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ABSTRACT

Frost on roadways and bridges can present hazardous conditions to motorists, particularly when it occurs in patches or on bridges when adjacent roadways are clear of frost. To minimize materials costs, vehicle corrosion, and negative environmental impacts, frost-suppression chemicals should be applied only when, where, and in the appropriate amounts needed to maintain roadways in a safe condition for motorists. Accurate forecasts of frost onset times, frost intensity, and frost disappearance (e.g., melting or sublimation) are needed to help roadway maintenance personnel decide when, where, and how much frost-suppression chemical to use. A finite-difference algorithm (BridgeT) has been developed that simulates vertical heat transfer in a bridge based on evolving meteorological conditions at its top and bottom as supplied by a weather forecast model. BridgeT simulates bridge temperatures at numerous points within the bridge (including its upper and lower surface) at each time step of the weather forecast model and calculates volume per unit area (i.e., depth) of deposited, melted, or sublimed frost. This model produces forecasts of bridge surface temperature, frost depth, and bridge condition (i.e., dry, wet, icy/snowy). Bridge frost predictions and bridge surface temperature are compared with observed and measured values to assess BridgeT's skill in forecasting bridge frost and associated conditions.

1. Introduction

Frost on roadways and bridges can present hazardous conditions to motorists, especially when it occurs in patches or on bridges when adjacent roadways are clear of frost. The Iowa Department of Transportation (IaDOT) chemically treats roadways and bridges to prevent frost formation to maintain safe driving conditions during the frost season. To minimize negative environmental impacts, vehicle corrosion, and materials costs, frost-suppression chemicals should be applied only when, where, and in the amounts needed to maintain roadways in a safe condition for motorists. Accurate forecasts of frost onset times, frost intensity, and frost disappearance are needed to help roadway maintenance personnel decide when, where, and how much frost-suppression chemicals should be used.

Accurate frost forecasts rely on accurate forecasts of bridge surface temperature and ambient atmospheric conditions (i.e., air temperature, humidity, precipitation, and wind speed). All of these factors, except bridge surface temperature, are routinely calculated by many weather forecast models. Although numerical weather models do not forecast bridge temperature, many models calculate the ambient parameters needed to derive the temperature of a bridge that is being influenced by the predicted weather.

Forecasting frost by weather forecast models presents a particularly difficult challenge for two reasons. Forecasting rare events like frost usually is difficult for forecast models because models frequently cannot resolve the weather scenario with enough detail to determine if the rare event will occur. Forecasting frost is doubly difficult because components of the surface water budget are highly nonlinear, are often binary, and are highly heterogeneous in space. Furthermore, light precipitation, a key factor for frost nonoccurrence, is highly dependent on the particular cloud parameterizations used and may be subject to large errors (Gutowski et al. 2003).

Several roadway and bridge temperature prediction models have been developed in recent years to fulfill

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the need for accurate road or bridge temperature forecasts. Physically based models such as the Roadway Conditions Model (Sass 1992, 1997), the German Weather Service [Deutscher Wetterdienst (DWD)] version-3 model (Jacobs and Raatz 1996), and the Model of the Environment and Temperature of Roads (METRo) (Crevier and Delage 2001) forecast roadway or bridge temperature and conditions based on formulations of heat and vapor transfer between the atmosphere and the road or bridge. Statistical models such as the "HS4Cast" model (Hertl and Schaffar 1998) and the neural network described by Temeyer (2003) use statistics and pattern analysis rather than energy balances to predict road surface conditions.

Our goal was to simulate bridge surface temperature and frost accumulation by using a simple module that could easily be incorporated into most weather forecast programs. Our module ("BridgeT") is a physically based finite-difference program that predicts the surface temperature of a two-lane highway bridge by simulating vertical heat transfer in a bridge in response to evolving weather conditions produced by a forecast model. BridgeT outputs values of the bridge deck temperature, frost depth, and bridge condition (e.g., frosty, icy/snowy, dry).

