Ensemble forecast of road surface temperature by the METRo-CZ model

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1 Introduction

The road surface temperature (RST) and road surface condition (RSC) are usually forecasted by models based on solving the energy balance and heat conduction equations (e.g., Bouilloud et al., 2009; Crevier and Delage, 2001; Kangas et al., 2015; Rutz and Gibson, 2013). The energy balance equation prepares boundary conditions for the heat conduction equations and significantly influences the accuracy of RST forecasts. The boundary conditions depend on the current and future states of the atmosphere and are obtained from forecasts of numerical weather prediction (NWP) models. The RST forecast is also influenced, among others, by parameterizations of surface fluxes calculated from NWP forecasts and by shading effects. The model that describes the heat conduction in the road body also contributes to the overall errors, particularly because the specifications of the road layers (their thicknesses, thermal conductivities and capacities) may not be accurate. However, the contribution of those errors is not very important, especially for shorter lead times, because of the slow response of the surface temperature to the subsurface characteristics.

Deterministic forecasts, which are the result of the model applications, do not provide sufficient information for users and it is important to have additional information about their accuracy. To solve this task, we developed an ensemble technique that quantifies the accuracy of the RST forecast and allows expressing the forecasts in a probability form.

The ensemble technique for RST forecasting using the METRo-CZ model is presented (Sokol et al., 2014). We developed a method for generating ensembles that simultaneously modifies the forecasted air temperature and humidity 2 m above the ground (T_{2m}, H_{2m}), wind speeds at 10 m (W_{10m}) and the total cloud cover N in octas obtained from the NWP model. N is used to estimate the shortwave and longwave radiation fluxes.

This paper is divided into four sections. Section 2 describes the METRo-CZ model and the ensemble technique. An evaluation and discussion of the ensemble technique is contained in Section 3, and the conclusions are presented in Section 4.

2 Model METRo-CZ

2.1 Model description

The Institute of Atmospheric Physics Czech Academy of Sciences, Prague, and the Czech Hydrometeorological Institute (CHMI) developed and currently run the METRo-CZ model for forecasts of the RST and RSC. The model is based on solving the energy balance and heat conduction equations (model METRo; Crevier and Delage, 2001; http://home.gna.org/metro/). METRo-CZ is a 1D model that calculates independent forecasts at single points. It uses measured data from road weather stations (RWS) and forecasted data by the Aladin NWP model as initial and boundary conditions (Sokol et al., 2014).

The current version of METRo-CZ differs from METRo in various aspects. The original code was completely rewritten in Fortran 90 and the data preprocessing was modified and tailored to the data used in the CHMI. The physical core of the model equations is the same as in METRo, but the basic differences between the METRo-CZ and the original METRo are as follows:

- METRo-CZ uses cloud cover N to calculate the shortwave and longwave radiation fluxes and a new relationship between N and the shortwave radiation fluxes was derived using surface measurements of global radiation and N observations at synoptic stations in the Czech Republic (CR).

- METRo-CZ focuses on nowcasting (i.e., very short-range forecasts) with lead times up to 6 h. It uses NWP data with time steps of 6 h and all available data from RWSs and calculates new forecasts every hour.

2.2 Model input data

METRo-CZ uses prognostic data from the Aladin NWP, which is operated by the CHMI and run 4 times per day. The following data are utilized: air temperature T_{2m} and humidity H_{2m} at 2 m, wind speeds W_{10m} at 10 m, pressures at the ground, cloud cover N and accumulated precipitation and its type (rain/snow). Those data are available for each prognostic hour 4 hours after the start of the Aladin integration.

METRo-CZ uses measurements from the RWSs: air temperatures T_{2m} and humidity H_{2m} at 2 m, wind speeds W_{10m} at 10 m and the code of road weather conditions (dry/wet surface). If any T_{2m}, H_{2m} or W_{10m} data are not available, their values are obtained by temporally interpolating available Aladin data. If information on the road weather conditions is missing, a dry surface is assumed.

We used 27 RWSs, which were selected to cover various parts of the western and central Czech road network (highways and 1st class main roads) with various road conditions (lowlands and mountains). The data from the selected stations were of good quality with little downtimes (Fig. 1).

