METRo: A New Model for Road-Condition Forecasting in Canada

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ABSTRACT

A numerical model to forecast road conditions, Model of the Environment and Temperature of Roads (METRo), has been developed to run at Canadian weather centers. METRo uses roadside observations from road weather information systems stations as input, together with meteorological forecasts from the operational Global Environmental Multiscale (GEM) model of the Canadian Meteorological Centre; the meteorologist can modify this forecast using the ''SCRIBE'' interface. METRo solves the energy balance at the road surface and the heat conduction in the road material to calculate the temperature evolution; it also accounts for water accumulation on the road in liquid and solid form. Radiative fluxes reaching the surface are taken from the GEM model in automatic mode or are parameterized as a function of cloud cover and temperature when run in manual mode. The road-condition forecast is done in three stages: initialization of the road temperature profile using past observations, coupling of the forecast with observations during the overlap period when the meteorological forecast and the roadside observations are both available, and the forecast itself. The coupling stage allows for adjusting the radiative fluxes to local conditions. Results for road temperature are presented for three stations in Ontario for a period of 3 months. The 24-h forecasts are issued 2 times per day at 0300 and 1500 LT. Overall, about one-half of the time the error in surface road temperature (verified every 20 min) is within ± 2 K, and the nighttime rms error is about 2 K. The impact of the coupling stage is large and allows METRo to produce automatic forecasts almost as good as the manual ones, especially for the first few hours. When METRo is run in manual mode, several nearby stations can use the same meteorological input, saving preparation time for the meteorologist. METRo also contains a mechanism for correcting systematic errors at each station, and it is hoped that this capability will permit its application to many new sites without major adjustments.

1. Introduction

Road weather information systems (RWIS) have been in use in Europe since the beginning of the 1980s and are becoming more widely used in North America to help winter road maintenance activities. RWIS consist of roadside observation stations gathering weather and road-condition information on a continuous basis, a system to forecast these conditions some time ahead, and a mechanism to communicate to the road maintenance personnel the relevant information to help to plan deicing and snow removal. Road maintainers combine information obtained from several sources to determine if maintenance is, or is likely to be, required. They can save a significant amount of money and time while increasing road safety by acting on the road in the most efficient manner.

Several systems have been developed during this period using different approaches, from purely physical models (Rayer 1987; Sass 1997; Jacobs and Raatz 1996) to ''fuzzy logic'' models (Hertl and Schaffar 1998). At the same time the equipment has also evolved from simple air and road temperature measurements to complete roadside weather stations with cameras. In the last few years, a large number of RWIS installations were deployed. This trend should continue as more and more road maintenance authorities install RWIS networks. A large number of RWIS stations are currently being installed (or planned) on Canadian highways.

The importance of an RWIS infrastructure has been clearly demonstrated, both from the point of view of safety and for economic reasons. Economic benefits from the reduced number of accidents and the increased availability of roads because of more timely maintenance are considerable. Furthermore, maintenance authorities can recover the cost of RWIS by using more efficient and timely salting procedures, thus reducing the cost of road maintenance itself. Quoted benefits: costs ratios are about 2 for direct benefits and about 10 for indirect benefits (Wikelius et al. 1996).

This paper describes the recent effort undertaken in the Meteorological Service of Canada to help the weather forecasters to deliver a useful forecast of road conditions to an increasing number of sites, using automated or semiautomated techniques. The main part of such a system is a new physically based numerical Model of

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the Environment and Temperature of Roads (METRo), which has close connections with the Global Environmental Multiscale (GEM) operational regional numerical weather prediction model run at the Canadian Meteorological Centre (CMC) in Montreal. METRo was first implemented at the Ottawa Regional Centre in October of 1999 and is currently in operational use at other Canadian weather centers.

METRo incorporates a full road-condition forecasting system that can predict the road surface temperature as well as the pavement condition. However, results in this paper mainly concern road temperature because the objective evaluation of pavement condition forecasts has not yet been completed. METRo also contains an observation assimilation mechanism to help to initialize the forecast and a local bias-correcting mechanism. The system was designed to adapt as automatically as possible to the local observations and to atmospheric model biases at each station. This capability will allow METRo to be deployed easily over a large number of stations with similar local environments across Canada without too much calibration effort being needed for every station and region.

Section 2 of the paper will describe the model itself. Section 3 illustrates the forecast process. Section 4 will discuss the model performance.

2. Model description

Although Hertl and Schaffar (1998) have shown that a statistical approach can provide a reliable forecast of road surface temperature, the model described here is in the tradition of physically based models, along with models described by Rayer (1987). We believe that a good representation of the physical processes can better account for situations in which the weather is changing. METRo in many respects resembles Sass's (1997) model, one difference being that Sass's model forecasts a few hours ahead whereas METRo typically makes 24-h forecasts. Other differences will be pointed out below. METRo is composed of three modules: the energy balance of the road surface (the central part), a heat-conduction module for the road material, and a module to handle water, snow, and ice accumulation on the road.

a. Surface energy balance model

The main part of the road-condition forecast lies in the correct evaluation of the energy fluxes at the road surface. Seven terms contribute to the energy balance from the atmospheric side:

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

The residue R is evaluated as the sum of the net solar radiation flux (S is the incoming flux and α is the albedo), the difference between the absorbed incoming infrared radiation flux εI (ε is the emissivity) and the emitted flux (σ is the Stefan–Boltzmann constant and T_S is the temperature of the road), the sensible turbulent heat flux H, the latent heat flux $L_a E$ (L_a stands for either the vaporization heat or the sublimation heat and E is the water vapor flux), the flux associated with phase changes of precipitating water $\pm L_f P$ (P is the precipitation rate, L_f is the heat of fusion of water and, $\pm$ indicates freezing or thawing), and an anthropogenic flux A.

The incoming radiation fluxes are either calculated by METRo or are taken from the GEM model output. In both cases and as will be explained in the next section, METRo introduces correction factors to these fluxes to remove the discrepancies between forecast and observed road surface temperatures during the coupling phase. The road surface albedo varies linearly from a snow-free value of 0.1 to a snow-covered value of 0.5 between 1 and 6 kg m^{-2} of snow. The emissivity is set at 0.92. These values were chosen through experimentation during our initial calibration of METRo. Shading effects have been neglected in this version of the code. The three stations used to validate METRo are all in open areas for which shading is not an issue. However, shading will be included in future versions of the code. It will take the form of a function of the sun angle to be applied to the $(1 - \alpha)S$ term. The actual method of determining the form of this function for each station remains to be finalized.

