

# 지표면 에너지 수지 이론을 이용한 도로노면온도예측을 위한 예단 모델 개발

## The Prognostic Model for the Prediction of the Road Surface Temperature by Using the Surface Energy Balance Theory

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### Abstract

In this study, the prognostic model for the prediction of the road surface temperature is developed using the surface energy balance theory. This model not only has a detailed micro meteorological physical attribute but also is able to accurately represent each surface energy budget. To verify the performance, the developed model output was compared with the German Weather Service (DWD)'s Energy Balance Model (EBM) output, which is based on the energy budget balance theory, and the observations. The simulated results by using both models are very similar to each other and are compatible with the observed data.

### 요 지

본 연구는 지표면 에너지 수지 이론을 이용한 도로노면온도예측을 위한 예단 모델을 개발하기 위한 것으로, 개발된 모델은 지표면 에너지 수지를 정확하게 표현함으로써 매우 복잡한 미기상학적 물리 과정을 표현할 수 있다. 모델의 성능을 검증하기 위하여 독일 기상청의 모델과 비교 실험을 하였으며, 독일의 관측자료 그리고 한국 기상청의 도로기상 관측 시스템의 관측자료를 이용하여 비교 검증하였다. 비교 결과 독일의 모델 결과와 매우 유사한 결과를 나타냈으며, 각 관측 자료값들과 잘 일치하였다.

**Keywords** : Prognostic model, Road surface temperature, Surface energy balance, Micro-meteorological physics

### 1. Introduction

The thought of surface energy balance has been extensively applied for various purposes especially in micro-meteorological analysis of phenomena relating to management of the Earth's resources. Carson (1982) has given a comprehensive review of land-surface and the atmospheric boundary schemes used in many general circulation models

with an emphasis on surface processes. Schmugge and Humes (1995) applied the surface energy balance model to monitor land surface fluxes. Many studies used Bowen ratio between sensible and latent heat fluxes to estimate the evaporation rate through surface energy balance equation (Brutsaert, 1982; Gutierrez *et al.*, 1994). Other papers deal with specific topics in more details, including Zhihao *et al.* (2002), Du *et al.* (2013), Lagos *et al.* (2011), Senay

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\* 본 논문에 대한 토의를 원하는 회원은 2015년 5월 31일까지 그 내용을 학회로 보내주시기 바랍니다. 저자의 검토 내용과 함께 논문집에 게재하여 드립니다.

*et al.* (2010), Sato (2009).

The inclusion of soil surface and road condition is very important in an attempt to improve a land surface parameterization for use in different scale atmospheric models.

The major meteorological factors determining the road condition, such as freezing temperature and micro-meteorological variables, are affected by the road surface temperature. Also topographic features can affect thermally driven road conditions, either directly, by causing changes in the wind direction (Atkinson, 1981) or indirectly, by inducing significant variations in the road surface temperature. But under the condition of the wide flat road or bridge, topographical features on the road condition are not significant.

Except for the topographical perturbations, the road-air energy budget exchange has also been found to significantly affect not only the local ground heat budget and but also the surface temperature distribution (Segal *et al.*, 1989; Betchtold, 1991).

It is evident that the reliable prediction of the road surface temperature, such as determining the freezing temperature, requires a powerful calculational tool that is able to represent each surface energy budget as accurately as possible, and to reproduce temporal variation of the road surface temperature more realistically.

The prognostic model for the prediction of the road surface temperature is developed using the surface energy balance theory. This model tends to calculate the several micro-meteorological variables, such as sensible heat flux, latent heat flux, ground heat flux, wind stress, and friction temperature (Fig. 1).

