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A Numerical Forecast Model for Road Meteorological Services in Beijing

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ABSTRACT

A fine numerical forecast model (BJ-ROME) is improved and developed for road meteorological services. The RST observation data is assimilated in order to obtain a more accurate initial field. The RST prediction during raining days is also improved after the parameterization of road evaporation. The road water depth is added in the output parameters of BJ-ROME which is extremely important in a metropolitan such as Beijing during summer flood season. Snow ice is added in the output which is also important in winter. This model had already been coupled with 3-hr rapid update cycle system at the Beijing Meteorological Bureau (BJ-RUC) and placed in vocational operation. The forecast time span and the update interval of BJ-ROME in vocational operation are 24 hours and 3 hours, respectively. The prediction results could be used as a reference of maintenance decision support system (MDSS) to mitigate the traffic jam situation especially in large cities.

Keywords: numerical forecast model, RST, road water depth.

1 INTRODUCTION

With urbanization and the rapid development of the national economy, road traffic safety problems caused by weather-related factors have become an important issue. The development and improvement of forecasting methods for road meteorological information are topics of great significance.

Road surface temperature (RST) is a key parameter in road weather forecasting. Extremely high RST may cause tires to burst in the summer and have a major role in determining whether snow on the road surface will melt or freeze during the winter. Road surfaces have many characteristics different to those of other land cover classifications, and a traditional land surface model must be modified to satisfy the needs of RST and road snow/ice/water depth predictions.

Parameters relevant to RST and road snow/ice/water depth that have already been studied include topography [1-2], traffic effects [3-5], wind [1], air temperature [6] and cloudiness [7] etc. Models for road surface forecasting may be classified as the statistical models [8], GIS-based models [9-10] and physically based models [11-13]. In some of the physically based models, the road surface heat balance equation [4] is used in conjunction with the road characteristics and vehicle traffic effects, such as anthropogenic heat (AH) [4].

In China, the progress of Chinese and international research on major road weather forecasting systems was reviewed, and their characteristics, difficulties and future developing tendencies were discussed [14]. The Fine-Resolution Road Weather Information System was built in 2008 in China [15]. This system used the 3-hrs rapid update cycle system at the Beijing Meteorological Bureau (BJ-RUC, based on weather research and forecast model WRF2.2) [16-17] to predict road parameters. At present, in conjunction with the building of road meteorological monitoring stations in Beijing city, using an apparatus from Vaisala Company Finland, a fine forecast of RST and road snow depth is also available.

A fine numerical forecast model for urban road surface temperature (RST) and road snow depth prediction (BJ-ROME) [18] is developed based on the Common Land Model (CoLM). BJ-ROME not only takes into account road surface factors, such as imperviousness, relatively low albedo, low heat capacity and high heat conductivity, but also considers the influence of urban anthropogenic heat (AH). The validation results indicate that BJ-ROME can successfully simulate the diurnal variation and maximum value of RST under clear-sky condition

especially with extremely high RST values. The validation results also indicate that BJ-ROME can successfully simulate the accumulation time and the variation and maximum value of snow depth.
In this paper, BJ-ROME is improved and developed for urban road surface temperature (RST), road snow depth, road ice depth, road water depth and road slipperiness prediction. This model had already been coupled with BJ-RUC and placed in vocational operation. The forecast time span and the update interval of BJ-ROME in vocational operation are 24 hours and 3 hours, respectively. The forecast results of the coupled model have also been used as an important reference for decision making by the Department of Road Traffic and Road Management to mitigate the traffic jam situation especially in large cities.
Section 2 describes the improvement of BJ-ROME for RST, road water depth, road snow depth and road ice depth prediction. Section 3 provides an overview of the data used in this study. Section 4 demonstrates the results and provides a discussion of the validation results of BJ-ROME. The conclusions and scope for future research are discussed in the last section.