BridgeT's output and radiation calculations are similar to those of METRo. BridgeT differs from METRo in that the bridge bottom surface temperature is not fixed at the ambient air temperature, but is allowed to be forced by convective and conductive heat transfer. Additionally, BridgeT has been designed to allow the transfer of sensible heat between fallen precipitation and the bridge surface because the bridge surface temperature can be very different from that of fallen precipitation and could have a significant impact on bridge surface temperature. METRo uses Monin–Obukhov similarity for convective parameterization, whereas BridgeT uses modified Reynolds similarity. Reynolds similarity was chosen to represent convective transfer because it is applicable to the length scales of bridge surface boundary layers. BridgeT currently has no ability to simulate roadways.

2. BridgeT description

BridgeT simulates bridge surface temperatures by numerical (finite difference) solution of the one-dimensional heat diffusion equation

$$\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) = \rho_b c_b \frac{\partial T}{\partial t}. \qquad (1)$$

Here T is the temperature of the node, k is the thermal conductivity of the bridge, ρ_b is bridge density, and c_b is the specific heat of the bridge material. Temperatures are calculated at 20 nodes positioned vertically from top to bottom of the bridge deck. BridgeT calculates heat fluxes resulting from natural and forced convection on the upper and lower surfaces, conduction through the bridge deck, long- and shortwave radiation, and latent heat processes resulting from phase changes of water on the top of the bridge deck. A vapor flux calculation uses the bridge surface temperature and concurrent meteorological variables from a weather forecast model to produce forecasts of the incremental volume per unit area (i.e., depth) of frost deposited, melted, or sublimed and the pavement condition. Thermophysical properties of the bridge can be altered by the user to adapt BridgeT to different bridge characteristics. Initial temperatures are calculated using recent Road Weather Information System (RWIS) Environmental Surface Station (ESS) bridge surface temperature data. Output of BridgeT includes the bridge deck temperature, frost depth, and bridge condition (e.g., frosty, icy/snowy, dry).

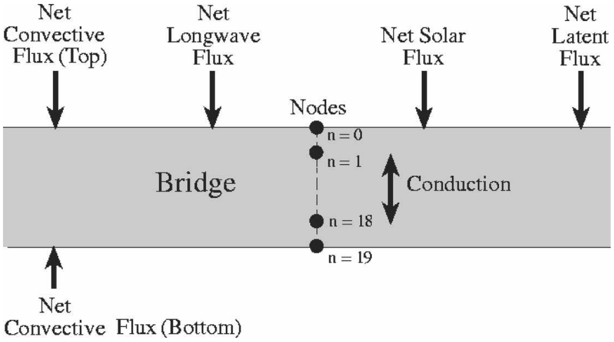

FIG. 1. BridgeT fluxes and node assignment. The surface node (n = 0) experiences conduction, convection, latent heating, and radiation. Interior nodes experience only conduction. The bottom node (n = 19) experiences conduction and convection. Net fluxes into the slab are considered positive.

a. Surface energy balance

Incoming fluxes at the top surface (Fig. 1) include radiative and latent heat fluxes and convection. The bottom node experiences convection, but not latent heat or radiation because it is assumed that the bottom will stay dry, be shielded from the sun, and be in approximate longwave radiative equilibrium with the surfaces directly under the bridge.

1) CONVECTION

The convective flux (q_{conv}) is defined as

$$q_{\text{conv}} = h(T_a - T_s) \qquad (2)$$

(see, e.g., Stull 1988), where h is the surface convective heat transfer coefficient (W m^{-2} K^{-1}), T_a is the temperature of the free-stream ambient air, and T_s is the bridge surface temperature; h is dependent on the velocity and temperature boundary layers in the air. In BridgeT, the coefficient h is the assumed average value over the entire length of the bridge. The convection calculations use Reynolds similarity, which assumes that the wind column affected by the bridge is vertically uniform before encountering the bridge and that the air is incompressible. Reynolds similarity is used to describe boundary layers over flat surfaces whose characteristic length L satisfies