The evaluation of the turbulent fluxes H and E must be an approximation in view of the complexity of the actual transfer processes that are taking place on the road. METRo uses Monin–Obukhov similarity theory despite the fact that it is not strictly applicable because the road does not have a long enough fetch for the wind to adjust to an equilibrium value, as pointed out by Chen et al. (1999). The model also takes the meteorological variables needed for surface flux calculations at 1.5 m (temperature and humidity) and 10 m (wind) above the surface, whereas this height ideally should be large enough for the meteorological variables not to be affected by the presence of the road. This holds especially true when the variables come from the 24-km horizontal-resolution GEM model. We chose these heights for practical considerations, given that observations at roadside stations are part of the forecast process, as described in the next section. The passing vehicles, which would tend to increase the transfer between the road and the air, also generate turbulence. METRo contains a mechanism to compensate for the increased turbulence by setting a minimum value for the wind at different times of the day. However, in all of the experiments presented here but one, the minimum wind V_c was set to zero, because we did not have reliable traffic data at our disposal. The turbulent fluxes are thus expressed as

$$H = -\rho c_p C_m \max(V, V_c) C_h (T_a - T_s), \quad \text{and} \quad (2)$$

$$E = -\rho C_m \max(V, V_c) C_h (q_a - q_s), \quad (3)$$

where ρ is the air density, c_p is the specific heat of air at constant pressure (set to 1005.46 J kg^{-1} K^{-1}), V is the wind speed at 10 m, T_a is the air temperature, and q_a is the specific humidity at 1.5 m. Variable q_S is the specific humidity at the surface and is given by

$$q_s = \min[q_a, q_{\rm sat}(T_s)] \quad \text{if } W_l + W_s = 0, \quad \text{and} \tag{4a}$$

$$q_s = q_{\rm sat}(T_s) \quad \text{if } W_l + W_s \geq W_c, \tag{4b}$$

where $q_{\rm Sat}(T_S)$ is the saturated value of specific humidity, W_l is the water accumulation on the surface in liquid form, W_S is the water in solid form (snow or ice), and threshold value W_C is 0.5 kg m^{-2}. For $W_S + W_l$ between 0 and W_C, a linear variation between (4a) and (4b) is used to calculate q_S. This formulation differs from Sass (1997) in that it allows for the formation of dew and frost. The calculation of the dimensionless surface layer transfer coefficients C_m for momentum and C_h for heat and moisture follows Delage and Girard (1992) and Delage (1997) with the addition of a Prandtl number of 0.85 as in the GEM model (Mailhot et al. 1998). The roughness length used in C_m is 0.001 m; that used in C_h is 0.0005 m. Equations (3) and (4) state that evaporation will occur only if water or snow/ice is present on the road but dew or frost formation (negative values of E) will take place whenever the specific humidity of the air is larger than that of the surface, assumed to be saturated with respect to water or ice (depending on whether T_S is above 0°C).

The phase-change flux accounts for the release of energy when rain freezes on the road at less than 0°C and the expense of energy when snow melts on an above-0°C road. For the purpose of this calculation, all the precipitation is said to have melted or frozen during one model time step (30 s).

The last term of (1) attempts to account for the positive contribution of traffic to the energy budget. It represents the global effect of friction from the tires and the heat released by the engines. As in other road-condition models, the value of A is arbitrary. During model development using data from a single station (Kinburn), A was set to a constant value of 15 W m^{-2}, close to the 14 W m^{-2} used in Jacobs and Raatz (1996). When we tested the model at other locations, a bias in road temperature sometimes developed for part of the season; we decided to correct for it by introducing a variable value of A determined by the performance of METRo during the previous days. A bias can be caused by many factors, such as a bias in the forecast of air temperature at the station, the presence of water underneath the pavement, special exposure of the site, and so on. To simplify the issue, we introduced a single error feedback on A. Because this term is particularly important at night, in the absence of the dominant solar forcing during the day, the value of A is determined using mean errors in nighttime road temperatures only. The current algorithm is to modify A once per day by 1.0 W m^{-2} for each degree Celsius of bias in the mean nighttime temperature of the previous day.

The residue of (1), R, represents the energy flux provided to the road surface from above the surface. It will be used to force the road conduction model (to be presented in section 2b) or will contribute, together with the ground heat flux, to the melting or the freezing of water in the surface accumulation model, which will be discussed in section 2c. Note that the road-surface temperature T_S is kept constant during the evaluation of the energy balance.

b. Road heat-conduction model

The evolution of the temperature profile in road material T is calculated using the one-dimensional heat diffusion equation,

$$C(z)\frac{\partial T(z, t)}{\partial t} = -\frac{\partial G(z, t)}{\partial z}, \tag{5}$$

in which C is the heat capacity and G is the ground heat flux given by

$$G(z, t) = -k(z)\frac{\partial T(z, t)}{\partial z}, \tag{6}$$

where k is the heat conductivity. Variables C and k are specific to each road material and thus will take different values with depth z. Two numerical grids are available to METRo. The choice of grid depends on the kind of road for which the forecast is attempted. For normal roads, a variable-resolution grid is used; a uniform-resolution grid is employed for bridges and overpasses. The different grids are used because of the difference in bottom conditions for both road types. A normal road rests on soil; a bridge or overpass is suspended in midair. The air temperature on the bridge underside therefore also affects the temperature profile. A uniform grid allows for better resolution of the forcing on both sides of the bridge. On the other hand, only the temperatures near the surface need to be resolved well for normal roads, and the grid resolution can be reduced accordingly as the diurnal heat wave moves deeper below the road surface with decreasing amplitude. This is accomplished by using a coordinate transformation ξ of the form

$$\xi = a \ln(1 + bz), \tag{7}$$

similar to the one described in Delage (1974). The resolution for the uniform grid is 0.01 m; for the variable grid, the constants a and b in (7) are chosen to give a maximum resolution of 0.01 m at the surface and about 0.05 m at a depth of 0.5 m; the bottom of the variable grid is at 1.4 m, and 24 out of its 29 levels lie above 0.5 m. The number of levels for the uniform grid depends on the thickness of the bridge.

The upper boundary condition is either an imposed downward flux, that is, $G_0 = R$, or, when melting or

TABLE 1. Heat conductivity and capacity for road materials used in METRo.