2 MODEL IMPROVEMENT

BJ-ROME was developed on the basis of the Common Land Model (CoLM) [19]. BJ-ROME adequately considers the physical characteristics of the road surface such as imperviousness, relatively low albedo, low heat capacity and high heat conductivity, while the surface energy balance model and the water accumulation model are also modified according to these characteristics. The influences of the AH and the UBL on the RST are also taken into account in BJ-ROME. The wind, temperature and humidity observation data for March 19-29, 2001 and August 11-25, 2003 from the 325-m meteorological tower of the Institute of Atmospheric Physics (IAP) were used to fit the profile of the atmosphere in the boundary layer. The surface snow accumulation model of BJ-ROME is based on the CoLM. The snowpack is modeled with up to five layers, depending on the total snow depth. The snow melt, compaction, combination and subdivision are also considered in detail in the model.

2.1 RST assimilation

To obtain an accurate initial field, a variational data assimilation algorithm was used in BJ-ROME to assimilate the RST observation data. A simplified variational data assimilation algorithm was applied, which uses only the energy balance model of the road surface as the physical constraint, whereas the road surface heat transfer coefficient (CH) is used as the tuning factor to link the RST to the sensible heat flux, because it is nearly constant during one day and the forecast time span of BJ-ROME is 24 hours. The corresponding cost function J is:

$$
\begin{aligned}
J(T_g, CH, \lambda) = {} & \frac{C_1}{2}\left(T_g(t_1) - T_{obs}(t_1)\right)^2 + \frac{C_T}{2}\int_{t_0}^{t_1}\left(T_g - T_{obs}\right)^2 dt \\
& + \frac{C_{CH}}{2}\int_{t_0}^{t_1}\left(CH - CH^{'}\right)^2 dt \\
& + \int_{t_0}^{t_1}\lambda\left[c\Delta z\frac{\partial T_g}{\partial t} - \frac{t_k}{\Delta z}(T_2 - T_g) - R_{n,g} + H_g + L_v E_g + L_f I - A\right]dt
\end{aligned}
\qquad (1)
$$

The parameter T_g is RST (K) and CH is the road surface heat transfer coefficient (kg m^{-2} s^{-1}). The first term on the right side of the equation represents the forecast error at the end of the observing period, while the second term represents the same error over the entire period. The parameter T_{obs} is the observed RST (K). The third term on the right side of equation (1) represents the error in road surface heat transfer coefficient estimates with respect to the “true” yet unknown value. The fourth term on the right side of equation (1) is the adjoint physical constraint of the road surface. The parameter λ is the Lagrange multiplier. C_1, C_T and C_{CH} in the cost function J are the weights of the different terms often defined as the inverse of the covariance matrix. To simplify the algorithm, these weights are assumed as constants in this paper. The detailed solutions of the cost function and the procedures of the LST assimilation algorithm are similar to those of Meng et al. [20]. The only difference is the tuned factor. Evaporative fraction (EF) is replaced by CH because road evaporation is zero if road surface is dry.

2.2 Road Water Depth and Road Evaporation

Road evaporation is important in road water and RST prediction when precipitation happens. Road water depth and road slippery prediction is crucial important in summer because in China, large cities such as Beijing often suffers from water logging. Considering the imperviousness of the road surface, the evaporation can be treated as a minor value of the potential evaporation and the water accumulation depth of the road surface [21]:

$$E_g = \min\left(E_p, \left(P - D_{rain}\right)\right) \qquad (2)$$

Where E_p is the potential evaporation (mm s^{-1}), P is the precipitation (mm s^{-1}), and D_{rain} is the drainage of the road surface (mm s^{-1}). Because surface runoff depends on topography and drainage, we assume that the drainage of the road surface is equal to light to moderate rain, which is approximately 5 mm h^{-1}. E_p could be parameterized as follows:

$$E_p = \rho_a \frac{q_{sat} - q_m}{r_d} \qquad (3)$$

Where ρ_a is air density (kg m^{-3}); r_d is aerodynamic resistance for evaporation (s m^{-1}); q_m is specific humidity of the air (kg kg^{-1}); q_{sat} is saturated specific humidity of water surface (kg kg^{-1}), which is associated with the aerodynamic air temperature at the surface and will be discussed in detail later.

Because road water depth is probably larger than zero even if precipitation is smaller or equal than drainage, so equation (2) is corrected as follows:

$$E_{imp} = \begin{cases} E_p & (W > 0) \\ \min\left(E_p, \max\left(0, \left(P - D_{rain}\right)\right)\right) & (W = 0) \end{cases} \qquad (4)$$

Where W is the road water depth (mm).