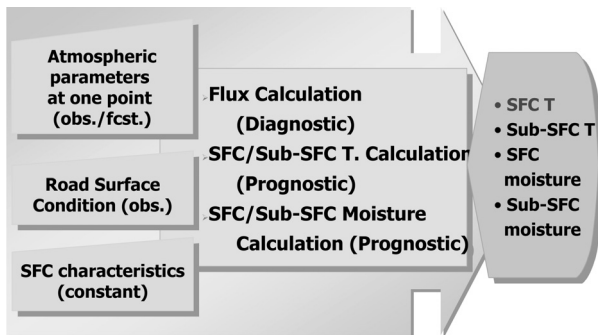


Fig. 1. Overview of schematic process of the developed model

## 2. Model Description

### 2.1 Surface fluxes

The turbulent scales, such as friction velocity  $u_*$  and friction temperature  $\theta_*$ , are usually computed iteratively starting from neutral values. However, this method is computationally time consuming. An analytical approach is suggested by Garratt (1992) with the use of the bulk Richardson number  $Ri_b$  and by Park (1994) in his surface parameterization.

The bulk transfer relation for surface fluxes is given by

$$u_*^2 = C_{DN} f_M (Ri_b) u_a^2 \quad (1)$$

$$u_* \theta_* = C_{HN} f_H (Ri_b) (\theta_a - \theta_g) u_a \quad (2)$$

where  $C_{DN}$  and  $C_{HN}$  are drag coefficients for momentum and heat in neutral stability,  $f_M$  and  $f_H$  are stability parameters that are the function of the bulk Richardson number for momentum, heat, and substring  $a$  and  $g$  represent each air and ground level.

### 2.2 Latent heat flux and evaporation

For evaporation calculations, soil moisture is required. Soil moisture levels are usually obtained through the bucket method or the force-restore method. One of the disadvantages of bucket method is that evaporation does not respond rapidly to short-period occurrences or precipitation. In the case of two-layer scheme (force-restore method), a thin soil surface layer volumetric moisture content  $W_g$  and the bulk layer volumetric moisture content  $W_2$  are represented (Noilhan and Planton, 1989) by

$$\frac{\partial W_g}{\partial t} = -C_1 \left[ \frac{(1 - \sigma_f) E_g - [(1 - \sigma_f) \times P \rho_w + \sigma_f P_g \rho_w + M_s \rho_{snow} - R \rho_w]}{\rho_w d_1} \right] - C_2 \frac{W_g - W_{eq}}{\tau} \quad (3)$$

$$\frac{\partial W_2}{\partial t} = -\frac{\sigma_f E_t}{\rho_w d_2} + \frac{d_1}{d_2} C_2 \frac{W_g - W_2}{\tau} \quad (4)$$

with

$$\frac{W_{eq}}{W_{sat}} = \frac{W_2}{W_{sat}} - a_1 \left( \frac{W_2}{W_{sat}} \right) \left[ 1 - \left( \frac{W_2}{W_{sat}} \right)^{8r} \right] \quad (5)$$

where  $P$  is the precipitation rate,  $E_g$  the evaporation at the soil surface,  $M_s$  the snow-melt,  $\rho_{snow}$  the density of snow,  $R$  the run off,  $E_t$  the transpiration rate,  $a_1$  and  $\tau$  are constants which depend upon soil types (Noilhan and Platon, 1989).  $P_g$  is the intercepted rainfall by the canopy. For a bare ground  $P_g = P$  and for a canopy, rain must first fill a reservoir of water on a canopy ( $m_c$ ), so that

$$P_g = \begin{cases} 0 & \text{if } m_c < m_c^+ \\ P & \text{if } m_c \geq m_c^+ \end{cases} \quad (6)$$

When  $m_c$ , the depth of water residing on the foliage, reaches  $m_c^+$ , the maximum depth of it, rain will no longer be intercepted but can reach the ground as throughfall. The variable  $W_{eq}$  in Eq. (5) represents an equilibrium moisture content where the force of gravity balances capillary forces.