Units	Conductivity (W K^{-1} m^{-1})	Volumetric capacity (J K^{-1} m^{-3})
Asphalt	0.80	2.1×10^6
Concrete	2.20	2.1×10^6
Crushed rock	0.95	2.1×10^6
Deep soil (undetermined)	1.00	2.0×10^6

freezing is taking place at the surface (see section 2c below), an imposed temperature of 0°C. The bottom boundary condition is one of no flux for the normal road or an imposed temperature (air temperature T_a) for bridges. The model uses an explicit scheme with a 30-s time step, limited by the high vertical resolution currently used in METRo; if desired, a reduced resolution would allow shorter execution time on the computer.

Model heat conductivities and heat capacities are set close to the measured values of each material simulated, which are asphalt, concrete, crushed rock, and soil (see Table 1). These measured values and road composition were obtained through discussions with a civil engineering firm. In some test experiments with the heat conduction model, we included the possibility to have a nonzero water content in the road to simulate water infiltration. The water in the road was allowed to freeze and thaw as it crossed the freezing point. In one experiment, we attempted to reproduce the winter road temperature evolution at one RWIS station using the road surface temperature as forcing and the 0.40-m-depth temperature to validate. This study revealed that the road water content is a highly variable quantity. The model required volumetric water contents of up to 40% in some instances to reproduce the observed deep temperatures. Other experiments showed that inclusion of nonzero road water contents in a road-condition forecast did not significantly improve the quality of the forecast. This mechanism was therefore not included in subsequent versions of METRo.

c. Surface water/ice accumulation model

A system of two reservoirs is used to simulate the evolution of liquid water W_l and snow or ice W_S at the road surface. The system is based on the one presented in Sass (1992) with some modifications. Only one of the two reservoirs can be nonempty at a given time, except during a phase transition in which the content of one reservoir is transferred to the other. The processes controlling the amount of water and snow at the road surface are governed by the following equations:

$$\frac{dW_l}{dt} = P - E + \frac{R - G_1}{L_f} - r, \quad \text{and} \tag{8}$$

$$\frac{dW_s}{dt} = P - E - \frac{R - G_1}{L_f} - r, \tag{9}$$

where G_1 is the downward heat flux between the first and the second model layers in the road and r is the runoff. Precipitation P and evaporation E affect only one of the reservoirs depending on the surface temperature (if above or below 0°C). On the contrary, the transfer term $(R - G_1)/L_f$ is active only at 0°C. A more complex situation exists when precipitation occurs while T_S is at 0°C, but energy and water are conserved in all cases. Water runoff toward the side of the road is simulated using an exponential relaxation function of the form proposed by Sass (1992):

$$r = c(W_l - W_r) \quad \text{if } W_l > W_r, \quad \text{and} \tag{10a}$$

$$r = 0 \quad \text{if } W_l \leq W_r, \tag{10b}$$

where $c = 0.003$ s^{-1} and $W_r = 1.0$ kg m^{-2}.

Snow removal, either by traffic or maintenance operations, is also parameterized with the same exponential relaxation function, with W_S replacing W_l in (10). This parameterization stems from the observation that the passage of cars tends effectively to remove all but a thin layer of snow at the road surface.

3. Forecast process

a. Atmospheric forcing

The weather forecast needed to force METRo is provided either by completely automated means or by meteorologist intervention in the forecast process. For both approaches, METRo is linked to the CMC ''SCRIBE'' expert system, which was designed and developed at CMC during the 1990s to assist meteorologists in the preparation of the great number of products that are needed each day. A set of objective weather-element guidance matrices for a large number of sites across Canada, currently containing forecasts at three-hourly intervals, is prepared centrally from GEM model outputs and statistical forecast methods. The matrices are then transmitted to the regional weather centers, where they are decoded. The meteorologist on duty can edit the weather elements using a graphical user interface. The resulting forecast weather elements are then fed to a product generator, which produces a variety of forecasts, including road condition through METRo. Such a system preserves the consistency between the different products.

1) AUTOMATIC MODE

In this mode, METRo inputs are taken from two sets of SCRIBE matrices: the regular operational set plus a set of extended matrices that contain radiative fluxes. METRo then extracts the forecast from the matrices that are associated with the RWIS station. Air temperature and humidity, wind, and precipitation are linearly interpolated to the METRo time steps. Interpolation of the radiative fluxes S and I is done using instantaneous and cumulative three-hourly values for greater accuracy.

TABLE 2. Coefficients for radiatives fluxes [(11) and (12)].

Cloud cover (octals)	D_1	D_2 (W m^{-2} K^{-1})	D_3 (W m^{-2})
0	1.00	3.79	214.7
1/8	0.97	4.13	226.2
2/8	0.94	4.13	234.8
3/8	0.89	4.26	243.5
4/8	0.85	4.38	250.7
5/8	0.80	4.19	259.2
6/8	0.71	4.40	270.9
7/8	0.65	4.34	280.9
8/8	0.33	4.51	298.4

For the solar flux, correct sunrise and sunset times are also used in the interpolation. All the variables needed for the surface energy balance are contained in the matrices, and therefore METRo simply proceeds with the forecast with no manual intervention.

2) MANUAL MODE (GROUP FORECASTS)

In manual mode, meteorologists can use the SCRIBE interface to modify the forecast of meteorological variables (temperature, humidity, wind, precipitation amount and type, and cloud cover). This can be done in a single intervention for all RWIS stations within the region affected by the forecast. Each station will have its own METRo forecast using observations at each specific site, but the meteorological forcing can be made the same for many nearby stations, saving precious time for the meteorologist.

A complication arises in manual mode from the fact that meteorologists have not been trained and do not have the tools to forecast incoming solar and infrared radiation fluxes. These variables come from the GEM model in automatic mode but can no longer be provided by the model in manual mode given that the meteorologist may have changed the forecast, in particular the cloud amounts that affect the radiation reaching the surface. Therefore, instead of using direct GEM output for radiative fluxes, METRo in manual mode uses parameterizations developed from a statistical analysis of the radiative fluxes produced by the radiation packages of GEM. These parameterizations rely on the forecast cloud cover in the solar case and on the cloud cover and surface air temperature for the infrared radiation. They are presented here:

$$S = S_t D_1 F(S_t), \quad \text{and} \tag{11}$$

$$I = D_2 T_a + D_3, \tag{12}$$

where S_t is the incoming solar radiation at the top of the atmosphere above the station and D_1, D_2, and D_3 are coefficients that vary with cloud cover as defined in Table 2. The attenuation factor F is defined as

$$F = a_4 S_t^4 + a_3 S_t^3 + a_2 S_t^2 + a_1 S_t + a_0, \tag{13}$$

with $a_4 = -1.56 \times 10^{-12}$ m^8 W^{-4}, $a_3 = 5.972 \times 10^{-9}$ m^6 W^{-3}, $a_2 = -8.364 \times 10^{-6}$ m^4 W^{-2}, $a_1 = 5.183 \times 10^{-3}$ m^2 W^{-1}, and $a_0 = 0.435$.