$$1\ \mathrm{m} \le L \le 500\ \mathrm{m}. \tag{3}$$

In BridgeT, L was assumed to be 10 m, roughly the width of a two-lane bridge. Vertical velocity is assumed to be independent of bridge position, and the change in velocity with height above the bridge is assumed to be greater than changes along the bridge surface. The thermal gradient normal to the bridge surface is much greater than the gradient parallel to the surface, and heat generation resulting from viscous dissipation can be ignored. For simplicity, the wind was assumed to flow perpendicular to the direction of the bridge centerline. Flux calculations contain only coarse representations of the effects of bridge railings and surface slope. Figure 2 illustrates convective boundary layer development over the bridge and the coordinate system for convective parameterization.

The surface convective heat transfer coefficient h at the surface of the bridge is of the functional form

$$h = \frac{k_f}{L}\overline{\mathrm{Nu}} = \frac{k_f}{L} f(\mathrm{Pr}, \mathrm{Re}, \mathrm{Gr}), \tag{4}$$

where k_f is the conductivity of the ambient air. The Nusselt number ($\overline{\mathrm{Nu}}$) is the bridge deck average dimensionless vertical temperature gradient (Greenfield 2004). The Reynolds number (Re), a dimensionless coefficient describing the ratio of inertial to viscous forces, is proportional to the speed of the wind above the boundary layer formed by the bridge in the flow. It is defined as

$$\mathrm{Re} = \frac{VL}{\nu}, \tag{5}$$

where V is the velocity of the undisturbed air and ν is the kinematic viscosity of air. The Prandtl number (Pr) is a dimensionless ratio of the momentum and thermal diffusivities of air and is set to 0.71. The Grashof number (Gr) is the ratio of the buoyant forces to the viscous forces of the flow and is defined as

$$\mathrm{Gr} = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}, \tag{6}$$

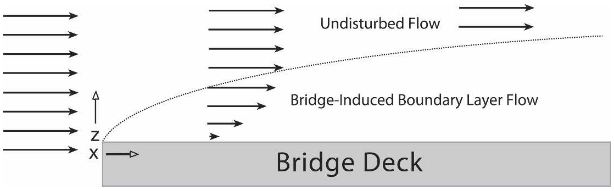

FIG. 2. Bridge-induced boundary layer and coordinates used in convective parameterization.

where g is gravitational acceleration, β is the expansion coefficient, T_s is the surface temperature, and T_∞ is the temperature of the undisturbed air.

From Incropera and DeWitt (2002), $\overline{\mathrm{Nu}}$ is composed of a contribution of the forced flow (wind) plus or minus a contribution from the natural flow (buoyancy forces):

$$\overline{\mathrm{Nu}}^3 = \overline{\mathrm{Nu}_{\mathrm{forced}}}^3 \pm \overline{\mathrm{Nu}_{\mathrm{nat}}}^3. \tag{7}$$

Natural convection suppresses mixing when the temperature profile is stable, and enhances mixing when the temperature profile is unstable.

The dimensionless temperature gradient is calculated as if the flow over the entire bridge surface is turbulent using an experimentally derived relationship between the Reynolds number and the Prandtl number (Incropera and DeWitt 2002),

$$\overline{\mathrm{Nu}_{\mathrm{forced}}} = A(0.037)(\mathrm{Re})^{0.8}(\mathrm{Pr})^{(1/3)}. \tag{8}$$

Here A is the convective multiplier that represents the effects of surface roughness, existing turbulence in airflow, and other flow complications resulting from the bridge structure (e.g., railings, medians, and surface slope). The value of A was set to 1.5 for this study.