The soil moisture content is relate to a scaling depth  $d_1$  and a subsurface soil layer of a physical depth of  $d_2$ . They are

$$\begin{aligned} d_1 &= (K_s \tau)^{1/2} \\ d_2 &= (365 K_s \tau)^{1/2} \end{aligned} \quad (7)$$

where  $K_s$  is the thermal diffusivity of the soil.

The soil evaporation is found from,

$$E_g = f \left( \frac{W_g}{W_{sat}} \right) E_1 \quad (8a)$$

Where  $E_1$  is the potential evaporation from the ground estimated by the Penman - Monteith equation (Monteith, 1981), which is given by

$$E_1 = \frac{s}{s + \gamma} (R_N - G_0) + \left( 1 - \frac{s}{s + \gamma} \right) \rho_a \lambda \delta q_a / r_{aq} \quad (8b)$$

Where  $s = dq_s/dT = \varepsilon \lambda q_s / (R_a T_a^2)$ ,  $\varepsilon = 0.622$ ,  $\lambda$  the latent heat of evaporation,  $q_s$  the saturation specific humidity,  $R_a$  the gas constant,  $T_a$  the air temperature, and  $\delta q_a = q_s(T_a) - q_a$ , the humidity deficit.

### 2.3 Road surface temperature and Subsurface temperature

The prognostic equations for the road surface temperature  $T_g$  and subsurface temperature  $T_2$  are obtained from the force restore method proposed by Bhumralkar (1975) and Blackadar (1976). That is,

$$\frac{\partial T_g}{\partial t} = C_T G_O - \frac{2\pi}{\tau} (T_g - T_2) \quad (9)$$

$$\frac{\partial T_2}{\partial t} = \frac{1}{\tau} (T_g - T_2) \quad (10)$$

where  $C_T$  is the road thermal coefficient,  $G_O$  the heat storage rate and  $\tau$  the time scale as 24 hour. The coefficient  $C_T$  is given by,

$$C_T = \left[ \frac{(1 - \sigma_f)}{C_g} + \frac{\sigma_f}{C_v} \right]^{-1} \quad (11)$$

where  $C_g$  and  $C_v$  are thermal coefficient of soil and vegetation system respectively.  $C_v$  is assumed to be  $10^{-3} J^{-1} m^2 K$  (Noilhan and Planton (1989)). For no vegetation system, (e.g.  $\sigma_f = 0$ ), the coefficient  $C_T$  equals to  $C_g$ , thermal coefficient of soil system  $C_g$  depends on both the soil texture and soil moisture.

This is estimated by,

$$C_g = 2 \left( \frac{\pi}{\nu C_T} \right)^{1/2} \quad (12)$$

The thermal conductivity  $\nu$  and volumetric heat capacity  $C$  vary with the volumetric moisture contents  $W_g$  and matric potential  $\Psi$ . That is,

$$\nu = \begin{cases} 419 \exp[-\log|\psi| + 2.7], & \text{If } \log|\psi| < 5.1 \\ 0.171, & \text{If } \log|\psi| > 5.1 \end{cases} \quad (13)$$

where  $\Psi$  is in unit cm (McCumver, 1980 ; Pielke, 1984) and the matric potential is,

$$\Psi = \Psi_{sat} \left( \frac{W_{sat}}{W_g} \right)^b \quad (14)$$

where  $\Psi_{sat}$  is the saturated moisture potential, and  $W_{sat}$  the saturated volumetric moisture contents and  $b$  the slope of retention curve on logarithmic graph.

The volumetric heat capacity  $C$  is expressed by the density of the road soil, the specific heat and the soil moisture contents.

The ground heat flux  $G_0$  can be calculated by the surface energy budget conservation theory. That is,

$$G_0 = R_n - H_0 - \lambda E_0 \quad (15)$$

where  $H_0$  is the sensible heat flux that is the function of friction velocity and friction temperature,  $\lambda E_0$  the latent heat flux and  $R_n$  the net radiation flux.