The water accumulation model of the road surface could be described as:

$$\frac{\partial W}{\partial t} = P - E_g - D_{rain} \qquad (5)$$

Equations (4) and (5) also could be used to predict road slipperiness, when W is zero and E_p is bigger than zero, road surface is considered as wet and slipper.

2.3 Road Ice Depth

Compared with road snow, road ice is also very important in transportation because of its slipperiness. In this paper, road ice depth is also added to the prediction output. The road ice depth prediction method in BJ-ROME is the same as that in CoLM; but in CoLM, snow ice depth is not included in the output. Road ice depth is calculated simultaneously with road snow depth. The snow melt, compaction, combination and subdivision are also used to compute road ice depth. Snow ice depth is calculated as follows:

$$Z_{ice} = \frac{\sum_{i=1}^{snl} W_i}{\rho_{ice}} \qquad (6)$$

Where Z_{ice} is road ice depth (mm), W_i is mass of ice in snow layer i (kg m^{-2}), snl is number of snow layers, ρ_{ice} is ice density (kg m^{-3}).

3 DATA

The observed data were measured by ROSA road weather stations of Vaisala Company, Finland. The ROSA road weather stations acquire measurements every five minutes. The Lugouqiao site RST data was used to accomplish the RST assimilation; the Xihongmennan site was chosen to validate the RST and road water depth during a rainy day; the Wenyuhe site was chosen to validate the road snow and road ice depth during a rainy day. They are located in Jinggangao, Jingkai and the airport express, respectively.

The forcing data to drive BJ-ROME for validation is from the observation of road weather stations and global land data assimilation system (GLDAS) [22]. The surface air pressure, 2m air temperature, 2m relative humidity, wind speed, wind direction and precipitation rate are from road weather stations; the downward shortwave and longwave radiation are from GLDAS. GLDAS data was interpolated spatially and temporally in order to accomplish the validation.

4 RESULTS AND DISCUSSIONS

The aim of the RST assimilation for the prediction is to obtain an accurate initial field. Two BJ-ROME runs were carried out for the Lugouqiao site to validate the effect of the RST assimilation: one using the RST initial field predicted from BJ-RUC and another using the RST initial field after the assimilation.

The RST observation data from 7:00 AM on the 8th of August to 7:00 AM on the 9th of August 2009 (with intervals of 1 hour) were used in the variational assimilation to obtain an accurate initial value. Time series of the resulting RST estimates from these BJ-ROME runs using the RST initial field predicted from BJ-RUC and from the RST initial field after the assimilation at the Lugouqiao site were compared with the observations and are plotted in Figure 1. From Figure 1, we can conclude that in the first day, especially before noon, RST results after assimilation are better than that before assimilation. These improved results are because, after assimilation, the initial field of the RST is improved. However, after noon, the results of the RST simulation obtained using the RST initial field after the assimilation are not much improved as compared to those acquired using the RST initial field predicted from BJ-RUC. Because the update interval of BJ-ROME in vocational operation is 3 hours, so the RST assimilation algorithm could improve the RST forecast definitely.

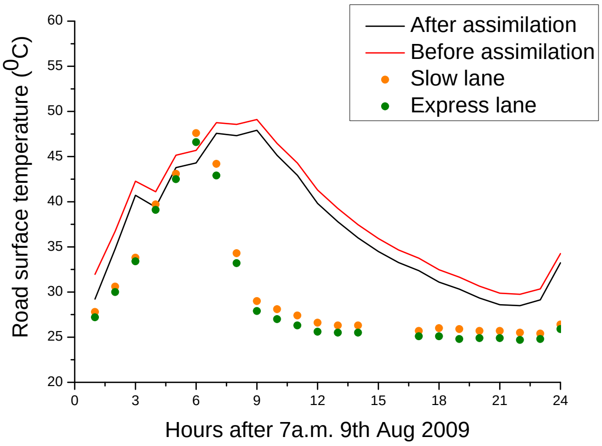

Figure 1 Time series of the resulting RST estimates from these BJ-ROME runs using the RST initial field predicted from BJ-RUC and from the RST initial field after the assimilation at the Lugouqiao site compared with the observations.

