Convective Model version 2 (Pleim, 2007)
Horizontal resolution	d01: Δx=Δy=50km d02: Δx=Δy=10km d03: Δx=Δy=2km
Vertical levels	35 levels

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. Four meteorological parameters were used for comparison of surface data: atmospheric pressure (PRES), air temperature at 2m (TMP), specific humidity at 2m (SPFH) and wind speed at 10m (WIND). The measurements were available at various frequency, from 1h (Wroclaw station), to 3h. The ravisonde measurements were performed at Wroclaw station every day at 12:00 UTC, and TMP, SPFH and WIND data up to the 750 hPa level was used for vertical model – measurements comparison. All the measurements were checked for quality and unreliable data were removed.

The model – measurement errors were calculated for each observation and summarised using three commonly used error statistics: mean bias (MB), mean absolute error (MAE) and index of agreement (IOA). The error statistics are described in Willmott (1982) and Yu et al. (2008).

RESULTS

The evaluation results show that the model is able to correctly resolve temporal changes of surface PRES, TMP and SPFH, with the IOA calculated for all measurements >0.9 (Table 2, Fig. 2 and Fig. 3). Overall, there is a general tendency of the model to underestimate the observed TMP and SPFH for the selected period, described by the negative MB values for the majority of the stations. The meteorological parameters 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 grid height at Śnieżka station is 1293m, while the real station elevation is 1615m 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 at 2km x 2km model grid, and actual deformations of air streamlines produced by topography is more significant than estimated by the model.

The IOA calculated for WIND is lower than for the remaining meteorological parameters 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 (Fig. 2 and 3). The model performance for Śnieżka station is also rather poor, and the WIND values are significantly underestimated by the model. The reasons for the underestimation calculated for Śnieżka are expected to be the same as provided above for PRES and TMP.

From the perspective of air pollution dispersion, it is important to know how accurately the meteorological model is able to resolve the low wind speed, 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). The model calculated the wind speed below this threshold 139 times. However, only for 15% of the measured cases of low wind speed, 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, SPFH and WIND are in good agreement with ravisonde measurements collected in Wroclaw. 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 and WIND. The largest errors are found for the lowest model layers. Also, for the specific days, the model is not able to reproduce the vertical profile of air temperature.

Table 7 Error statistics for PRES, TMP, SPFH and WIND for surface and ravisonde measurements (N – number of measurements)

site	N	PRES [hPa]			TMP [K]			SPFH [g/kg]			WIND [m/s]		
		MB	MAE	IOA	MB	MAE	IOA	MB	MAE	IOA	MB	MAE	IOA
All	2020	0.46	6.46	0.98	-1.49	2.71	0.92	-0.15	0.58	0.91	0.53	2.22	0.62
Wrocław	600	-2.75	3.72	0.92	-1.63	2.74	0.91	-0.12	0.57	0.91	0.84	1.88	0.50
Legnica	180	-1.48	3.31	0.94	-1.59	2.77	0.89	-0.24	0.58	0.91	0.35	1.61	0.73
Wieluń	179	-2.20	3.53	0.92	-1.45	2.40	0.93	-0.19	0.55	0.93	1.67	2.05	0.62
Jelenia Góra	179	-6.72	6.87	0.84	-0.88	2.76	0.91	-0.10	0.57	0.92	0.96	1.87	0.57
Śnieżka	178	33.92	33.92	0.34	1.02	2.36	0.93	0.25	0.65	0.86	-4.38	5.46	0.54
Kłodzko	179	2.32	3.74	0.93	-1.55	2.47	0.92	-0.11	0.47	0.94	0.42	2.32	0.70
Racibórz	166	-3.82	4.46	0.89	-2.51	3.02	0.90	-0.30	0.62	0.92	0.85	1.89	0.58
Rudniki	179	-0.67	3.32	0.93	-2.43	2.99	0.91	-0.31	0.66	0.91	2.35	2.55	0.41
Opole	180	-4.17	4.69	0.89	-2.04	2.79	0.92	-0.36	0.64	0.92	0.95	1.55	0.66
Wrocław ravisonde	265	-	-	-	-0.02	2.31	0.95	0.11	0.77	0.85	-0.61	3.66	0.73