### 3. Verification of Model

To verify the developed model, its output was compared with the data from the German Weather Service (DWD), which utilizes the Energy Balance Model (EBM) based on the energy budget balance theory.

DWD's EBM calculates the energy transfer through 21 sub-surface medium and classifies 160 types of the climatology for road condition. And 5 types of other road characteristics are considered.

We carry out the simulation for the L857 region (Hanau)

of Germany by using both DWD's EBM and the developed model with the same initial conditions and period (November 2012 ~ March 2013).

To compare the results of both models, the forecasted road surface temperatures of both models and the observed one are shown in Figs. 2 and 3.

The simulated results by using both models were very similar to each other and had a good match with the observed data. But the forecasted road surface temperature by using the developed model is about 1 K ~ 2 K lower than that of DWD's EBM. To find the cause of the under-estimation of the developed model, we checked the calculated several flux amounts. Major difference was that when the heat is transferred between the road surface and the subsurface layer, the response of the developed model (2-layer model) occurs more quickly than that of DWD's EBM (multi-layer model). So, the minimum temperature is affected by the heat transfer rate.

Two scatter diagrams and regression analysis results, which represent the relationship of the DWD's EBM output, and those of the developed model and the observation, are shown at Fig. 3.

We can easily find that it is evident that the two model's outputs and observed values are highly correlated, if the coefficient of determination  $R^2$  and the slope of regression line are nearly unitary. But the developed model's output has a little bit cold bias as already discussed in previous chapter.

The developed model was run on 5 Oct., 2012, using the measurements of the KMA (Korea Meteorological Administration)'s pilot site which is located in Sindaebang-

Table 1. Differences between the DWD's EBM and the developed model

	DWD's EBM	Developed Model
Original model	• UK Open Road model	• Soil-Canopy Energy Balance Model
Introduction	• Forecasting the SFC temperature and condition for several types of the different road characteristics	• Same as DWD's EBM
Energy exchange between the SFC and sub-SFC layer	• Calculating the Energy exchange for 21 multi-layers • No considering the moisture process between the 21 multi-layers, but considering between the air and the road SFC	• Calculate the Energy exchange for 2 multi-layer (Forced and Restore Layer) • Considering the moisture process between the forced and restore layer and between the air and the road SFC
Output Feature	• Climatological prognostics	• Point prognostics