The choice of automatic or manual mode does not affect the following stages of the forecast production, and METRo will run identically in both situations. These stages, shown in Fig. 1, are initialization, coupling, and the forecast itself.

b. Initialization phase

For each forecast, an initial road temperature profile is needed. To produce such a profile METRo uses road temperature observations at the surface and subsurface from the last two days to force the heat-conduction model. Subsurface sensors for the sites in our study were installed at 0.4-cm depth. The surface temperature is used as the boundary condition for the heat-conduction model, and the temperature at the level closest to 0.4 m is overwritten with the observed subsurface value at each time step. The temperature profile at the end of the initialization period is used as the initial condition for the coupling phase. Should surface observations be missing for a period exceeding 4 h, METRo will start the initialization after this 4-h period using an analytical

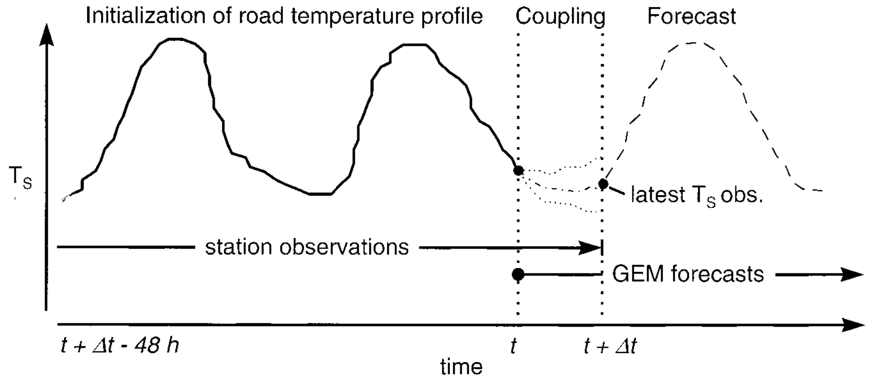

FIG. 1. The three stages of the forecast process. During the coupling stage, both station observations and meteorological forecasts are used to determine a correction coefficient for radiative fluxes. Time t can be either 0000 or 1200 UTC. Variable Δt in this application is 7 or 8 h.

solution to the heat-conduction equation. This solution is based on a sinusoidal road-surface temperature diurnal cycle of fixed amplitude. If observations are completely missing during the initialization phase, the latter method will provide the initial profile for the coupling phase or even for the forecast itself if observations are also missing during the coupling (the minimal requirement to run a METRo forecast is one observed or estimated road-surface temperature at initial time). Results using this analytic road temperature profile were surprisingly close to those using the full initialization method. The difference in road temperature after a 24-h forecast was never greater than 0.1°C in tests that compared forecasts with full initialization to ones for which no initialization data were supplied. This result is encouraging, because it indicates that METRo can produce reliable results even when few observations are available.

c. Coupling phase

The coupling phase allows METRo to adjust the atmospheric forecast to actual station observations. Atmospheric forecasts are routinely provided via SCRIBE every 12 h, at 0000 and 1200 UTC (see Fig. 1). RWIS forecasts are issued at various times during the day, and generally there is a delay between the beginning of the most recent atmospheric forecast period and the time when METRo forecasts are issued; in our example, this delay is 8 h. METRo uses this overlap period during which atmospheric forecasts and roadside observations are both available to make suitable adjustments to its initial energy balance for the road-condition forecast period.

METRo proceeds by performing a short-term road temperature forecast within the coupling period. During this forecast the energy-balance model is forced with all the available observations except the road-surface temperature; that is, observed air temperature is used instead of forecast air temperature, observed dewpoint instead of forecast dewpoint, and so on. If an observation is missing, the forecast variable is used instead. However, the radiation fluxes are not observed variables and cannot be replaced during the coupling. To solve this problem, the model fluxes are modified so that the forecast surface temperature at the end of the coupling period is within 0.1 K of the observed surface temperature. The modification consists of a multiplying coefficient applied to one of the two radiation fluxes: S during the day and I at night. The forecast is reiterated with different values of the coefficient for the entire coupling period until convergence is achieved. The resulting coefficient is used, with some relaxation, during the forecast phase.

One current limitation of this system is that it requires at least 3 h of observations to produce results reliably and to be representative of the temporal resolution of the atmospheric forecast. In cases for which there are insufficient data or large gaps in the observations, coupling may be skipped by METRo and replaced by the initialization procedure describe above. In such a case, the atmospheric forecast may still be modified to reflect the actual station observations (see next section). Another difficulty is the choice of either S or I on which to apply the coefficient. The cutoff time between a ‘‘day’’ (solar) and ‘‘night’’ (infrared) coupling condition is currently arbitrary and may be adjusted with experience.

d. Forecast phase

At the end of the coupling period, the atmospheric forcing (T_a, q_a, V, and P) may be different from the original forecast issued from the SCRIBE matrices. To retain this useful information during the forecast phase, the original values of these quantities are modified to reflect the initial discrepancy between the atmospheric forecast and the observation. This modification is done by initializing METRo with the most recent observed values and forcing it at subsequent times with a blend of the initial values and of the original forecast values, the weight passing exponentially from the initial to the forecast values over a period of about 6 h. The same relaxation function is applied to the coefficient modifying the radiative flux.

In its current operational configuration at the Ottawa center, METRo forecasts are issued 2 times daily at 0300 and 1500 local time for a forecast period of 24 h. All results in this paper will be obtained for this configuration.

