Validation of numerically forecasted vertical temperature profile with measurements for dispersion modelling

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Abstract: Modelling of air pollution dispersion in the immediate vicinity of industrial sources over a complex terrain requires proper meteorological input data regarding the state of the atmosphere. For this purpose, numerical weather prediction-model results, rather than direct measurements, are becoming more widely used. In order to ensure high-quality modelling of the air-pollution dispersion, the forecast meteorological input data have to be of high quality. The quality of numerically obtained data has to therefore be validated with measurements. Measurements of the vertical temperature profile, which is vital, with Radio Acoustic Sounding System (RASS) were used in this study. The paper presents the validation of the forecast vertical temperature profile over the complex terrain of the Krško Basin. The validation is carried out with sensor measurements from a 70-metre-tall tower and remote RASS measurements. 13 months' worth of data is used for the validation study.

Keywords: vertical temperature profile, weather forecast validation, WRF, RASS, complex terrain

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1 Introduction

Adequate meteorological input data concerning the state of the atmosphere is required to model the air-pollution dispersion in the immediate vicinity of pollution source over complex terrain satisfactorily. Without high-quality meteorological data, it is very difficult to obtain dispersion simulation results that match accurately enough the measured concentrations in space and time in fine resolution over the complex terrain. In the aspect of the recent state of the modelling science, such accuracy is requirement of contracting entities commissioning research. The matching of forecast meteorological input quantities from numerical prediction models has to be validated with measurements in order to ensure high-quality modelling of the pollution dispersion in the atmosphere.

The contribution of this paper is the validation of the accuracy of one of the vital components of meteorological input data – the vertical temperature profile of the atmosphere. The focus of this study is on the validation of forecasts of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008), with global input data from the Global Forecast System (GFS). The forecast results are acquired for three different spatial resolutions, namely 14 × 14 km, 4 × 4 km and 2 × 2 km. Remote measuring of the vertical profile with Radio Acoustic Sounding System (RASS) is considered as the proper utility for this task (U.S. Environmental Protection Agency 2000; Masuda 1988; Argentini et al. 2009; Emeis et al. 2012).

The validation is carried out for a specific site, namely the area around the nuclear power plant, which is located in the Krško basin, Slovenia. Air-pollution dispersion modelling is intended for the surrounding area of the Krško Nuclear Power Plant (NPP) in order to determine the correct doses for the population in the case of radionuclide release into the atmosphere. The dispersion model is usually fed with meteorological measurements when operating in the diagnostic mode, and with numerical weather-forecast data when operating in the prognostic mode (Mlakar et al. 2015). Detailed descriptions of the dispersion modelling are beyond the scope of this article. Dispersion modelling is the key reason why we conducted an extensive validation of the forecast vertical temperature profile.

High-quality remote measurements of the vertical temperature profile by RASS at the site where the NPP Krško is located are a prerequisite for this study. We have provided temperature measurements at four different heights of the 70-metre-tall tower for the ground-level layer in addition to RASS measurements. 13 months' worth of data is used for the validation study.

The paper is structured as follows. Methods of data acquisition and validation are described in the next section. The results are presented in Section 3. The conclusions are drawn at the end of the paper.

2 Measurement system for the vertical temperature profile and validation of the prognostic system's predictions

A set of measurements of the atmosphere temperature profile for a period long enough, in our case 13 months, has been obtained for the site around the Krško NPP, Slovenia. The site is located in a semi-closed basin over a highly complex terrain. The Krško Basin is blocked by relatively high hills to the north and south, leaving it partly open to the southwest and east. The meteorological situation of the basin is further complicated on the account of the deep and narrow Sava River canyon that cuts the way through the hills in the northwest and from there opens up to the Krško Basin. Figure 1 shows the site of the Krško NPP in the basin.