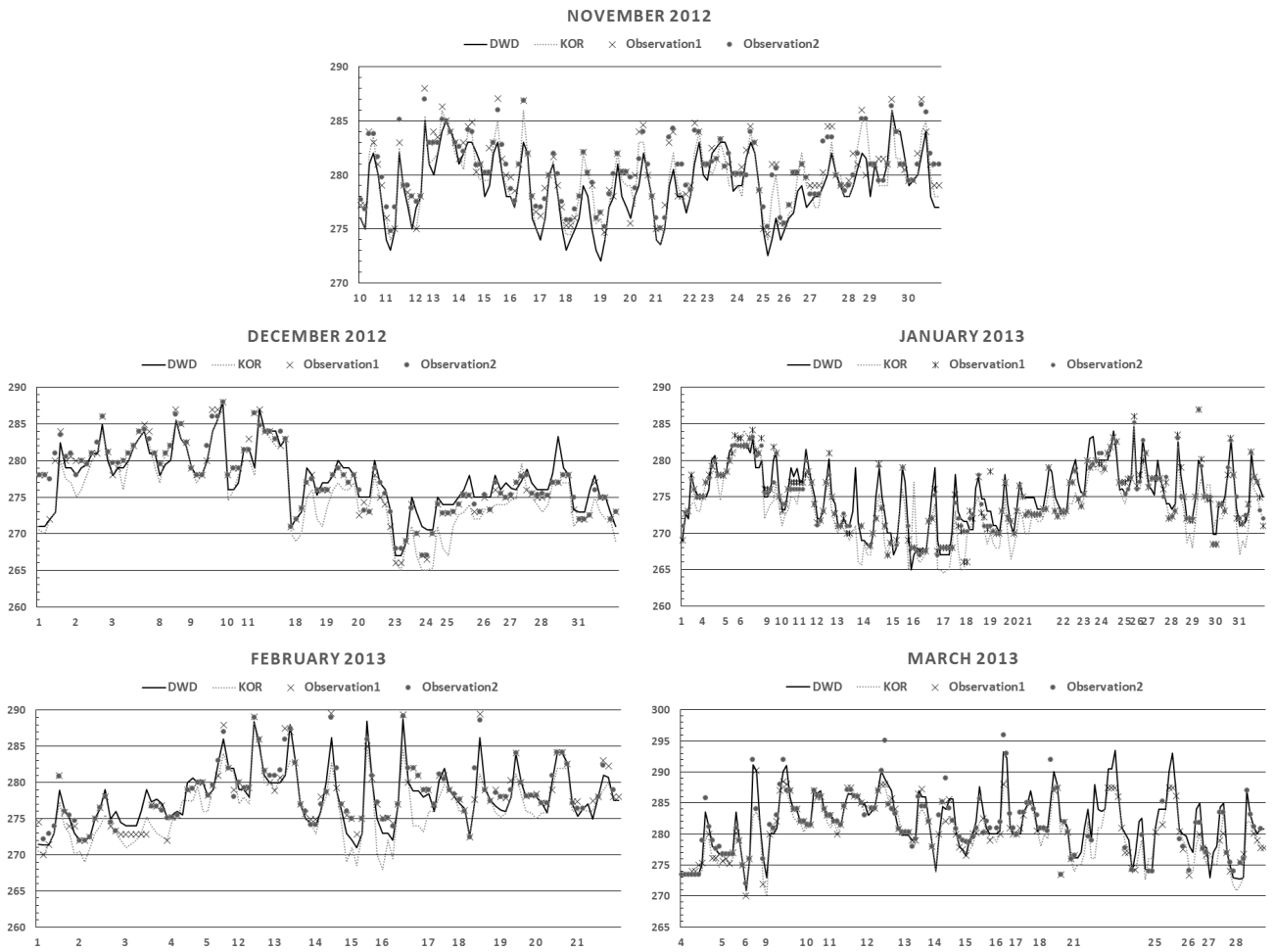


Fig. 2. Time series of the calculated and observed road SFC temperature (DWD : calculated value by using the DWD's EBM, KOR : calculated value by using the developed model, and Observation 1 and 2 : observed value on the observation site 1 and 2)

