



Upgraded METRo model within the METRoSTAT project

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ABSTRACT

This paper presents the upgrade of the METRo model for forecasting the road surface temperature and conditions with the energy-balance approach. The METRo model was upgraded with two new inputs: the anthropogenic flux and the depth of the subsurface temperature sensor, and with a new sun-shadow algorithm to determine if a selected location is exposed to sun at a particular time (on the assumption that there are no clouds in the sky).

The upgrades are described in detail and some interesting tests with results are presented. With the new user defined inputs, it is possible to significantly influence the road surface temperature forecasts and achieve better results with more realistic anthropogenic flux and the depth of the subsurface temperature sensor. The sun-shadow algorithm was developed and verified with sensor measurements at the selected locations. The inputs to this algorithm are: the geographic location of the road weather station (latitude and longitude), date and time (UTC) and digital terrain/elevation model (DEM) for the wide area of the road weather station. The results show great improvements of the METRo predictions when using the sun-shadow algorithm, especially in the period of time between noon and evening.

The described upgrades were done within the Eurostars project called METRoSTAT. The main goal of the METRoSTAT project is to develop a new high resolution web-based service for significantly improved forecasting of road surface temperature and condition.

Keywords: Road Surface Temperature (RST), Road Weather Station (RWS), METRo model, METRoSTAT project

1 INTRODUCTION

During the winter period, many countries experience severe winter conditions. Especially snow and ice make the transportability difficult and present several challenges for the winter maintenance service. Road maintenance decisions have to be optimized (i.e. types and rates of salt treatment, as well as timing) based on accurate predictions of road conditions. Such predictions can provide safer roads [1-2], reduce winter road maintenance costs (i.e. salt consumption, work hours) [3-4] and reduce the environmental damage from over-salting [5].

The most common approach to forecasting road conditions is the energy-balance model, based on a one-dimensional diffusion equation [6-7]. Physical models can predict the RST, which is the most important parameter for determining the road surface condition (i.e. dry, wet, ice, snow). A widely used physical model for forecasting the RST and road condition is METRo [7], which was first implemented in 1999 at the Ottawa Regional Centre in Canada and is now also used in many countries around the world (i.e. in Slovenia [8]). The METRo is composed of three modules:

- the energy balance of the road surface module which describes the energy fluxes at the road surface,
- the heat-conduction module for the road material which can predict the RST, based on the one-dimensional diffusion equation, and
- the surface water/ice accumulation module.

This paper presents several upgrades of the METRo model: the anthropogenic flux input, the depth of the subsurface temperature sensor input, and the new sun-shadow algorithm to determine if a selected location is exposed to sun at a particular time (on the assumption that there are no clouds in the sky).

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2 ANTHROPOGENIC FLUX AND DEPTH OF THE SUBSURFACE TEMPERATURE INPUTS

In METRo, the anthropogenic flux A is part of the energy-balance equation:

$$R = (1 - \alpha)S + \varepsilon I - \varepsilon \sigma T_s^4 - H - L_a E \pm L_f P + A, \quad (1)$$

where R is net radiation flux, α albedo, S incoming solar flux, ε emissivity, I incoming infrared flux, σ Stefan-Boltzmann constant, T_s temperature of the road, H latent heat flux, L_a vaporisation or sublimation heat, E water vapour flux, L_f heat of fusion of water, P precipitation rate, and A anthropogenic flux. METRo can show a large degree of error at some problematic sites because of the anthropogenic conditions. One possible solution is to have an option in the model to estimate the anthropogenic flux. In the case that a user specifies the anthropogenic flux, METRo will use the values in an input forecast file instead of the constant value 10 W/m^2 . As an optional input, the anthropogenic flux is included in the public version of METRo 3.2.7.

There is an important increase in the road surface temperature (and changes for other parameters) when the forecasts are used with the constant anthropogenic flux of 80 W/m^2 in comparison with the constant anthropogenic flux of 10 W/m^2 (Figure 1). With the user defined anthropogenic input, it is possible to significantly influence the road surface temperature forecasts and achieve better forecasts with more realistic anthropogenic flux values.