The area has a continental climate with cold winters and hot summers. The surrounding hillsides shelter the basin; the winds are thus mostly weak, intensifying only at the passage of weather fronts. Typical for the colder part of the year are events of temperature inversion. The determination of temperature inversions is essential for the proper modelling of the atmosphere-pollution dispersion. Using RASS, which is the instrument designed for measuring the vertical temperature profile, is the easiest way to detect inversions. However, it is much more difficult to model inversion based on numerical weather forecasts.

The measurements are measured in two ways. Firstly by RASS – its altitude range normally reaches a few hundred meters over the basin. Secondly, with conventional temperature sensors at heights of 2 m, 10 m, 40 m and 70 m mounted at the 70-metre-tall tower. Numerical Weather Prediction (NWP) results are obtained by WRF model in already mentioned different spatial resolutions (Gradišar et al. 2016; Skamarock et al. 2008; Kain 2004; Lin, Farley, and Orville 1983; Hong, Noh, and Dudhia 2006; Mlawer et al. 1997; Dudhia 1988). Figures 2 and 3 show the 70-meter-tall tower fitted with sensors and RASS.

The WRF model operates in three spatial resolutions for the relevant validation area (horizontal cell sizes: 14 × 14 km, 4 × 4 km and 2 × 2 km) (Mlakar et al. 2012; Božnar, Mlakar, and Grašič 2012; Mlakar et al. 2015). The subject of the validation is WRF forecast for the ongoing day in 30-minute increments with the described measurements.

The measurements are obtained for temperature point sensors as time series of 30-minute average values. RASS also provides 30-minute average values for 20 vertical levels of 20-meter-thick layers. Figure 4 illustrates the measured vertical temperature profile up to 500 m over the basin tracked over several days acquired at the site in 30-minute increments. Measurements made with RASS are relatively sensitive to many disruptive factors and it is quite normal that the system cannot cover the full altitude of 500 meters over the site, reaching instead a lower range. Therefore there are fewer measuring results available for the upper layers compared to lower layers. We take this realistic limitation into account.

Figure 5 depicts the vertical temperature profile for the same site and in the same time intervals, calculated by WRF model, with the horizontal resolution of 2 × 2 km.

Comparing the two figures enables us to make a preliminary qualitative assessment of the matching between the measurements taken and the forecast temperature profile. Such assessment is highly subjective and may serve only as a qualitative estimate.

A statistical analysis is conducted in the next step to generate a numerical, statistically supported, validation for the forecast quality of the vertical temperature profile. The validation is illustrated with scatter diagrams. Calculations of frequently used statistical measures are added.

The validation is conducted in three clusters. The results obtained at three different horizontal resolutions in WRF are validated in every cluster. Temporally, the measurement averages and modelled results pertain to 30-minute periods.

In the first cluster, we compare the temperature predictions from WRF concerning the vertical levels at 40 m and 70 m above the ground with measurements obtained with conventional temperature sensors mounted on the meteorological tower at corresponding levels (Figure 6).

In the second cluster, we compare the temperature predictions from WRF for vertical levels 60 m, 160 m and 260 m over the ground, with the measurements obtained by RASS at corresponding levels (Figure 7).

In the third cluster, we compare the quality of the forecast for the derived variable – vertical temperature difference. This variable reveals whether there is a temperature inversion occurring at the site. As such the vertical temperature difference is essential for modelling of the dispersion of pollutants in the air. The validation covers temperature differences between the following levels: 2 m and 60 m, 60 m and 160 m, and 160 m and

260 m. A validation is made between RASS measurements and WRF predictions of vertical temperature difference (Figure 8).

3 Discussion

The validation assessment is based on the hypothesis that WRF-model forecasts of the vertical temperature-profile values of the atmosphere operating at three different resolutions are comparably good to point measurements of sensors mounted on measurement tower as well as to RASS measurements.

WRF-model forecasts are compared with half-hourly average observations, i.e., measurements, for the period of thirteen months (August 1, 2016 – September 15, 2017), which is the period that enables inclusion of most of the natural variability of the weather.