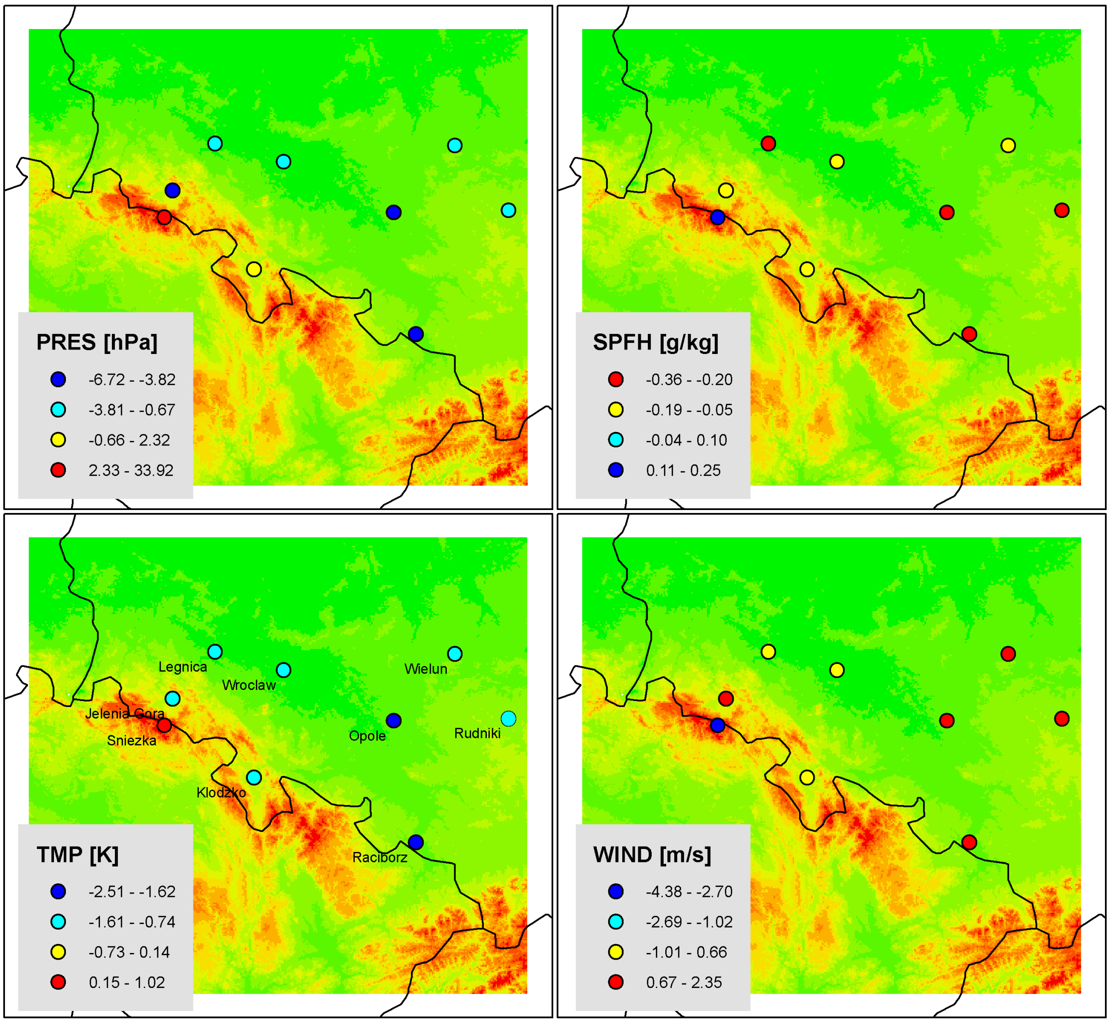

Figure 2. Mean bias for the meteorological stations operating in d03

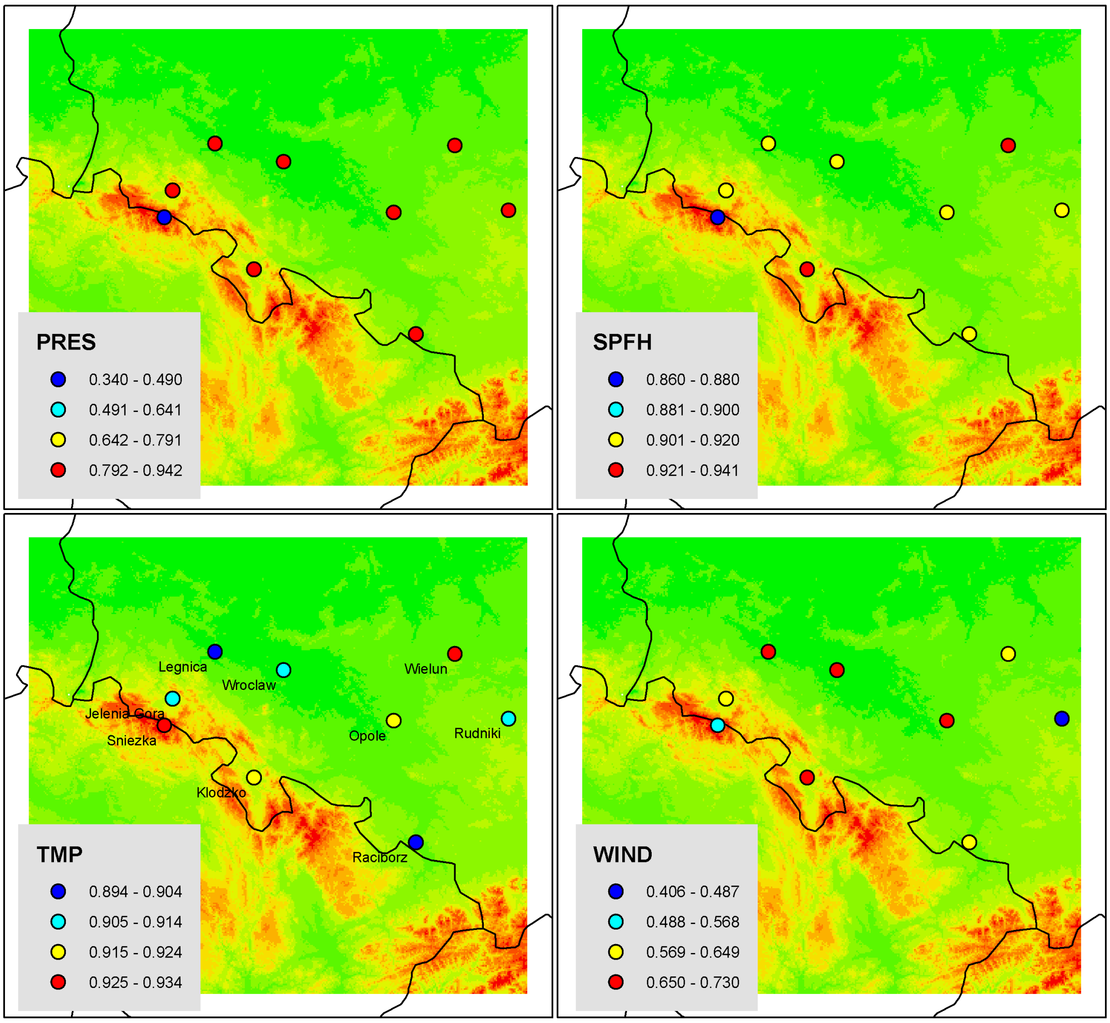

Figure 3. Index of agreement for the meteorological stations operating in d03

If the modelled and observed values are compared more directly, a period of large errors for PRES is evident for days 17 – 21 Dec 2009 for all stations (time series for Wroclaw are presented in Fig. 4). The model is not able to reproduce the significant decrease in atmospheric pressure. For the coldest day of the selected period (20 Dec), the modelled air temperature is close to the measured value, but the lowest modelled TMP value is calculated for the next day and not confirmed in the measurements. For WIND, the model is capable in reproducing the time of observed peaks of increased wind speed.