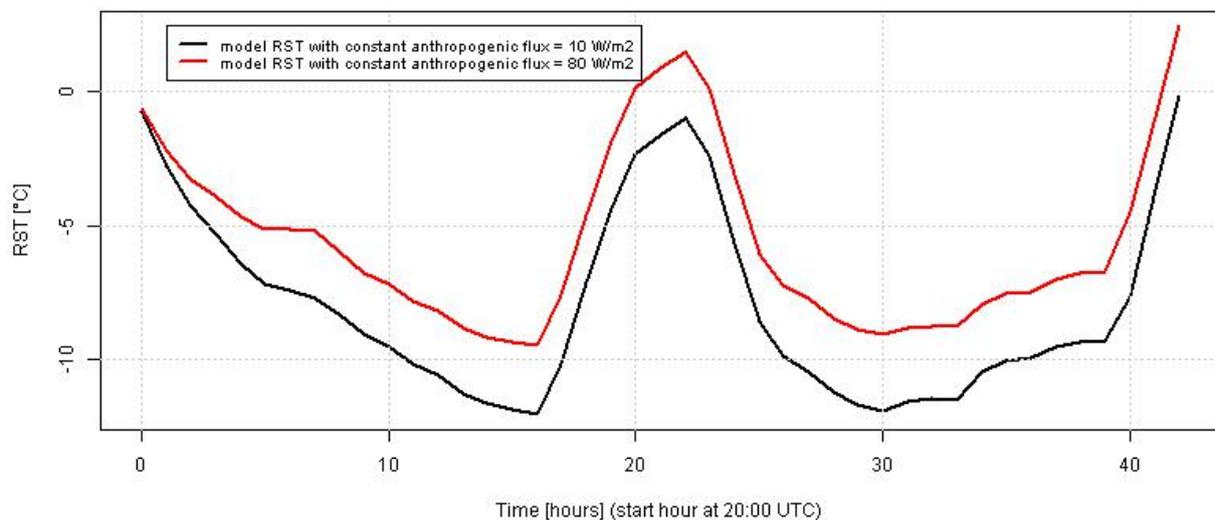


Figure 1. METRo forecasts with a constant anthropogenic flux of 80 W/m^2 in comparison with a constant anthropogenic flux of 10 W/m^2 .

Because the road subsurface structure retains the stored heat, METRo also considers the subsurface temperature (SST) measurements. The METRo model has now the ability to define the depth of the subsurface temperature sensor in the station XML file since in many countries, the RWS depth of the subsurface sensors is not 0.4 m , which is the default value in the model. It turns out that the influence of the SST sensor depth is quite small, but can be significant in some specific cases.



3 SUN-SHADOW ALGORITHM

The main problem of road condition forecasting is to determine all important energy (heat) fluxes on the road surface. Using these fluxes in the energy balance equation (1) allows to obtain the net heat flux R (sum of all energy fluxes), which subsequently enters the heat-conduction equation as an upper boundary condition. The most important one is the net solar radiation flux, given as $(1-\alpha)S$ where S is the incoming solar radiation flux and αS is the reflected solar flux (SF).

Road forecasting requires reliable predictions of the future time evolution of SF, based on the predictions of future atmospheric conditions. The solar flux is a function of time and position on the Earth, the position of the Earth on its orbit around the Sun and the atmospheric condition. It depends on the sun rays incident angle and the atmosphere condition, primarily the cloud cover and the clearness index. SF can be directly measured at the location of interest by the instrument called a pyranometer.

This paper discusses the approach to correcting the SF predictions by taking into account the shading of the sun by the visible horizon. It can completely shield the direct part of the solar flux at a particular location for certain time duration and thus notably reduce the amount of overall energy (heat) incident on the road surface.