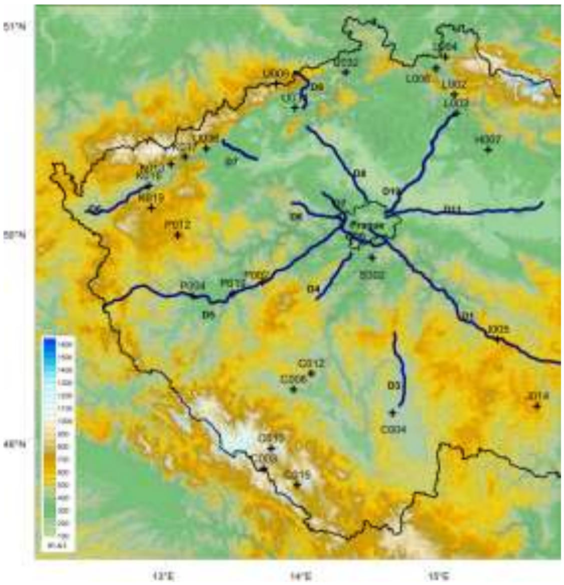

Figure 1. The highway network (blue/thick lines indicate opened highways) in the western and central part of the CR. The positions of the road weather stations used in this study are denoted by crosses with RWS codes. The orography is shown in the background.

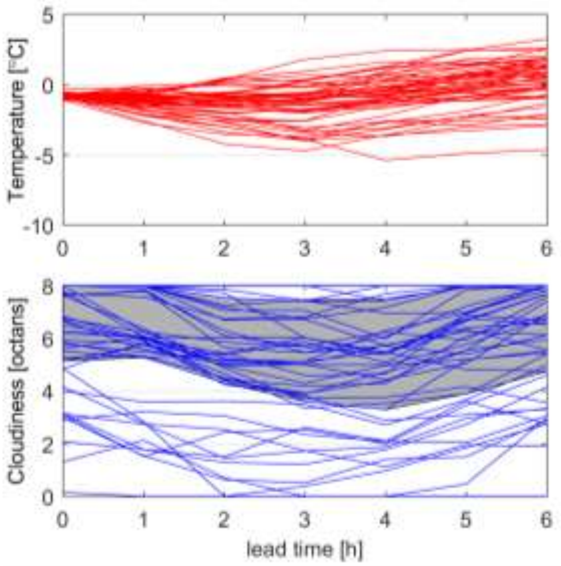

Figure 2. An example of the generated ensembles of T_{2m} (upper subfigure) and N (bottom subfigure). The ensemble has 50 members and was prepared for the P002 station (Fig. 1) for 15 November, 2012, 06 UTC. The filled area in the bottom subfigure contains 50% of the N values.

2.3 Ensemble generation

The purpose of the ensemble technique is to statistically describe the uncertainty in the deterministic forecasts. The forecast errors depend on model errors (caused, for example, by the application of simplified equations and inaccurate numerical solutions) and on errors in the input model data (initial and boundary conditions). In our opinion, the errors in forecasted atmospheric data that represent boundary conditions in METRo-CZ are the most significant sources of errors. We focused on creating ensembles by simulating uncertainty in values of T_{2m}, H_{2m}, W_{10m} and N (N is related to radiation), i.e. we perturbed these variables. We neglected errors/inaccuracies caused by the METRo-CZ equations and also did not consider errors in the precipitation forecasts because their statistical characteristics are complicated and it is not clear how to use them in the context of the applied ensemble technique.

We calculated the ensemble of forecasts by generating an ensemble/set of boundary data and used them in the METRo-CZ. The set of boundary data was prepared in the following way. For forecasts starting at T_{MET} and with projection times $\delta = 6$ h, we had available hourly NWP forecasts of T_{2m}, H_{2m}, W_{10m} and N. Let the lead time $t_1 = 0$ corresponds to T_{MET} and t_2 to $T_{MET} + \delta$ and let a vector $\boldsymbol{T}$ contains hourly forecasts for all lead times and for all variables,

$$T = \left(T_{2m}\left(t_1\right), H_{2m}\left(t_1\right), W_{10m}\left(t_1\right), N\left(t_1\right), \ldots, T_{2m}\left(t_2\right), H_{2m}\left(t_2\right), W_{10m}\left(t_2\right), N\left(t_2\right)\right). \quad (1)$$