A whole rainy day in summer (21st Aug 2010) was chosen to fulfill the road evaporation and road water depth simulation of BJ-ROME. The time resolution is 5 minutes. Figure 2 is the precipitation during the simulation period. Precipitation happened almost all of the day, but it is not very heavy, the cumulative precipitation is about 8mm.

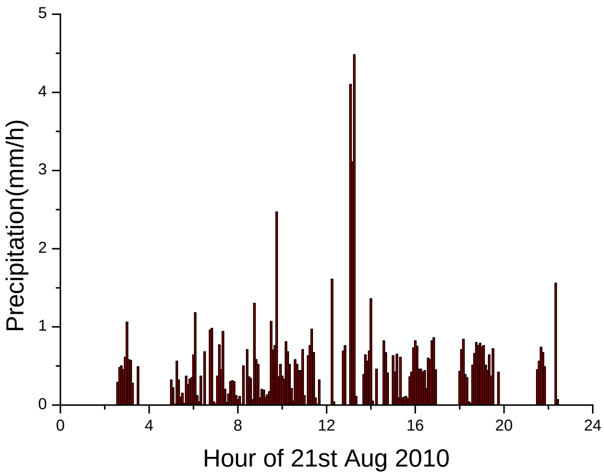

Figure 2 Precipitation during 21st Aug 2010

The aerodynamic air temperature at the surface is hard to observed and simulated. In order to test the effect of road evaporation in RST and road water depth simulation in rainy days, three cases were used to parameterize the potential evaporation: 1) Set the potential evaporation to zero; 2) using road surface temperature to parameterize potential evaporation; and 3) using road water temperature to parameterize potential evaporation. In case 3, road surface is considered as shallow lake, and the lake model [23-25] in CoLM is used to compute the road water temperature.
Figure 3 is the simulated potential evaporation of these three cases respectively; figure 4 is the RST simulation results for these three cases compared with the observation. Because of the effect of evaporation, the road surface temperature is smaller than road water temperature; that caused the potential evaporation in case 3 is

bigger than that in case 2 in most times. From figure 4, it is concluded that in case 3, the simulated RST matched the observations very well when the potential evaporation is larger than zero; for this reason, road water temperature can be used to parameterize the aerodynamic air temperature at the surface. In cases 1 and 2, because of low potential evaporation simulation, the simulated RST are apparently larger than the observation, the error is from 5 to 15 centigrade. This indicates that evaporation is very important in RST simulation when the precipitation is light or medium. Figure 5 is the water depth simulations of these three cases. From figure 5, it is concluded that road evaporation plays an important role in road depth simulation.

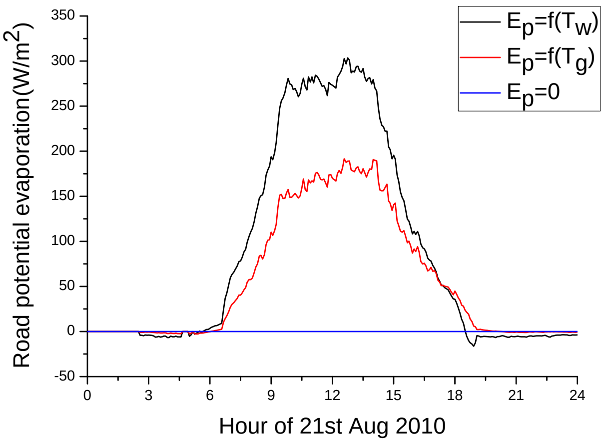

Figure 3 Simulated potential evaporation of three cases respectively.

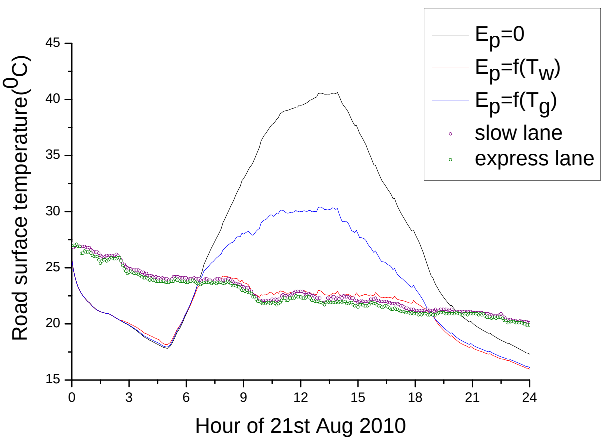

Figure 4 RST simulation results of three cases compared with the observation.