Accuracy of temperature measurement devices, namely sensors and RASS, is 0.3 degrees centigrade of difference to the actual value or lower. This difference to actual value is lower than the differences between measurements and models results.

The validation is performed with measurements in one point, namely the location of the measurement tower and RASS. The location of the point of validation is shown in Figure 1 (marked with pin point "NEK"). The validation is done in three stages: forecasts' validation with tower measurements, forecasts' validation with RASS and validation of forecasts' temperature differences with those of RASS. Forecasts are done with WRF models with the following resolutions: 14 × 14 km, 4 × 4 km and 2 × 2 km. All these forecasts are assessed separately. Statistical measures used to show goodness of fit are as follows (Badescu et al. 2013; Kocijan et al. 2016):

- the root mean square error (RMSE),
- the mean squared error (MSE),
- the Pearson product moment correlation coefficient (R),
- the coefficient of determination (R^2).

Forecasts' validation with tower measurements

The validation is done as the statistical comparison of tower measurements at 40 and 70 meters, which are heights of point sensors and corresponding WRF-model forecasts of half-hour average values.

Scatter plots in Figure 6 and corresponding statistical measures show good matching of tower measurements and WRF-model forecasts for heights of 40 m and 70 m and WRF-model resolutions of 14 × 14 km, 4 × 4 km and 2 × 2 km resolutions, with high correlations and very good fit according to statistical measures.

The linear regression line of measurements vs. forecasts is very close to the line of equality between measurements and forecasts which confirms the goodness of fit.

Forecasts' validation with RASS

The time plots of WRF forecasts at 2 × 2 km resolution and RASS measurements from Figures 4 and 5 show the period of one week only and can be used mainly for an illustration.

The validation is done as the statistical comparison of RASS measurements at 60 m, 160 m and 260 m and corresponding WRF-model forecasts of half-hour average values.

Scatter plots in Figure 7 and corresponding statistical measures show comparably good matching of RASS measurements and WRF-model forecast for heights of 60 m, 160 m and 260 m and WRF resolutions of 14 × 14 km, 4 × 4 km and 2 × 2 km. Correspondingly, the linear regression line of measurements vs. forecasts is very close to the line of equality between measurements and forecasts which confirms the goodness of fit.

Validation of forecast's temperature differences between vertical levels with RASS

Temperature differences of the vertical temperature profile between 2 m and 60 m, 60 m and 160 m and 160 m and 260 m for all three local resolutions of WRF model are validated with RASS measurements and shown with scatter plots and corresponding statistical measures in Figure 8.

It is clear from scatter plots and statistical measures that temperature differences are more accurate at the lower height difference, i.e., between 2 m and 60 m, where the difference is 58 m, while the goodness of fit between temperature differences is worse at higher height difference, where the height difference is 100 m.

But the reader should be careful when comparing Figure 7 and Figure 8 due to different axis' scales. 10°C on Figure 7 axis is short in comparison to the same difference on Figure 8. We intentionally emphasize differences shown on the Figure 8. All scatter plots from Figure 8 prove that differences measured by RASS can be significantly bigger than the ones reproduced by WRF. WRF has especially limited capacity to forecast negative differences (less than -4°). This is an important limitation when using WRF temperature profile forecast for dispersion modelling.

The reason for this WRF limitation comes from its practical implementation. The reason is the relatively small number of vertical levels in the model set-up.

When we use WRF as operational model for weather forecast for Krško NPP we have set its runs automatically in a cost-effective manner. This operational model is the source of data used in this article. It was our intention to test operational modelling system capacities and not the best possible research WRF installation.

One of the features that cause smaller or bigger computational cost is the number of the vertical levels that are inherent in the model runs. In our case we have in total 45 levels in sigma coordinates. Their altitude varies and cannot be fixed. We have made a re-calculation to obtain the difference of the target levels to be compared with measured differences. If we want to get better forecast of differences we would have to install WRF with much more dense vertical levels closer to ground. That would require much bigger computational capacity which is not feasible within the existing project frame.