Using a set of historical NWP forecasts and observations we have matrices $\boldsymbol{T_{ij}}$ and $\boldsymbol{O_{ij}}$, where $i=1,\ldots,n$ refer to an individual forecast/observation for single terms, and $j=1,\ldots,4\delta$ indicates a component of the vector $\boldsymbol{T}$. Using $\boldsymbol{T_{ij}}$ and $\boldsymbol{O_{ij}}$ an error covariance matrix $\boldsymbol{C}$ can be calculated:

$$C = \left\{c_{k,m}\right\}, k, m = 1, \ldots, 4\delta, \quad (2)$$

where

$$c_{k,m} = \frac{1}{n}\sum_{i=1}^{n}\left(T_{i,k} - O_{i,k}\right)\left(T_{i,m} - O_{i,m}\right). \quad (3)$$

The matrix $\boldsymbol{C}$ was used to describe the error structure of the boundary conditions and using the procedure described by Huynh et al. (2008, page 65) we generated an ensemble (set) of vectors $\boldsymbol{T}$, whose components were selected such that they fulfilled the covariance relationships (3), and we calculated the ensemble of forecasts.

The covariance matrix $\boldsymbol{C}$ was calculated for each RWS separately. Values of T_{2m}, H_{2m} and W_{10m} are measured at all RWSs; thus, the observational data in (3) are available. N is not observed at stations and we used satellite data from the Meteosat Second Generation and an algorithm stemming from the Satellite Application Facilities (SAFs) algorithm PGE01 Cloud Mask (SAFNWC, 2013) to estimate N. In this paper, we used the covariance matrix $\boldsymbol{C}$ calculated using data from the winter season of 2012-2013 (October to March) and example of the generated ensembles of T_{2m} and N is shown in Fig. 2.

3 Forecast evaluation

3.1 Implementation of METRo-CZ

The RST and RWC were calculated using METRo-CZ for the 27 RWS (Fig. 1) and the period from 1st November 2012 to 28th February 2013. The forecasts started every hour and their projections were 6 h. For each hour, we performed ensembles of 10, 30, 100, 250 and 500 forecasts. The first forecast used the forecasted T_{2m}, H_{2m}, W_{10m} and N data by Aladin, and the remaining forecasts used the perturbed data.

3.2 Evaluation of the ensemble forecasts

Ideally, the true value should be just one more member of the ensemble, statistically indistinguishable from these members. This attribute can be evaluated by the rank histogram (VRH; Wilks, 2006), which shows the orders of the observed values over all forecasts. The ideal ensemble should have an approximately uniform VRH. Figure 3 shows that our ensembles are not ideal; the high rightmost and especially high leftmost columns indicate an underdispersion of the ensembles, which means that the ensembles are overconfident and do not cover the entire variability in the observations. The high relative number of measurements that are lower than the minimum of the ensembles can be explained mainly by two factors that were not considered when generating the ensembles. First, rain and/or snow often leads to cooler surface temperatures than in the case of a clean dry road surface, and second, the sky view factor, which may result in shadowing and significant temperature drops during the day.

To predict the road surface conditions, it is important to forecast whether the surface temperature will be lower or higher than 0 °C; this forecast may be in categorical or probabilistic forms. These types of forecasts are evaluated using the Brier score (BS; Wilks, 2006), which is similar to the standard mean-square-error calculated using probabilities or binary values. Figure 4, which shows the mean BS over all the RWSs, clearly demonstrates that the ensemble forecasts are preferable to the deterministic one and the accuracy increases with the ensemble size up to 100 members.