The shielding effect was neglected in the early version of the METRo since its effect in the open landscape is negligible, but in hilly regions it may have a significant impact on energy balance. The shading effect comes primarily from hills, but also from vegetation (high trees with rich tree-tops in the summer time) and buildings. The effect of buildings plays an important role in urban areas (towns, villages) where high buildings close to the road have a most notable impact.

Here an algorithm is needed to calculate if the selected location is exposed to the sun at a particular time (on the assumption that there are no clouds). The inputs to the algorithm are:

- location of the RWS on the earth surface specified by latitude and longitude (φ_0, λ_0);
- date and time (UTC) for which the shadowing is to be computed;
- digital terrain (elevation) model (DEM).

The output of the algorithm is the binary value 1 if the specified location at a given time is exposed to the sun or 0 if not.

3.1 Approach

Solution of the sun-shadow algorithm consists of two independent tasks:

- 1) Computing the visible horizon at a given location.
- 2) Computing an apparent motion of the sun across the sky.

The visible horizon is defined as a curve that separates the earth from the sky. It may include objects like trees, buildings, mountains, and other elevated parts of the landscape. The Earth's curvature may have a notable effect on the apparent elevation of distant objects. The elevation angle ε of any object X at a height h above the earth's surface as seen by observer O (i.e. RWS) at height h_0 is obtained from geometrical considerations shown in Figure 2. Having specified the observer position by φ_0 and λ_0 , we seek for the maximum elevation angle ε_{max} along the given azimuth. This procedure is also repeated for other azimuths producing the azimuth-elevation rosette or, in other words, a discrete representation of the visible horizon at point O . As an orographic source, the SRTM3 digital elevation model can be used [9].

There are several routines for computing the apparent sun motion with various precision. We have adopted a freely available C routine [10-11] and translated it into the Python language to link it easily with METRo and with the sun-shadow algorithm. Combining these two subtasks allows to obtain the time intervals when the sun is shaded by the visible horizon and when not. The only thing that must be done is to compare the sun elevation angle ε_s with the maximum terrain elevation angle ε_{max} in direction of the sun (given by azimuth) at the arbitrary time moment.

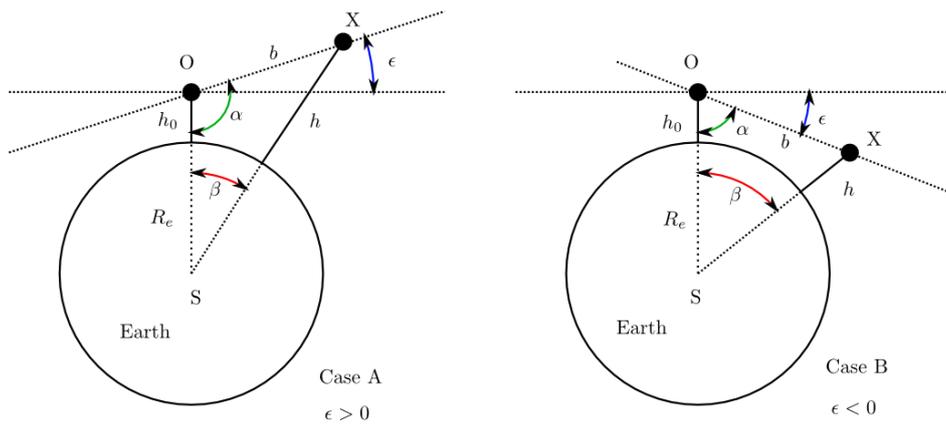


Figure 2: Illustration of geometry considerations used in the sun-shadow algorithm. The figure on the left illustrates the situation which leads to a positive elevation angle ϵ while the situation shown in the right figure leads to a negative elevation angle.

3.2 Incorporation into the METRo

Since the visible horizon does not change with time, the call to the sun-shadow routine in METRo uses the precomputed visible horizon for the considered RWS's in order to return the requested binary output. Information on the visible horizon can be included into the RWS station configuration XML file, which mostly contains static information about RWS.