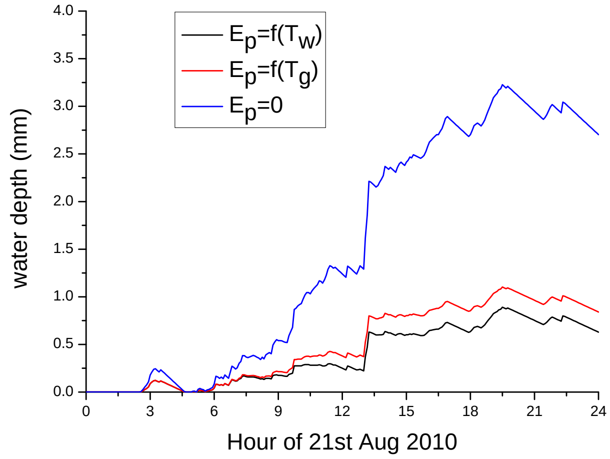

Figure 5 Water depth simulations of three cases respectively.

The energy and water balance research is very popular now, but seldom document could be seen for impervious surface energy balance especially when precipitation happens. The energy and water balance research in road surface in rainy day is discussed below. The discussion also could be extended to all kinds of impervious surfaces. Figure 6 is the energy fluxes variation during a rainy day. During a rainy day, sensible heat flux is very small because of low road surface temperature; impervious evaporation is nearly the same as the net radiation in the daylight; the ground heat flux is nearly the same as the net radiation at night; the energy imbalance is very close to zero. Figure 7 is the variation of cumulative water fluxes during a rainy day. The cumulative evaporation in the daylight is increased rapidly and nearly unchanged at night; the proportion of evaporation in precipitation is changed along with the intensity of precipitation. The cumulative water storage is equal to the road water depth, and is not big because the precipitation is not very heavy. The water imbalance is small and varied in the whole day. Figure 8 is the scatter plot of the cumulative precipitation and the sum of cumulative evaporation, water storage and drainage. A slope of 1.0248 is obtained from simple linear regression and the correlation coefficient is 0.9959.

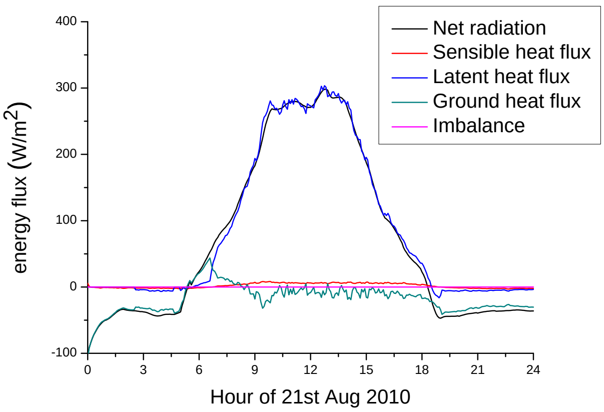

Figure 6 Energy fluxes variation during a rainy day.

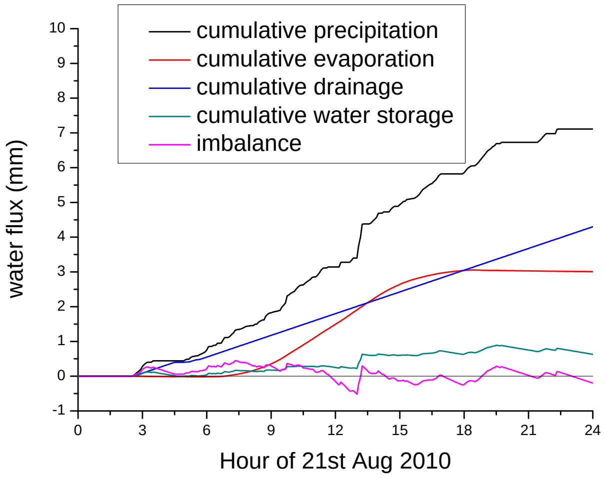

Figure 7 Variation of cumulative water fluxes during a rainy day.