Here $\overline{\mathrm{Nu}_{\mathrm{nat}}}$ is calculated using Gr and Pr and varies for stable or unstable temperature gradients as

$$\text{unstable: } \overline{\mathrm{Nu}_{\mathrm{nat}}} = 0.15[(\mathrm{Gr})(\mathrm{Pr})]^{(1/3)} \quad \text{and} \tag{9}$$

$$\text{stable: } \overline{\mathrm{Nu}_{\mathrm{nat}}} = 0.27(\mathrm{Gr})(\mathrm{Pr}). \tag{10}$$

2) PRECIPITATION AND VAPOR TRANSFER

BridgeT incorporates latent heat effects of water on the bridge and calculates total frost depth by distinguishing between water phases and calculating water fluxes toward or away from the bridge. The maximum amount of water substance that accumulates on the bridge is truncated to a depth of 0.0011 m of liquid water and 0.000 63 m (~0.25 in.) of snow accumulation. Excess precipitation is assumed to be removed by runoff or plowing. These limitations will help keep unreasonably high amounts of latent heat from influencing the bridge.

The vapor flux toward the bridge (i.e., the condensation/evaporation rate) is positive for condensation or frost deposition and negative for evaporation or sublimation. It is calculated by using the heat–mass transfer analogy that estimates the mass transfer coefficient using the convective heat transfer coefficient. BridgeT distinguishes between frozen and liquid precipitation by the temperature of the air. Precipitation is allowed to freeze, thaw, and evaporate from the bridge. The instantaneous equilibrium temperature between accumulated water and the top bridge node is calculated in all scenarios where precipitation accumulates on the bridge to allow heat fluxes between water substance and bridge.

Frost is allowed to accumulate when no precipitation or condensation exists on the bridge. If other precipitation or condensation is present on the bridge during deposition processes, the heat and mass transfers are calculated as usual, but the reported bridge condition will not be changed from any other hazard condition to "frost." Frost depth per unit area is calculated by dividing the newly accumulated frost mass by its density (assumed to be 0.1 times the density of water) and adding the result to the previous total. If frost or snow is assumed to be present on the bridge, the solar absorptivity is decreased by a factor proportional to the depth of the ice to account for gradual albedo increases through the development of frost or light snow accumulation.

3) RADIATION

Radiation heat fluxes are determined using surface incident short- and longwave radiation supplied directly by the forecast model. Longwave radiation lost from the bridge is computed by using the Stefan–Boltzmann relationship. Longwave radiation lost from the bridge and radiation reflected by the bridge are subtracted from the total incident radiation to find the net radiative flux toward the bridge.

b. *Node temperature calculation*

The equations for the nodes have been derived from the energy balance equation,

$$\text{Energy}_{\text{in}} - \text{Energy}_{\text{out}} = \Delta\text{Energy}_{\text{stored}}, \tag{11}$$

or specifically,

$$q_{\text{conv}} + q_{\text{rad}} + q_{\text{lat}} + q_{\text{cond}} = \Delta q_{\text{stored}}, \tag{12}$$

where q is the energy received by a bridge node by the processes of convection, radiation, latent heat, or conduction. By expanding for a node on the bridge–air interface using the definitions of q_{conv} and q_{cond}, we obtain

$$\left[h(T_a - T) + q'_{\text{rad}} + q'_{\text{lat}} + k\frac{\partial T}{\partial x}\right]\text{Area} = \left(\rho_b c_b \frac{\text{Volume}}{2}\right)\frac{\partial T}{\partial t}. \tag{13}$$

The Volume/2 on the right-hand side is because of the fact that the volume of bridge material represented by the upper and lower surface nodes are half of the volume represented by interior nodes. Here T is the temperature of the node, and T_a is the temperature of the free-stream air. Node temperatures are found by using the explicit finite-difference form of Eq. (13) (Greenfield 2004). Initial node temperatures are determined by running BridgeT with RWIS ESS observations of surface temperature, air temperature, and wind speed for a 2-day spinup period prior to the beginning of the model period (Greenfield 2004). The initialization period of 2 days was found to be sufficient to establish a temperature distribution independent of its initial state.

3. Analysis

a. *Input*

Experiments were conducted with two different forecast model systems supplying input to BridgeT. The fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5), version 3.4, run at Iowa State University, has been used as input for the BridgeT program during the months from November 2003 to March 2004. MM5 forecasts were issued twice daily, valid at 1200 and 0000 UTC.