For a given RWS, the sun-shadow routine is called only if an option flag is set for it. For any timestamp it is then enough to make a simple comparison of sun elevation with the elevation of horizon at the same azimuth. If the sun elevation becomes smaller than the visible horizon (sunset, obscuration), the solar radiation is turned off in the METRo pre-process sequence. Contrary, if the sun elevation becomes greater than the visible horizon (sunrise), the solar radiation is turned on.

3.3 Direct solar irradiation time course evaluation

Figure 3 (left) compares a typical sunny day course of the measured normalized global solar radiative flux with the sun-shadow algorithm output for RWS Žilina in Slovakia on 21 October 2012. The measured data are normalized to 1 in order to make a comparison with the computed values easier. The algorithm first gives a nonzero value about 30 minutes later than the pyranometer, while a down-step (from value 1 to 0) occurs 20 minutes earlier for the algorithm than for the measured data (the time step of the measured data is 10 minutes while for the sun-shadow algorithm output it is 2 minutes). The difference may be accounted to the fact that while the pyranometer measures the global solar irradiance, the output of sun shadow algorithm rather corresponds to the moments when direct (beam) irradiance becomes zero (sunset) or when it becomes nonzero (sunrise). Since the global solar flux consists of direct solar flux and diffusive solar flux, the pyranometer can still detect a low but nonzero diffusive flux for some time before sunrise or after sunset (twilight). We assume that the algorithm output could come very close to the measured data if a pyrliometer (measuring only the direct solar flux) was used rather than a pyranometer or quantum sensor, although this is not necessary for our purpose.

In Figure 3 (right), the output of the sun-shadow algorithm is compared with the data measured at RWS Črnova in Slovenia where a quantum sensor was installed on 11 December 2012. The explanation of results for RWS Črnova is quite similar to those for RWS Žilina. The only difference is that a part of the measured data corresponding to diffusion radiation is longer and more significant. The former can be explained with the fact that RWS Črnova is shielded from direct solar irradiation much longer, which has no effect on the diffusion radiation. The latter can be accounted for by the fact that the measurements at RWS Žilina correspond to a quite bright day at the end of October while the measurements at RWS Črnova correspond to a rather overcast day in the middle of December when diffusion radiation is more significant in comparison with the maximum solar flux.

The measured flux changes correspond qualitatively to the time when a RWS starts or ends to be directly irradiated by the sun. As seen in Figure 3, those moments correspond quite well to the moments when the output of the sun-shadow algorithm changes value (from 0 to 1 or from 1 to 0).

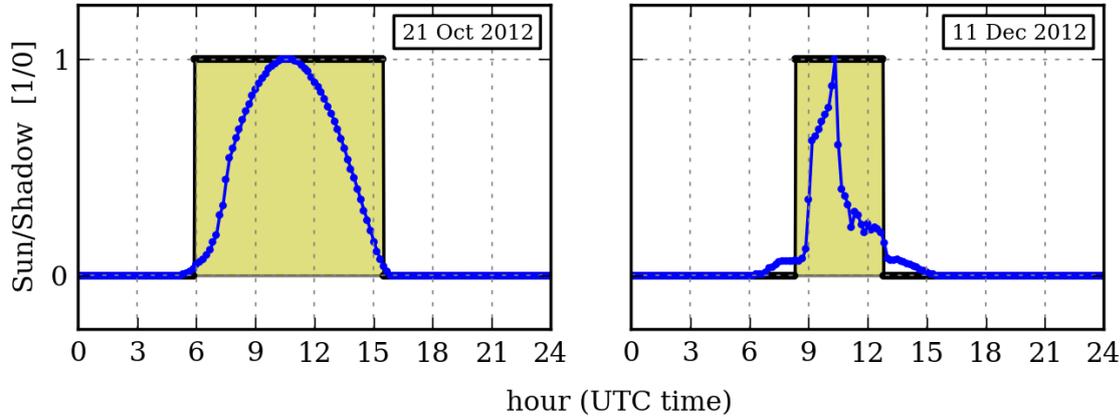


Figure 3: Comparison of normalized measured solar radiation flux (blue) with the sun-shadow algorithm output (black) for RWS Žilina (left) and RWS Črnova (right).