4. Model results

Results are presented for a period from 9 February to 1 May 1999 for three stations in Ontario. Two of the stations are located in the vicinity of Ottawa: Kinburn is a road site with 0.12 m of asphalt over 0.76 m of crushed rock; Ashton is an overpass with 0.19 m of asphalt over 0.46 m of concrete. The third station, Wallaceburg, is a road site located between Windsor and Sarnia, and the composition of the road is 0.25 m of asphalt over 0.70 m of crushed rock. The number of days included in the verification for each forecast period ranges from 65 for Ashton to 80 for Wallaceburg. The overall frequency distribution of road temperature errors of METRo in automatic mode for all three stations for both forecast periods, each extending to 24 h and verified every 20 min, is shown in Fig. 2. About one-half of the forecasts lie within plus or minus 2 K from the observed values, which is remarkable, given that the observed temperature range for the period is nearly 70 K.

a. Error feedback and coupling

Figure 3 shows mean (lower curves) and rms (upper curves) errors for forecasts issued at 1500 LT for the

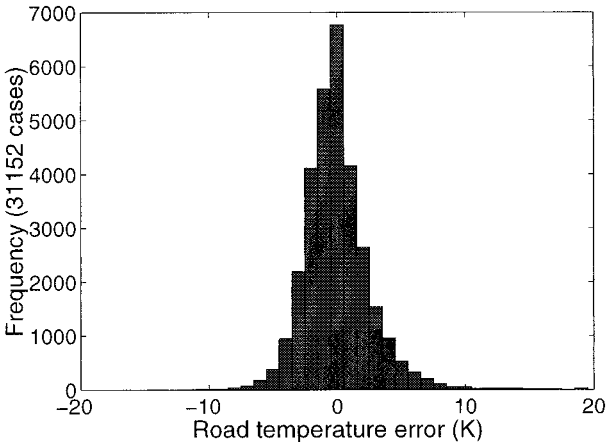

FIG. 2. Frequency distribution of road temperature errors for all three stations in automatic mode sampled every 20 min for the whole duration of forecasts (24 h) for both 0300 and 1500 LT runs.

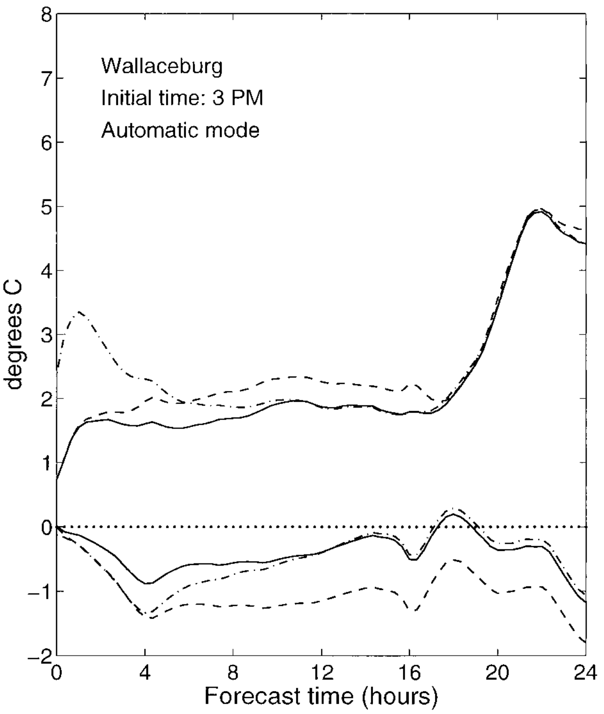

FIG. 3. (bottom) Mean and (top) rms road temperature errors for Wallaceburg in automatic mode. Solid lines are regular forecasts; dashed lines are without error feedback; dash–dotted lines are without coupling.

station at Wallaceburg. Three pairs of curves are presented: regular forecasts with error feedback and coupling, and the same forecasts but either without coupling or without error feedback. The impact of coupling is very well marked at the beginning of the forecast. This is a period of rapid cooling, and the better timing with coupling results in much lower rms errors for the first hours of the forecast. For this station, the impact of error feedback through the term A in (1) is noticeable, reducing the negative bias and keeping the rms error below 2 K from the beginning of the forecast until sunrise on the next day. For the other two stations, the error feedback effect (not shown) is smaller but positive on average. Figure 4 shows the magnitude of the correction term A for the three stations in automatic mode and for Kinburn and Ashton in manual mode. Starting with an arbitrary value of 15 W m^{-2} (the current default value without feedback) at the beginning of the period, A oscillates around this value for Kinburn but tends to increase in time for the other stations. This behavior has yet to be explained. The variations in the value of A are smaller when METRo is run in manual mode.

We present in Fig. 5 the results corresponding to Fig. 3 but for forecasts issued at 0300 LT. Here the rms error is small for the rest of the night but increases rapidly after sunrise and decreases to 2 K in the evening. It is the case that, in all our results, the rms error is always larger during daytime than at night. One plausible cause is that errors in forecasting cloud amounts will have more impact on maximum temperatures (50°C has been observed at Kinburn in late April) than on minimum temperatures, at least for the later part of the season. If we remove April from the statistics, the maximum rms error drops to about 3.5 K. In fact, just removing the five worst days in April (out of 30) achieves the same reduction in rms error. A closer examination of the weather forecasts for these days reveals that the cloud cover was very badly forecast in all of them. Clear days were forecast as overcast and vice versa. We also looked at the impact traffic might have on these statistics. Traffic reduces the difference between road temperature and air temperature; taking this effect into account also reduces the rms error, as will be shown in the next subsection. Figure 5 also shows that, as in Fig. 3 for the 1500 LT forecasts, the error feedback mechanism reduces the mean error for the entire forecast period but reduces the RMS error only during the night. The impact of coupling is still apparent during the first hours, but the reduction in errors is smaller than for the forecasts issued in the afternoon.

All following results will be for forecasts with error feedback and coupling.

b. Manual versus automatic modes

For the two stations in the Ottawa region, we were able to run METRo in manual as well as in automatic mode for the same period. However, the manual intervention of the forecaster was not done for the METRo forecast but for the operational system in use at the time, which centered on the model of Surface System, Inc. (SSI), of Saint Louis, Missouri. It is then possible that the meteorological forecasts were influenced by known biases of the SSI model. We also noticed that the atmospheric forecast file produced by the meteorologist does not contain rainfall rates given that the SSI model