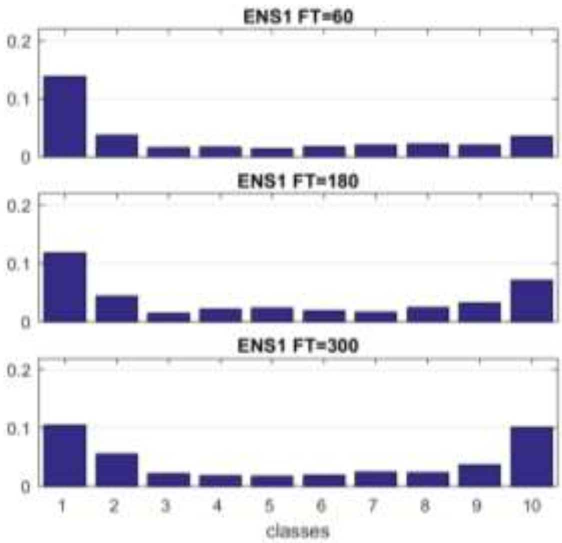

Figure 3. The VRH of the ensembles with 100 members for the K013 station and for lead times FT=60 (1st row), 180 (2nd row) and 300 (3rd row) min. The data are divided into 10 classes, and the vertical axes show the frequencies of their occurrences.

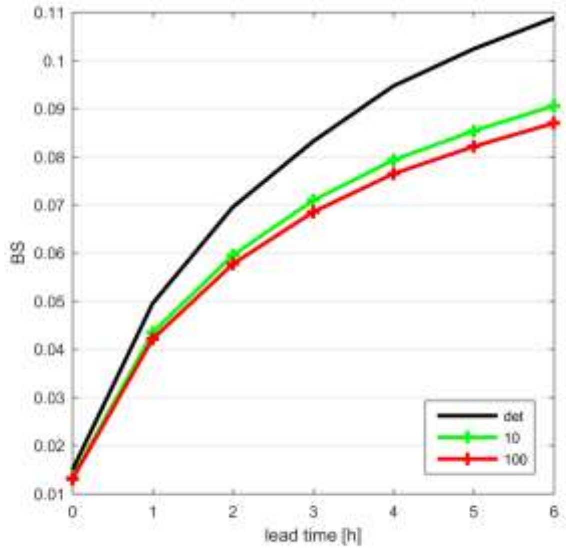

Figure 4. The mean BS over all the RWSs in dependence on the lead time for the deterministic (det) and ensemble forecasts. The results of ensembles with 10 and 100 members are drawn by the solid lines.

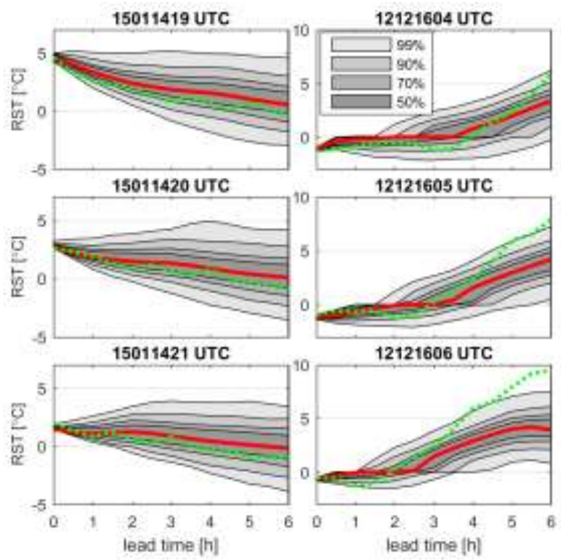

Figure 5. The ensemble forecasts of the RST for RWSs K013 (left column) and P004 (right column) for the lead times in hours. The full red and dashed green curves show the deterministic forecasts and observed data, respectively. The grey areas denote the intervals for probabilities 99, 90, 70 and 50% that the RST will be within that interval.