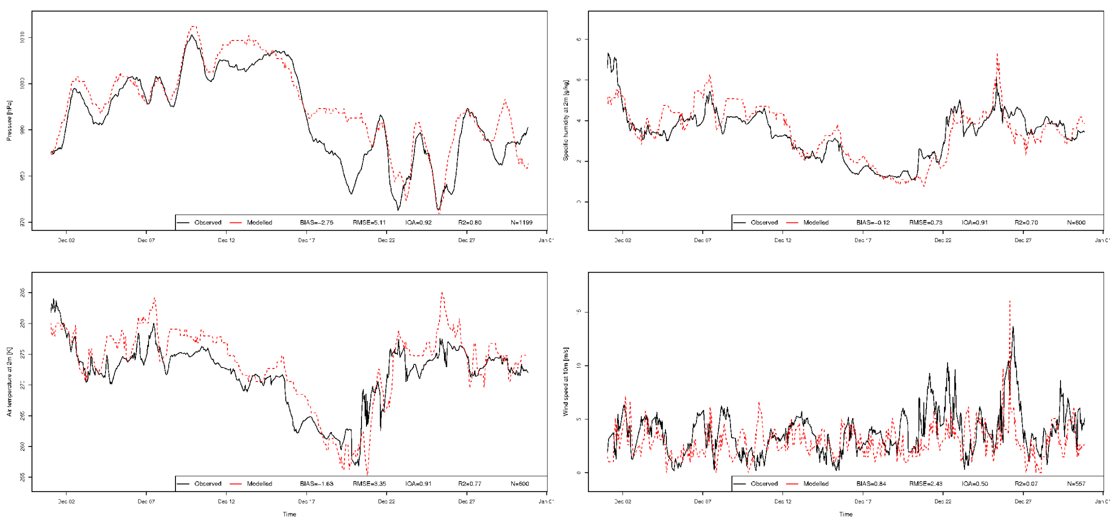

Figure 4. Modelled and observed PRES (top left), TMP (bottom left), SPFH (top right) and WIND (bottom right) at Wroclaw station

SUMMARY AND CONCLUSIONS

In this paper Weather Research and Forecasting model was applied to estimate meteorological parameters in SW Poland for the 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 air temperature, specific humidity, wind speed and atmospheric pressure.

The model is capable of reproducing the temporal changes of atmospheric pressure, surface temperature and specific humidity for the majority of the stations. The error values are similar to those reported from other areas and periods (e.g. Prabha and Hoogenboom, 2008). 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 2m and overestimates the wind speed. The overestimations of the WRF modelled wind speed are reported also by other authors (Cheng and Steenburgh, 2005, Shimada et al., 2011). However, for the August 2003 heat-wave in the United Kingdom (related with high ozone concentrations), the underestimation of the measured wind speeds are 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 for other cases with high PM_{10} concentrations measured in SW Poland, which are relatively frequent in cold seasons over the recent years.

The model capabilities of reproducing observed wind speed below 1m s^{-1} threshold are 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. These issues are of importance for air pollution modelling, as low wind speed or calm periods, together with strong inversion are favourable for high concentrations of atmospheric pollutants, including PM_{10}.

ACKNOWLEDGEMENTS

The authors are grateful to the Voivodship Inspectorate for Environmental Protection in Wrocław for providing the air quality measurement data for the study. Calculations have been carried out in Wroclaw Centre for Networking and Supercomputing (http://www.wcss.wroc.pl), grant No. 170.

REFERENCES

Borge, R., V. Alexandrov, J. J. Del Vas, J. Lumbreras, E. Rodriquez, 2008: A comprehensive sensitivity analysis of the WRF model for air quality applications over the Iberian Pennisula. *Atmos. Environ.*, **42**, 8560-8574.

Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface/ hydrology model with the Penn State/ NCAR MM5 modeling system. Part I: Model description and implementation. *Mon. Wea. Rev.*, **129**, 569–585.

Cheng, W.Y.Y., W.J. Steenburgh, 2005: Evaluation of surface sensible weather forecasts by the WRF and the Eta Models over the western United States. *Weather and Forecast.*, **20**, 812-821.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46**, 3077-3107.

Kain, J. S., 2004: The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181.

Thompson, G., R. M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev.*, **132**, 519–542.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102 (D14)**, 16663–16682.

Seaman, N.L., 2000: Meteorological modeling for air-quality assessments. *Atmos. Environ.*, **34**, 2231–2259.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Baker, D.M., Duda, M.G., Hwang, X.Y., Wang, W., and J.G. Powers, 2008: A description of the advanced research WRF version 3. Technical Note 475+STR, National Centre for Atmospheric Research, Boulder, CO.

Shimada S., 2011: Accuracy of the Wind Speed Profile in the Lower PBL as Simulated by the WRF Model. *Sola*, **7**, 109-112.

Pleim, J. E., 2007: A combined local and non-local closure model for the atmospheric boundary layer. Part 1: Model description and testing. *J. Appl. Meteor. and Clim.*, **46**, 1383–1395.

Prabha, T., G. Hoogenboom, 2008: Evaluation of the Weather Research and Forecasting model for two frost events. *Computers and Electronics in Agriculture*, **64**, 234-247.

Vieno M., A.J. Dore, D.S. Stevenson, R. Doherty, M.R. Heal, S. Reis, S. Hallsworth, L. Tarrason, O. Wind, D. Fowler, D. Simpson, M.A. Sutton, 2010: Modelling surface ozone during the 2003 heat-wave in the UK. *Atmos. Chem. Phys.*, **10**, 7963-7978.

Willmott, C., 1982: Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.*, **63**, 1309-1313.

Yu, S., B. Eder, R. Dennis, S.H. Chu, E. Schwartz, 2006: New unbiased symmetric metrics for evaluation of air quality models. *Atmos. Sci. Lett.*, **7**, 26-34.