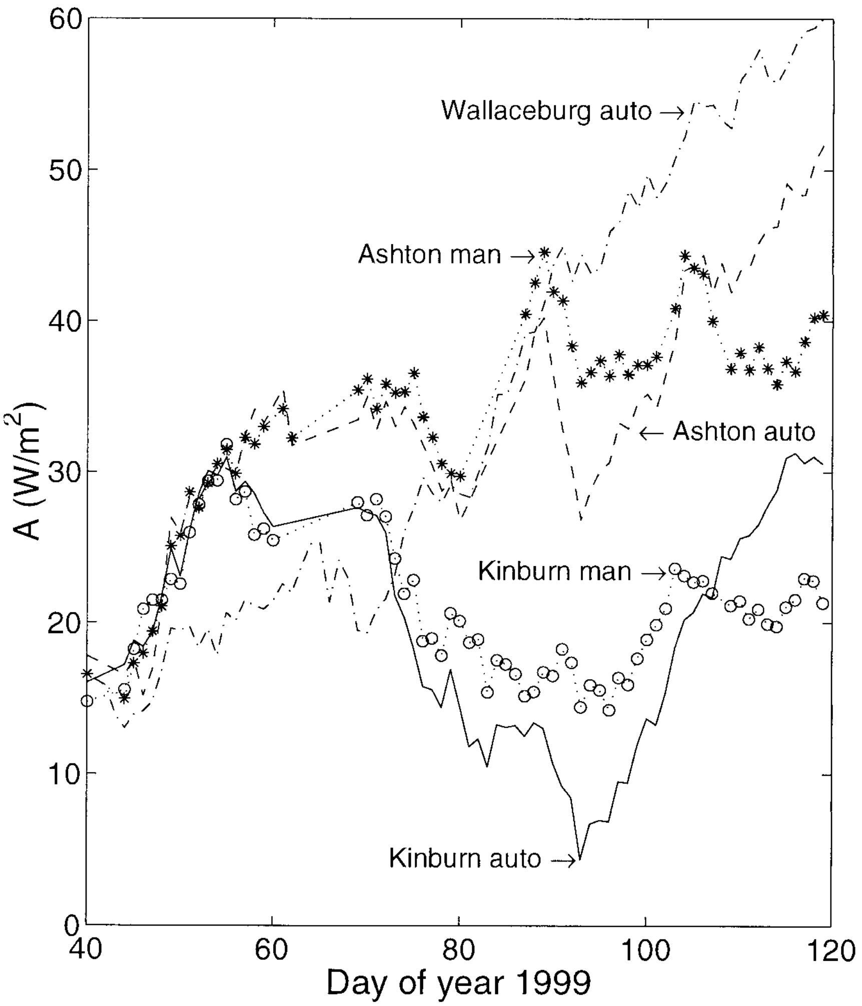

FIG. 4. Evolution of ''anthropogenic'' term A in (1) during the season for both automatic (auto) and manual (man) modes for Kinburn and Ashton, and for automatic mode for Wallaceburg (no manual mode available), starting with a value of 15 W m^{-2} on 9 Feb 1999.

does not use them; snowfall rates, however, are included.

Results of 1500 LT forecasts in both automatic and manual modes show no improvement from the manual mode for Kinburn (Fig. 6), but the meteorologist was able to reduce the negative bias and decrease the rms error during nighttime at Ashton (Fig. 7). The automatic forecast is better for the first few hours, as if the coupling were more effective in automatic mode than in manual mode. The exact cause for this behavior has not yet been investigated.

Figures 6 and 7 also show that the meteorologist introduces or adds a large positive bias during the day, which contributes to an increase in rms error. Discussions with the forecasters and closer analysis of the April forecasts show the same pattern as in Figs. 3 and 5. Large errors in the cloud-cover forecast for the month of April are responsible for a significant part of the bias and rms error. We were also surprised to learn that forecasters tended not to put much effort into the daytime forecast of road temperature unless the minimum temperature was forecast to cross the freezing point, which occurred on only 6 out of 30 days in April at Ashton. A closer examination of the weather forecast inputs shows that less detail is put into the cloud cover; skies are either clear or overcast, with fewer cloudy skies than for other months. Note that at the Ashton bridge the automatic-mode forecast also shows a positive bias during the day. We tested the impact traffic may have by applying a minimum wind speed V_c of 5 m s^{-1} during daytime. The results are shown in Fig. 8 for forecasts issued at 0300 for Ashton. The original midday bias of about 4 K is reduced to only 1 K with a V_c of 5 m s^{-1}. The rms error is also reduced from 6 to 4 K. A good simulation of the traffic can have a large impact on the accuracy of the road temperature forecast.

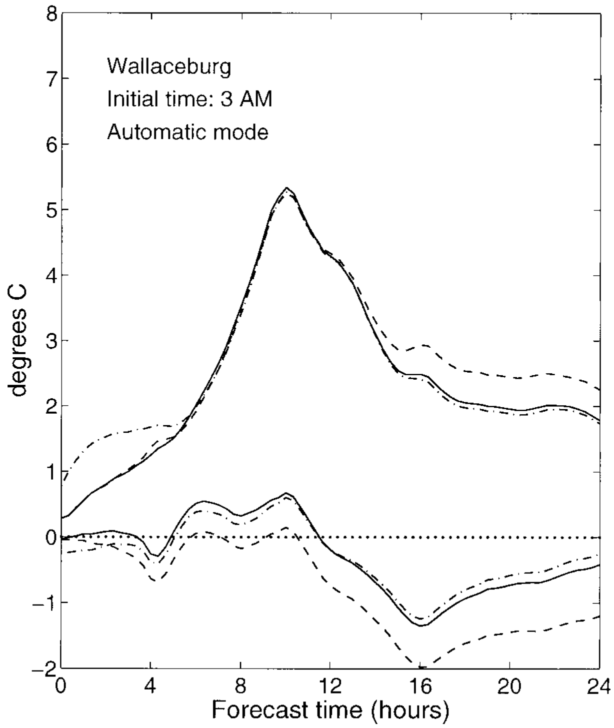

FIG. 5. Same as Fig. 3 but for forecasts issued at 0300 LT.

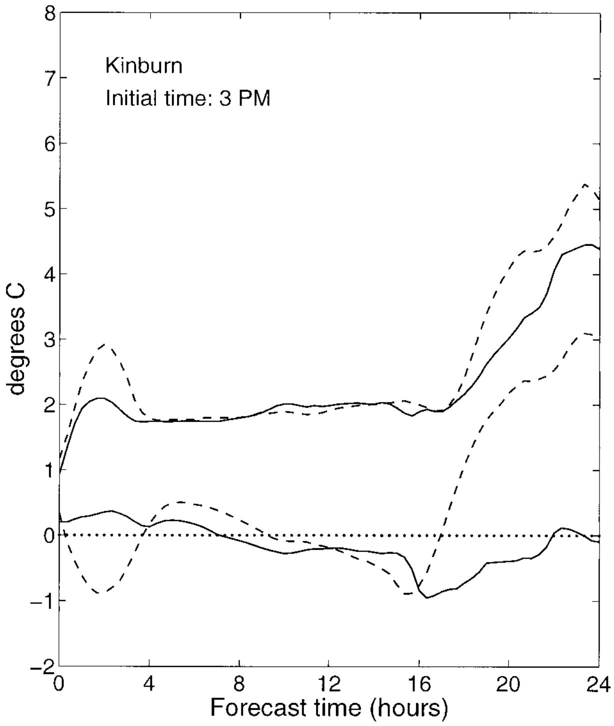

FIG. 6. (bottom) Mean and (top) rms road temperature errors at Kinburn in automatic (solid lines) and manual (broken lines) modes.