It can be concluded from the validation results that relatively good fit of forecasted point values at all three local resolutions is observed. Furtherly, the goodness of fit of temperature differences shows that some cautiousness has to be exercised when using WRF-derived-model forecasts for temperature profile differences.

4 Conclusion

Modelling the dispersion of pollutants in the atmosphere is oftentimes carried out with numerical weather forecasts of the meteorological state of the atmosphere. There are several reasons for opting for the modelling approach: one is a lack of measurements for some areas, and another are hypothetical scenarios that take place at some time in the future. To produce a high-quality atmospheric dispersion model it is necessary to have previous knowledge of the quality of predictions for those key meteorological variables that are not retrieved via measurements but are instead predicted by numerical weather forecasts.

It is important to focus on those variables of the meteorological description of the atmosphere that are vital for dispersion modelling.

One of the most important variables is arguably the vertical temperature profile, which is particularly hard to determine if the model covers a complex terrain.

The paper presented the validation of forecasted vertical temperature profiles, calculated by WRF model in different spatial resolutions with the measurements. The validation clearly pointed out one of the deficiencies of operational forecast - a limited capacity of vertical temperatures differences forecast. We have also suggested that configuration of WRF with significantly larger number of vertical levels would probably solve this shortcoming.

It was shown in the paper that the quality of the predictions is already good enough to be used instead of direct measurements. Based on the validation results it can be concluded that the meteorological model predictions in all validated resolutions are accurate enough to be used as input for the pollution dispersion model. Nevertheless, the presented temporal and statistical results, in particular for vertical temperature differences, clearly indicate opportunities for further improvements, which is the topic of the planned research.

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Title

Figures

Figure 1. NPP Krško site, measuring site for validation is marked with NEK

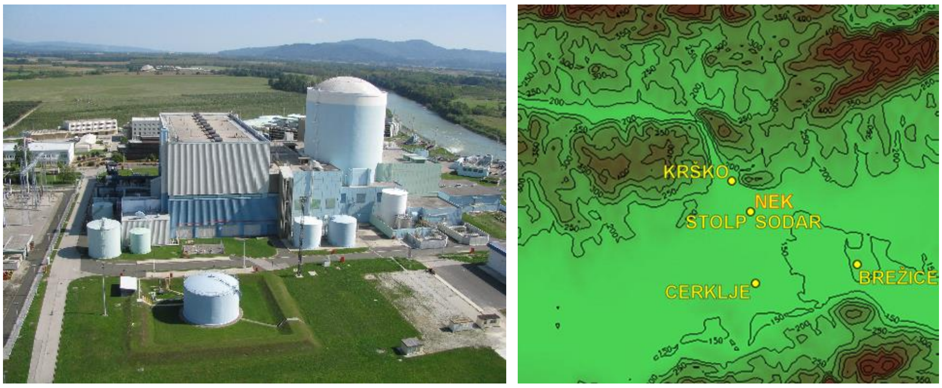
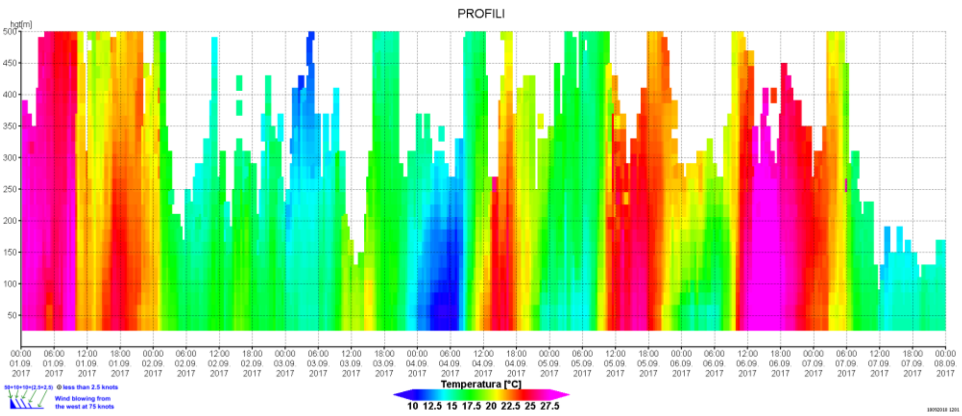