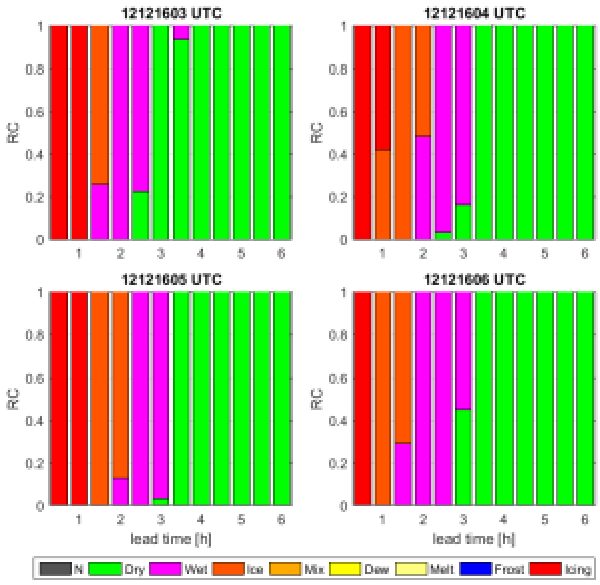

Figure 6. Statistically processed ensemble forecasts of road weather conditions. The vertical axis shows the probabilities, the colours indicate the RSC and the horizontal axis is the lead time. The METRo-CZ model recognizes 8 RSC (dry, wet, ice/snow, mixture of water and ice/snow, dew, melting ice/snow, frost and icing rain) and “not known” (N).

3.3 Examples of an ensemble forecast

Two examples of the sequence of ensemble forecasts, which illustrate typical cases, are shown in Fig. 5 for RWS K013 (left column), and for RWS P004 (right column). The left column shows a successful deterministic forecast that does not differ from the observations by more than 1°C. The grey areas graphically depict the expected intervals of the RST values for the given probabilities. A less successful forecast is presented in the right column. The ensemble approach is especially suitable for the prediction of RSC, which is illustrated in Fig. 6.

4 Conclusions

This paper describes the METRo-CZ model, a technique for generating ensembles and analyses of ensemble forecasts from the perspective of the ensembles' ability to represent real uncertainties in the forecast and its usefulness for practical applications. The obtained results are summarized as follows.

- Ensemble forecasts generated using perturbations of T_{2m}, H_{2m}, W_{10m} and N do not describe the natural uncertainty in the RST forecasts. The ensemble is too confident (the spread is not sufficient). One of the reasons is that errors in forecasted rain/snow by NWP models are not considered when generating ensembles. Other important reasons are of a technical nature, for example incorrect information on the sky view factor, unavailable or inaccurate information on the current state of surface conditions on roads.
- Although the ensemble technique underestimates the uncertainties in the RST forecasts, it can be used in decision making by road authorities who provide winter road maintenance. The outputs can be subjectively "corrected", or a technique like Model Output Statistics can be applied to objectively correct the forecasts.
- In our opinion, the ensemble approach is especially suitable for the prediction of the RSC because it can express the probability of the occurrence of dangerous states.

References

Bouilloud, L., Martin, E., Habets, F., Boone, A., Moigne, P.Le, Livet, J., Marchetti, M., Foidart, A., Franchistéguy, P., Morel, S., Noilhan, J., Pettre, P., 2009. Road Surface Condition Forecasting in France, J. Appl. Meteor. Clim., 48, 2513-2527.

Crevier, L.-P., Delage, Y., 2001. METRo. A New Model for Road-Condition Forecasting in Canada, J. Appl. Meteor., 40, 2026-2037.

Huynh, H.T., Lai, V.S., Soumaré, I., 2008. Stochastic simulation and applications in finance with MATLAB programs: John Wiley & Sons Ltd., ISBN 978-0-470-72538-2, pp. 338.

Kangas, M., Heikinheimo, M., Hippi, M., 2015. RoadSurf: a modelling system for predicting road weather and road surface conditions, Meteorol. Appl., 22, 544–553.

Rutz, J.J., Gibson, C.V., 2013. Integration of a Road Surface Model into NWS Operations, B. Am. Meteor. Society, 94.

Sokol, Z., Zacharov, P., Sedlák, P., Hošek, J., Bližňák, V., Chládová, Z., Pešice, P., Škuthan, M., 2014. First experience with the application of the METRo model in the Czech Republic, Atmos. Res., 143, 1-16.

SAFNWC, 2013. Algorithm Theoretical Basis Document for "Cloud Products" (CMa - PGE01 v3.2, CT-PGE02 v2.2 & CTTH-PGE03 v2.2).

Wilks, D.S., 2006. Statistical methods in the atmospheric sciences. Second edition: Academic Press, ISBN: 9780080456225, pp. 627.