3.4 METRo testing

The RWS Hronská Breznica in Slovakia was selected to test the sun-shadow algorithm with METRo. This station is specific because of its great elevation of the visible horizon and close proximity (≈ 50 m) to the river. The computed visible horizon at this station is shown in Figure 4 together with the apparent sun trajectories for selected dates. The additional height of 20 m was considered to represent the height of vegetation (beech forest), which also contributes to shading. The figure shows that the sun was completely shielded by terrain for the whole day in the period around 21 December.

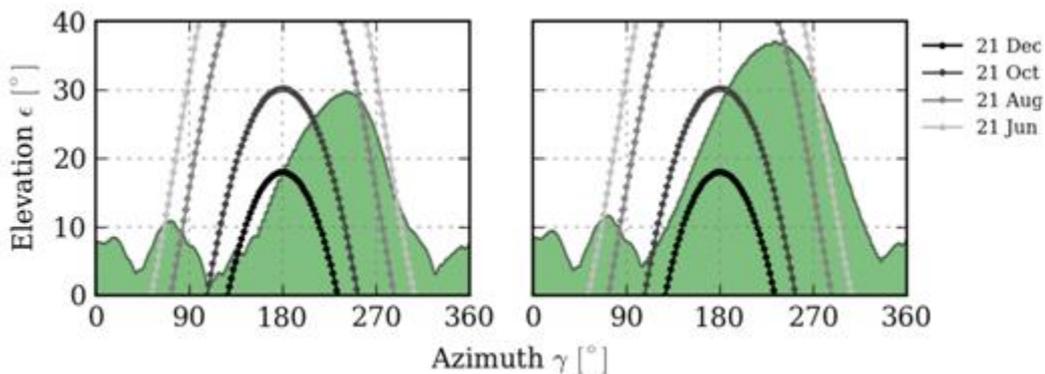


Figure 4: Visible horizon at RWS Hronská Breznica (Slovakia) with apparent sun trajectories for selected dates. Left: without vegetation; right: with additional vegetation of 20 m in height.

The analysis was done for several dates from autumn 2012 to spring 2013. Although METRo is intended primarily for winter conditions, the effect of the sun-shadow algorithm on the METRo results can be better identified for clear days with stable weather and good visibility. In such conditions, the NWP models (i.e. ALADIN) usually give most accurate weather forecasts and the influence of other effects like cloudy sky, water on the road, near zero temperatures and strong winds do not affect the road surface temperature. A few such favourable situations arose in autumn 2012 and spring 2013 and test runs were performed for them. For most of them, the modified METRo produced clearly superior results. The error in road surface temperature is further reduced if, additionally, 20 metres tall vegetation is considered in computing the RWS horizon. The examples of such improvements are shown in Figure 5.