Figure 2. 70-meter-tall tower at measuring site nearby NPP Krško (left: view from ground, right: air temperature sensor mounted at the height of 70 m)

Figure 3. RASS at measuring site nearby NPP Krško

Figure 4. RASS measured vertical temperature profile up to 500m at the site of NPP Krško for the time interval from 1st till 7th September 2017



Title

Figure 5. WRF model calculated vertical temperature profile at the site of NPP Krško for the time interval from 1st till 7th September 2017

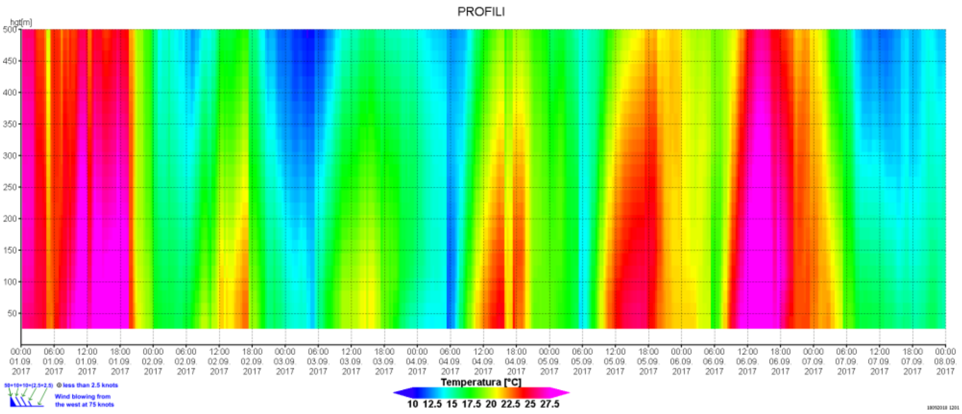


Figure 6. Comparison of the temperature predictions from WRF concerning the vertical levels at 40 metres and 70 metres above the ground with measurements taken with classic temperature sensors set up on the meteorological tower at the same levels.