c. *Time of freezing or thawing*

Results so far have shown global statistics on road-surface temperature error, but it is clear that errors in some situations have a greater impact than in other situations. One sensitive time is when road temperature crosses the freezing point. Correct timing of such events is particularly useful for road maintenance. We compiled the time of crossing 0°C upward and downward for both forecasts and observations and produced a summary in Figs. 9 and 10. Negative timing error indicates that METRo predicted the crossing too early. The station shown is Kinburn, and the forecasts are issued at 1500 in automatic mode. The frequency of error in the forecast time for the downward crossing is shown in Fig. 9; that for the upward crossing (later in the forecast, usually the next morning) is shown in Fig. 10. The limited number of cases (31 for the descents and 35 for the ascents) is due to the selection criterion for such a compilation, which is that a single descent or a single ascent is found in both the forecast and the observations. Most of the descents (18 out of 31) are concentrated within ±30 min, and 30 out of 35 ascents are between 30 min early and 50 min late. We examined the cases with the largest errors (3 h or more) in Fig. 9. In all cases, the temperature error was small but the temperature decrease during the night was very small for both the forecasts and the observations, leading to a large timing error for crossing the 0°C line.

d. *Model accuracy*

Studies of road-condition models have measured the accuracy of these models in terms of their ability to forecast the minimum road-surface temperature. For each station, the mean bias is −0.23, 0.03, and −0.27 K; the rms errors are 1.51, 1.76, and 1.48 K, respectively, for Kinburn, Ashton, and Wallaceburg in automatic mode. When all three stations are taken together, we obtain a mean bias of −0.15 K and an rms error of 1.65 K. In manual mode, the numbers for Kinburn and Ashton, respectively, become −0.40 and −0.29 K for bias and 1.54 and 1.72 K for rms error. These statistics were calculated using the 1500 LT forecasts. These results are similar to the ones in Thornes (1995) for the Met Office and the Oceanroutes models. That study presented mean biases of −0.48 K for both models and rms errors of 1.52 and 1.48 K for Met Office and Oceanroutes, respectively. The Oceanroutes model is the SSI model that was in use at the Ottawa Regional Centre during our study. We produced the same kind of analysis as in sections 4a–c for the same period and obtained results (not shown) similar to those of METRo. METRo was usually better in the short-term because of coupling with observations, and the two models were roughly equivalent later on. This result plus the minimum temperature analysis leads us to conclude that METRo is as accurate as other models available today.

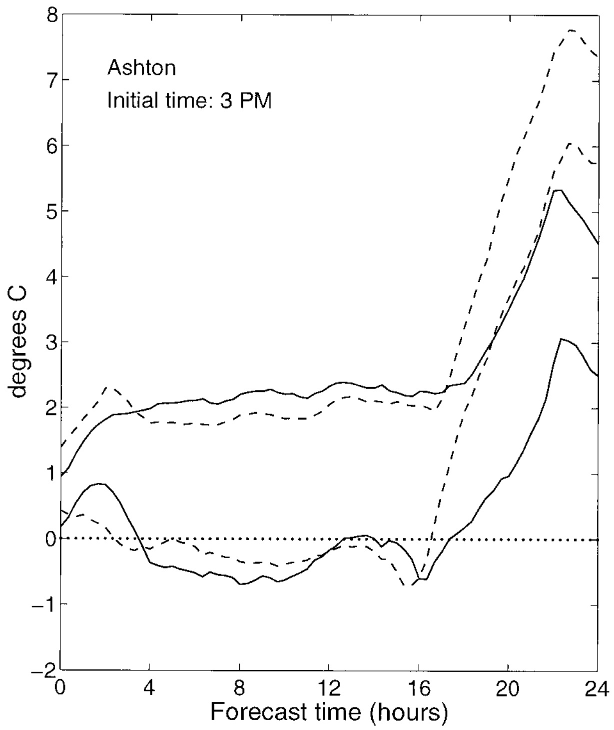

FIG. 7. Same as Fig. 6 but for Ashton.

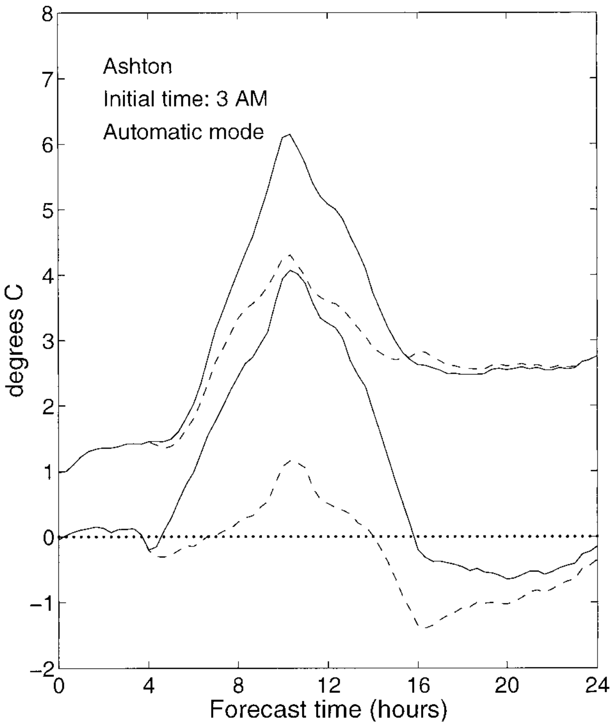

FIG. 8. (bottom) Mean and (top) rms road temperature errors for Ashton in automatic mode with and without a minimum daytime wind speed. Solid line is $V_c = 0$; dashed line is $V_c = 5$ m s^{-1}.

e. Road-condition forecast

The results presented up to now only concern METRo's ability to forecast the road temperature. This output is the fundamental one of the model, because without an accurate forecast of temperature there is no hope of obtaining good pavement-condition forecasts (dry, wet, snowy, icy, frosty, etc.). To produce a good road-surface temperature, METRo has taken into account the effects of precipitation, freezing and thawing of water at the road surface, evaporation, and dew or frost deposition; it is therefore capable of also providing forecasts of several hazardous road conditions.