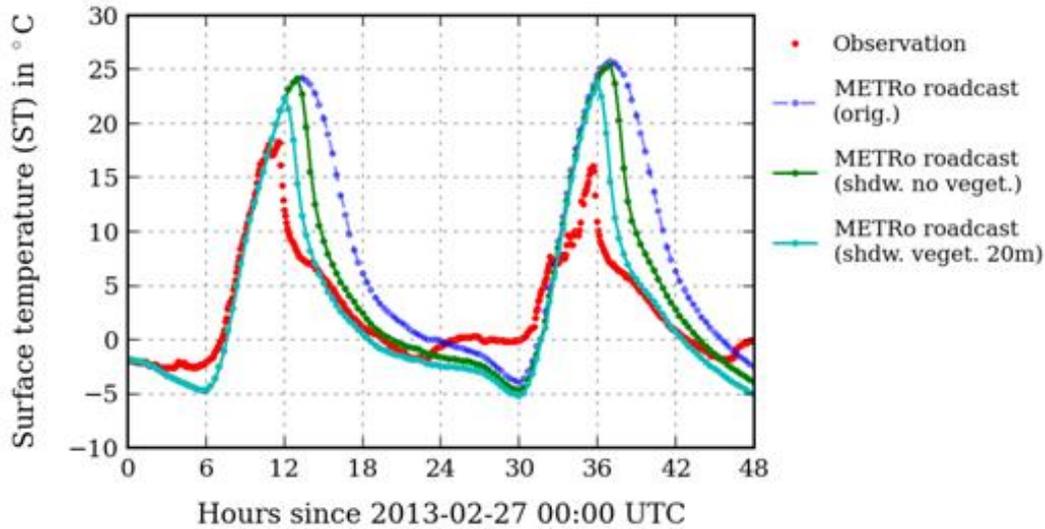


Figure 5: Improvements of the METRo forecasts without (violet line) and with the sun-shadow algorithm without vegetation shading (green line) and with vegetation shading (blue line) at RWS Hronská Breznica.

3.5 Enhanced sun-shadow algorithm

The main limitation of the basic sun-shadow algorithm is that immediately after the sun elevation becomes smaller than the visible horizon elevation (sunset moment), the global radiation is completely switched off. In other words, there is no overcast phase. This unrealistic behaviour leads to a sudden drop of road surface heating flux, which can result in a too rapid decrease of road surface temperature. The situation is similar but opposite at sunrise. In reality, only a direct solar flux becomes zero after sunset while the diffusive part of solar radiation remains the source of heat input to the road surface even after the sunset. Experience shows that in many cases heating by diffusive radiation after sunset cannot be neglected.

We have thus developed an improved version of the sun-shadow algorithm, which takes into account this effect. The basic idea is simple: the METRo model needs a global solar irradiance S on its input. If it is possible to divide it into direct S_{dir} and diffusive S_{dif} parts, the sun-shadow algorithm can be applied only to the S_{dir} part while the S_{dif} part is left unchanged. Making this simple idea work, a method for such decomposition (decomposition model) is required. One class of such decomposition models is based on an empirically found statistical relation (dependence, correlation), existing between the diffuse fraction f_d and the atmosphere clearness index K_t . The diffuse fraction is a number between 0 and 1 and it expresses a fraction of diffuse solar irradiance on global solar irradiance, i.e. $f_d = S_{dif}/S$. The value 1 means that the global solar flux consist completely of diffusive radiation and no direct radiation, the value 0 at other side means that there is only direct radiation and no diffuse. Of course, such extreme situations do not occur on the Earth. The clearness index K_t is defined as $K_t = S/S_{ext}$ where S_{ext} is horizontal extraterrestrial irradiance, i.e. the solar flux incident on horizontal surface of the Earth if there were no atmosphere (it is equal to the solar flux incident at the top of the atmosphere). It is given as $S_{ext} = C_s \sin(\varepsilon)$ where ε is the rays incident angle on horizontal surface and C_s is the solar constant – solar flux incident at perpendicular surface at the top of the atmosphere. The changes due to the Sun-Earth distance variation and the fluctuations due to solar activity changes can be neglected and its average value (normalized to the mean Sun-Earth distance) should be taken equal to 1366 W/m^2 . As the name suggest, the clearness index signify how clear the atmosphere is. Its value is also between 0 and 1. Value 1 means an ideally clear atmosphere with no reflection and absorption of solar radiation so that all incident light passes through and hit a surface. In this ideal case $S = S_{ext}$. There are several correlation models. The correlation relation is obtained by processing the pyr heliometric measurements taken at different locations around the world, usually during a several years period. We have implemented a few of them. The best results were obtained using the Orgill and Holland correlation model (see [12-13]):

$$f_d(K_t) = \begin{cases} 1 - 0.249K_t & \text{for } K_t < 0.35 \\ 0.177 & \text{for } K_t > 0.75 \\ 1.577 - 1.84K_t & \text{otherwise} \end{cases} \quad (2)$$

Good results were also obtained with the Reindl et al. [14] advanced variant of correlation model, which relates f_d not only to the clearness index K_t but also to the sine of solar elevation angle.