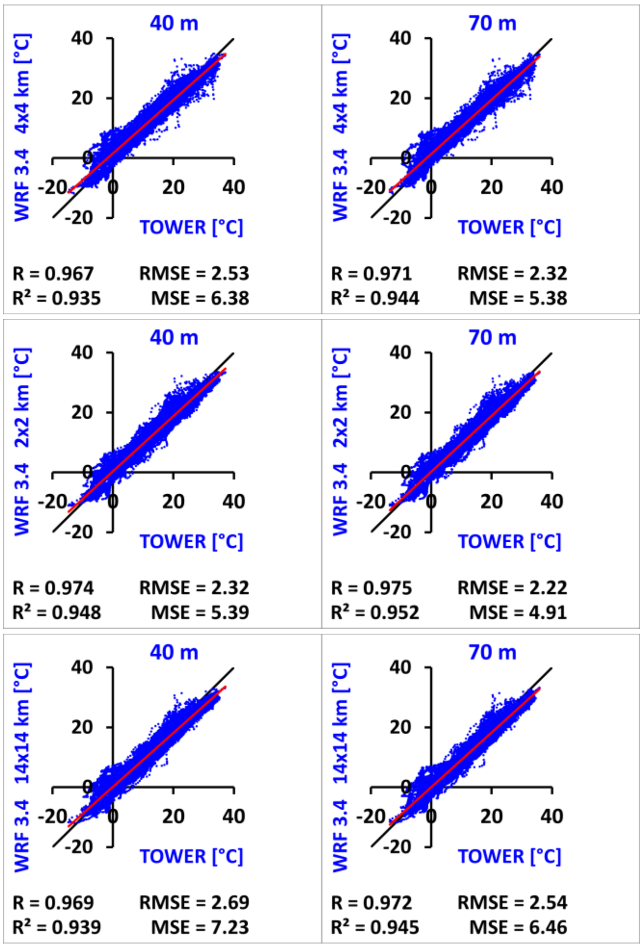


Figure 7. Comparison of the temperature predictions from WRF for vertical levels 60m, 160m and 260m over the ground, with the measurements made by RASS for the same levels

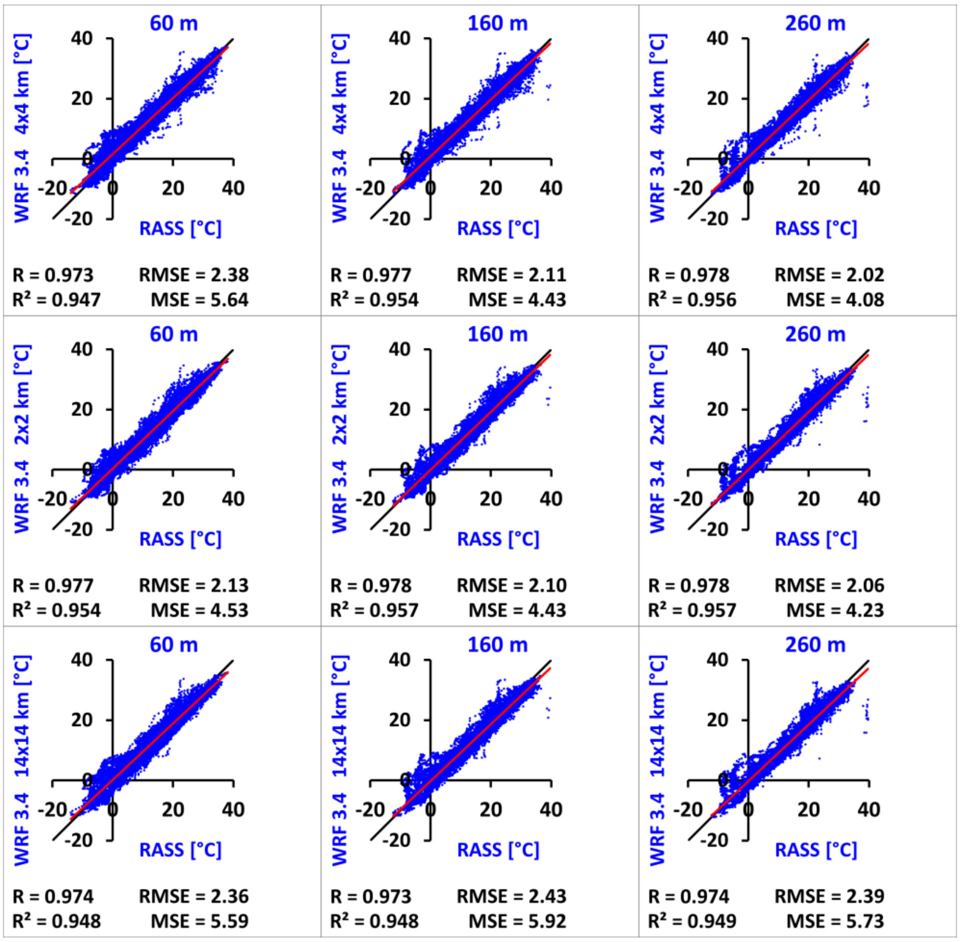


Figure 8. Comparison of the quality of the forecast for the derived variable – vertical temperature difference for levels 2m and 60m, 60m and 160m, and 160m and 260m. A comparison is made between the RASS measurements and WRF predictions of vertical temperature difference.