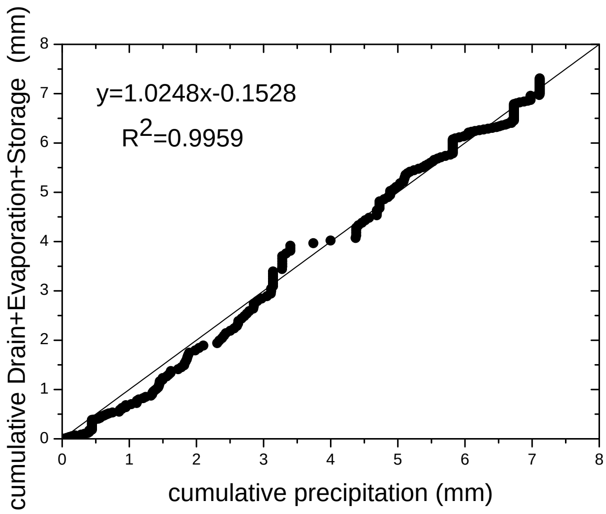

Figure 8 Scatter plots of the cumulative precipitation and the sum of cumulative evaporation, water storage and drainage.

BJ-ROME can simulate road snow depth well if snow removal is not considered [18]. In this paper, road ice depth is simulated and compared with road snow depth simulation. The simulation time period is from 12:00 2nd Jan 2010 to 12:00 4th Jan 2010. Figure 9 is the simulated road snow and road ice depth in Wenyuhe site. Road ice depth is associated with RST; because ice density is bigger than snow density, so road snow ice depth is always smaller than road snow depth.

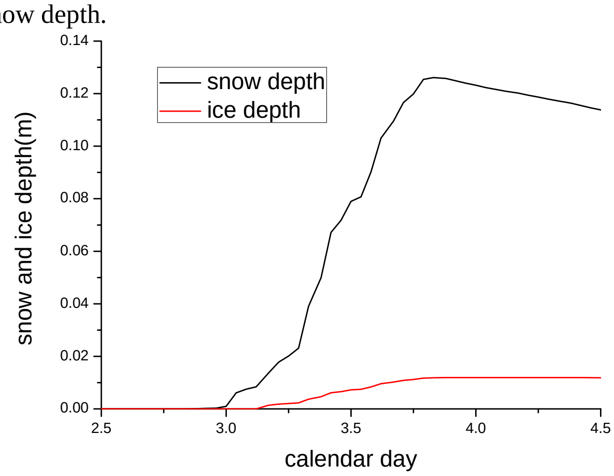

Figure 9 Simulated road snow and road ice depth in Wenyuhe site.

5 CONCLUSIONS AND FUTURE STUDY

A fine numerical forecast model (BJ-ROME) is improved and developed for urban road surface temperature (RST), road snow depth, road ice depth, road water depth and road slipperiness prediction. The prediction results of BJ-ROME could be used as a reference of maintenance decision support system (MDSS) to mitigate the traffic jam situation especially in large cities.

After the RST assimilation, the RST simulation in the first few hours is improved. Because the update interval of BJ-ROME in vocational operation is 3 hours, the RST assimilation algorithm could improve the RST forecast definitely.

Road water temperature could be used instead of aerodynamic air temperature at surface to parameterize the potential evaporation. In this case, the road surface is considered as shallow lake, and the lake model in CoLM is used to compute the road water temperature. The simulated RST in rainy day matched the observations very well in the daylight. Road evaporation plays an important role in road depth simulation if the precipitation is not very heavy.

This paper studied the energy and water balance in road surface in rainy days. During a rainy day, for impervious surface, sensible heat flux is very small because of low road surface temperature; impervious evaporation is nearly the same as the net radiation in the daylight. The cumulative evaporation in the daylight is increased rapidly and nearly unchanged at night; the cumulative water storage is equal to the road water depth and the water imbalance is small and varied in the whole day.

Road ice depth is associated with RST; because ice density is bigger than snow density, so road snow ice depth is always smaller than road snow depth.

In the near future, a more sophisticated method will be used to parameterize the AH in the road surface to forecast the RST more accurately. Road snow depth data should be assimilated in BJ-ROME; the man-made factor also should be considered in RST and road snow depth prediction.

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