In practice, the enhanced sun-shadow algorithm follows these steps: for a given location on the Earth (φ_0, λ_0) and for a given time range the sun elevation angle ε is computed first. This is then used to compute the horizontal extraterrestrial irradiance $S_{ext} = \sin(\varepsilon) \cdot 1366 \text{ W/m}^2$. Then the clearness index K_t is computed using the provided forecast for global radiation S and the corresponding values of S_{ext} according to the formula $K_t = S/S_{ext}$. The clearness index then enters into the correlation model (2) to get the diffuse fraction f_d . It is then used to obtain the diffuse part of solar flux $S_{dif} = f_d S$ while the corrected direct flux is obtained simply by subtracting the diffuse flux from the global flux $S_{dir} = S - S_{dif}$. Finally, the corrected direct flux and the unchanged diffuse flux are added together to obtain the corrected global flux.

The result of enhanced sun-shadow algorithm is more realistic. There is no sudden drop in global radiation after the sunset but rather a continual fade away which represents a twilight phase after the sunset. The results of METRo show a significant improvement of road surface temperature forecasts in comparison with the basic sun-shadow algorithm (Figure 6).

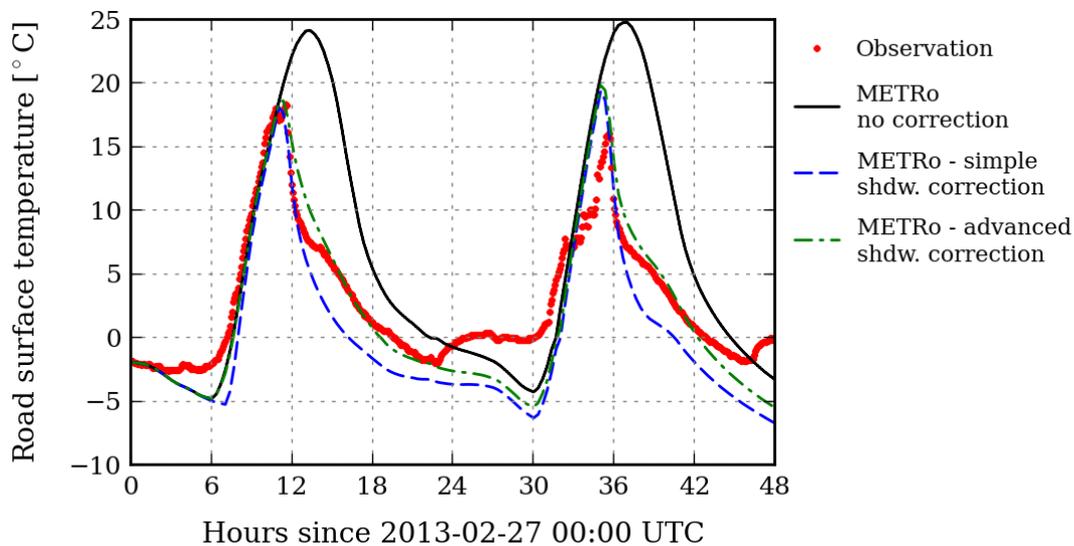


Figure 6: Comparison of METRo road surface temperature forecast for the RWS Hronská Breznica without the sun-shadow algorithm correction (black), with simple basic sun-shadow correction (blue dashed) and with enhanced sun-shadow algorithm (green dash-dotted). RWS measurements are shown with red points.