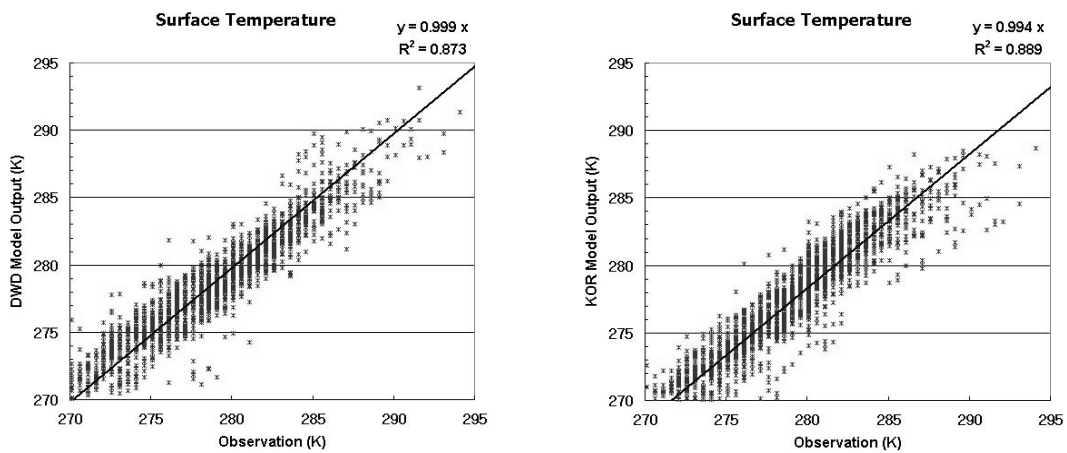


Fig. 3. Scatter diagram, regression line and regression analysis result for the modeled and observed road SFC temperature (DWD Model Output : calculated value by using the DWD's EBM, KOR Model Output : calculated value by using the developed model, and Observation : observed value on the observation site)

dong, Seoul and the model outputs are compared with the observations data. The pilot site is composed of both the meteorological tower and road sensor which can measure the road SFC/sub-SFC temperature and road condition.

The simulated results (Fig. 4) utilizing the developed model were compatible with the observed data, within the error of less than 2 K. At the same time, the time lag between air temperature and road surface temperature

Table 2. Initial condition for the test run using the measurements of the pilot site

Input Variable	Details
Wind Speed	Data Origin : MM5 Output Data (00Z Forecastings) Point Objective Site : 108 (Seoul) Site Producing Interval : 3 Hours Interpolation : Linear Final Input Interval : 10 Min. Initialization : per 1 Day (24 Hours)
Wind Direction	
Air Temperature	
Air Humidity	
Insolation	
Cloudness	
Precipitation	
SFC. Temp.	Data Origin : SFC. Observation Data Point Objective Site : 108 (Seoul) Site Producing Time : 3 LST.
Sub-SFC. Temp.	Using : For model Initial Condition Initialization : per 1 Day (24 Hours)

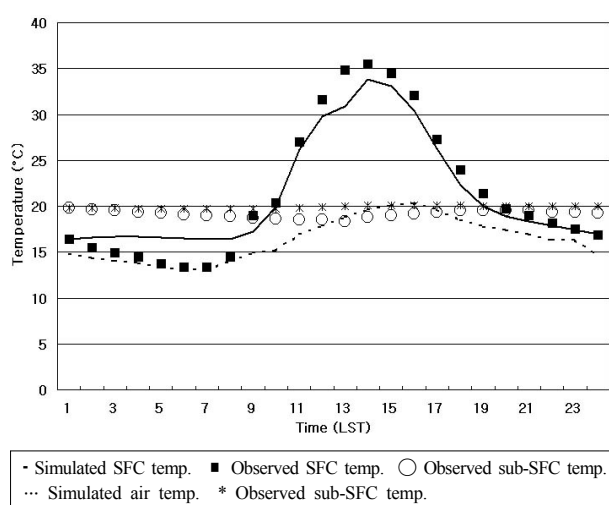


Fig. 4. Calculated road surface temperature and subsurface temperature by using the developed model and Observed data

(about 3~4 LST) was also well simulated by the model, as the measurement shows.

The numerical weather forecasting output from KMA/MM5 was used as the synoptic input data, for running model. Because of the initial error of the MM5 output, the simulated road surface temperature and ground temperature showed the difference in values from the measurement. As a result, the quality of road surface condition was found to be dependent on the quality of the NWP, when we operated the Energy Balance Model for road weather prediction.

#### 4. Conclusion

The prognostic model for the prediction of the road

surface temperature is developed using the surface energy balance theory. And the developed model output is compared with DWD's EBM outputs and the pilot site's observations to verify the developed model's performance. The simulated results by using both model were very similar to each other and were compatible with the observed one. But the developed model underestimates the minimum road surface temperature rather than DWD's EBM.

If the developed model is improved to have more subsurface layer, more accurate result will be produced.

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Received : March 28<sup>th</sup>, 2014  
 Revised : August 4<sup>th</sup>, 2014  
 Accepted : November 3<sup>rd</sup>, 2014