A classification algorithm based on Norrman (2000) is used to determine the forecast road conditions. Subjective analysis of these outputs shows that this kind of algorithm is very sensitive to small variations in temperature, especially near the freezing point, as is to be expected. Because of the small METRo time step, we encounter an oversampling problem in which we need to give the road condition for 20-min intervals based on 40 30-s intervals. Weights must be introduced in the algorithm to make the most threatening kinds of road condition come out more evidently. Adjustments to the weights will be needed as some condition types occur too often and others are underrepresented even though METRo may have them correctly forecast internally. The outputs of this algorithm are currently under objective evaluation to allow for these modifications to be performed. The difficulty in this evaluation resides in the fact that road maintenance operations, especially salting, greatly affect the observations against which the validation is made, more than with the road temperature. Therefore, in cases for which slippery driving conditions are forecast, maintenance operations affecting the road conditions will occur and will effectively prevent these dangerous road conditions. The forecast will therefore rarely realize itself. This is, in fact, the goal of road-condition forecasting but poses a significant problem in terms of verification. Road-condition models cannot take into account the maintenance operations, because one does not know when the trucks will head out and what actually will be done to the road surface. We were not able to gain access to enough maintenance reports for the winter-1999 trial period to be able to evaluate objectively the accuracy of METRo pavement-condition forecasts. This aspect will be part of further investigations as METRo gets tested in an operational context and these data become available.

With the effect of road maintenance being so critical to the road-condition forecast, it may seem odd that a 24-h forecast is performed operationally. It is useful to note that the 24-h forecast is used differently from a 6-h forecast by maintenance personnel. The short-term forecast is to be more trusted and is used in issuing maintenance orders; the longer-term one is used more as an advance planning tool that is meant to be updated as more information is gathered. METRo does not account for the instantaneous snow removal of maintenance operations, however, it does contain a ''snow run-

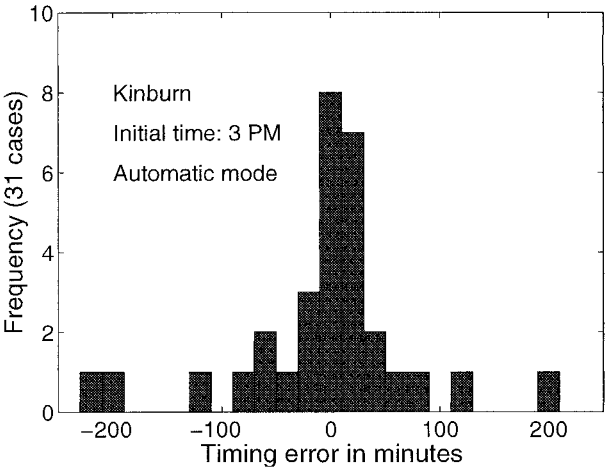

FIG. 9. Frequency distribution of timing error for downward crossing of the 0°C temperature for forecasts issued at 1500 LT for Kinburn in automatic mode.

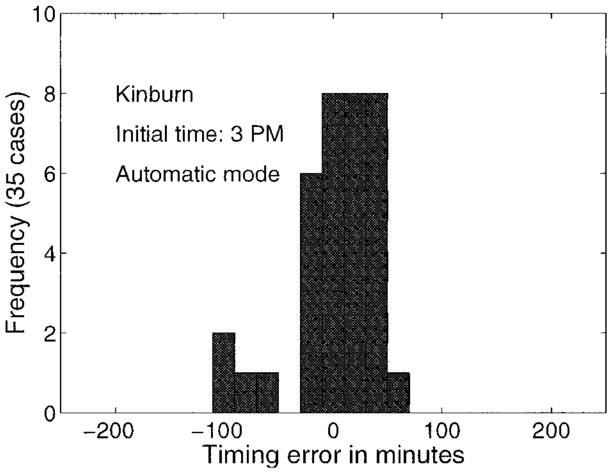

FIG. 10. Same as Fig. 9 but for the upward crossing.

off'' term to simulate crudely the clear-road policy applied to most roads by maintainers. This term effectively reduces any significant amount of snow as soon as it falls. This term is there to allow METRo a more reasonable chance to make a correct long-term forecast. Feedback from maintenance teams tells us that the 24-h forecast is a good planning tool despite this obvious limitation. We must remember that the maintenance crews are the ones making the final decision in this context, and they are aware of when maintenance operations may invalidate the forecast. Note also that a longer-term forecast may allow for a more advanced warning in cases in which the hazardous road conditions only occur later in the forecast period.

Road maintainers must also be aware that these kinds of models produce point forecasts, which implies that the location of the station is crucial to the appropriate use of the forecasts. A station that is placed in a location with unique characteristics will provide data that are specific to that situation. METRo and any other road-condition model will therefore provide forecasts for that station's situation only. In comparison, a station set on the side of a highway in a rural area with minimal shading will be representative of a much longer stretch of road. The associated forecasts will also be useful over a greater area. The METRo version presented here is well suited for open areas. The addition of a shading function to (1) will allow it to adapt better to cities and to mountainous regions for which the situation can change very rapidly over a few hundred meters of road. Nevertheless, maintainers will need another data source [thermal mapping of the road, other (partial) RWIS stations, or simply their own experience of the region] to extend the forecast from the RWIS station to adjacent areas.

5. Conclusions

We have described here the central part of a numerical modeling system that uses meteorological forecasts and RWIS station observations to provide 24-h road-condition forecasts. METRo is not the first model of its kind and incorporates many features also found in earlier models. The version described here does not include explicit shading effects. It is a flexible system that can be run in a completely automatic mode from inputs from the CMC operational regional model (GEM) that covers most of North America or can be run from manual corrections to these forecasts. The meteorological forecast modified by the meteorologist for a given area can be applied automatically to all the RWIS stations within that area, and each METRo forecast will reflect actual roadside observations. Station observations are used to initialize the road temperature profile and to modify the forecast, but METRo will also run when some observations are missing. Elaborate scenarios are provided within METRo to maximize the use of observations; even complete absence of observations will not prevent METRo from producing a forecast if an initial road-surface temperature is provided. Although only road-surface temperature has been analyzed in detail in this paper, METRo provides many other outputs regarding road condition, because it incorporates the physical processes involving water in its various phases. In view of the quality of the automatic forecast, mainly because of the coupling between the GEM forecast and RWIS observations during the coupling phase and because of the integration of METRo with SCRIBE, which permits efficient manual corrections to the forecasts, one can foresee a widespread application of METRo without increasing significantly the workload of the meteorologist. So far, METRo has been tested on only three stations (one of which is on an overpass), but it can be installed at other sites with a minimum of information: essentially, the road material structure and, possibly, shading characteristics. A single term in METRo takes care of local differences in microclimate or in other environmental features. It remains to be verified whether this setup will be adequate for all future sites.

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