4 CONCLUSIONS

With the new user defined inputs it is possible to significantly influence the road surface temperature forecasts and achieve better results with a more realistic anthropogenic flux and depth of the subsurface temperature sensor values. The results of the sun-shadow algorithm show great improvements of the METRo predictions especially in the time period between noon and evening. The extended version of the basic sun-shadow algorithm with the global radiation decomposition model further improved the METRo road surface temperature forecast. Anyway, we believe that there is still space for further improvements. For example, in the enhanced version of the sun-shadow algorithm the effect of visible horizon on the diffusive part of solar radiation flux can be taken into account. It is however probable that this effect has only a subtle impact in most situations. Probably a more significant improvement can be achieved by enhancing the accuracy of the computed visible horizon mainly by using a more accurate digital elevation model.



Acknowledgements. The Eurostars Programme is powered by EUREKA and the European Community. The Ministry of Education, Science, Research and Sport of the Slovak Republic is partner in Eurostars programme powered by EUREKA. The INCA [15-16] and ALADIN data were obtained from the Slovenian Environment Agency (ARSO) and from the Slovak Hydrometeorological Institute. The RWS data were obtained from the Slovenian Roads Agency (DRSC) and from the Slovak National Motorway Company.



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5 REFERENCES

- [1] Fridstrøm L, Ifver J, Ingebrigtsen S, Kulmala R, Thomsen LK. 1995. Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts. *Accident Analysis & Prevention* **27**: 1–20.
- [2] Norrman J, Eriksson M, Lindqvist S. 2000. Relationships between road slipperiness, traffic accident risk and winter road maintenance activity. *Climate Research* **15**: 185–193.
- [3] McClellan T, Boone P, Coleman MA. 2009. Maintenance decision support system (MDSS). Final report. *Indiana Department of Transportation*: Indiana, USA.
- [4] Chapman L, Thornes JE, Bradley AV. 2001. Modelling of road surface temperature from a geographical parameter database. Part 2: Numerical. *Meteorological Applications* **8**: 421–436.
- [5] Ramakrishna DM, Viraraghavan T. 2005. Environmental impact of chemical deicers – a review. *Water, Air, and Soil Pollution* **166**: 49–63.
- [6] Sass BH. 1992. A numerical model for prediction of road temperature and ice. *Journal of Applied Meteorology* **31**: 1499–1506.
- [7] Crevier LP, Delage, Y. 2001. METRo: A new model for road-condition forecasting in Canada. *Journal of Applied Meteorology* **40**: 2026–2037.
- [8] Kršmanc R, Šajn Slak A, Čarman S, Korošec M. 2012. METRo Model Testing at Slovenian Road Weather Stations and Suggestions for Further Improvements. Paper presented at *16th International Road Weather Conference (SIRWEC 2012)*, Helsinki, Finland.
- [9] Shuttle Radar Topography Mission digital elevation model (SRTM). Available from: http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/
- [10] Plataforma Solar de Almería (PSA) algorithm. Available from: <http://www.psa.es/sdg/sunpos.htm>
- [11] Blanco-Muriel M, Alarcón-Padilla DC, López-Mortalla T, Lara-Coira M. 2001. Computing the solar vector. *Solar Energy* **70**: 431–441.
- [12] Batlles FJ, Rubio MA, Tovar J, Olmo FJ, Alados-Arboledas L. 2000. Empirical modelling of hourly direct irradiance by means of hourly global irradiance. *Energy* **25**: 675–688.
- [13] Sokol D, Mahdavi A. 2011. Comparison of models for the derivation of diffuse fraction of global irradiance data for Vienna, Austria. Paper presented at *12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- [14] Reindl DT, Beckman WA, Duffie JA. 1990. Diffuse fraction correlations. *Solar Energy* **45**: 1–7.
- [15] Haiden T, Kann A, Wittmann C, Pistotnik G, Bica B, Gruber C. 2011. The integrated nowcasting through comprehensive analysis (INCA) system and its validation over the eastern Alpine region. *Weather and Forecasting* **26**: 166–183.
- [16] Bica B, Kann A, Meirold-Mautner I. 2012. Enhanced road weather warnings and improved communication strategies within central Europe as part of the INCA-CE project. Paper presented at *16th International Road Weather Conference (SIRWEC 2012)*, Helsinki, Finland.