The Road Weather Forecast System (RWFS) was designed by NCAR for use with a winter road maintenance decision support system. RWFS is designed to maximize forecast accuracy by blending output from several numerical weather models (i.e., Eta Model, Aviation Model, Nested Grid Model) with surface observations and statistical regressions (Bernstein et al. 2004). It produces 48-h forecasts 8 times daily (0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC). These model runs were available for the months of February and March and for 1–8 April 2003.

We evaluated errors specifically resulting from BridgeT (i.e., as distinct from errors in BridgeT output arising from errors in the weather forecast model input to BridgeT) by running BridgeT with observations of radiation, temperature, humidity, precipitation, and wind speed. Observations of surface incident longwave and solar radiation were taken during the days of 9 July and 11 through 19 July 2002. The radiation observations were taken over a soybean field southwest of Ames, Iowa, 19 km from the Ames RWIS ESS station. These observations were combined with SchoolNet precipitation observations (Iowa Environmental Mesonet 2004) and RWIS ESS humidity, wind, and 2-m air temperature measurements to drive the BridgeT model.

b. *Observation datasets*

Observations used for comparison with BridgeT model results included RWIS bridge temperature observations taken from the U.S. Interstate Highway 35 overpass over 13th Street on the east side of Ames, as well as early morning bridge frost and bridge temperature observations conducted by human observers on several overpasses in the Ames area. These overpasses were specifically chosen because they are not chemically pretreated to prevent frost formation.

Frost occurrence was observed for the 2001–02, 2002–03, and 2003–04 frost seasons on several local bridges (Greenfield et al. 2004). The distances from the ESS site to the observed bridges are approximately 8–11 km. Frost observations could not be conducted near the ESS bridge sensor site because the bridge was chemically pretreated to prevent frost formation and for safety reasons. The observer visited the bridges beginning at 0500 LST and observed frost conditions both from the vehicle and close-up on foot. While on the bridge on foot, the observers carefully examined the surface for frost and measured the temperature of the bridge surface with an infrared thermometer. The time and date and observations of bridge conditions, general weather conditions, frost characteristics, and surface temperature for each bridge were recorded. If frost was detected, the observer would return periodically until the frost dissipated for follow-up observations and measurements.

It is expected that this method of frost observation is very accurate. However, there may be situations (e.g., when frost is very light) in which frost is present but not visually detected by the observer. These situations would lead to an increased false-alarm rate because some actual frost events may be recorded as no-frost events.

c. *Validation methods*

1) FROST

Verification of frost prediction used the first 24 h of the forecast run. RWFS forecasts were updated 8 times per day, and MM5 forecasts were updated 2 times per day. For this reason, it was possible to use many separate forecasts to predict frost for a specific observed frost event. To remove performance dependency on the frequency of newly issued runs, frost forecasts were analyzed according to whether that forecast would elicit a response to treat the bridge from the IaDOT roadway maintenance personnel. The assumed response for a frost forecast is chemical pretreatment to prevent the formation of frost on bridges. If no frost event was forecast, bridges would not be pretreated. Pretreatment was assumed to be made only once per day, so multiple forecasts predicting frost for a particular morning are assumed to elicit only one treatment. If a subsequent run reverses a falsely forecast frost event, the assumed pretreatment cannot be undone, so that frost forecast is still counted as a false alarm. A frost forecast/response was considered a success if frost was calculated to occur during a time period when frost was seen on any one of the observed bridges. A frost forecast was considered a "miss" when no frost was forecast and no treatment was assumed to occur, but frost was observed on any of the bridges. A frost forecast is considered a "partial hit" if frost was forecast to occur in a run within 12 h of an observed frost event, but the previous runs did not forecast frost. A forecast like this has less (but still some) value because it would require the IaDOT to pretreat bridges at late hours and possibly within short time frames. Events lasting less than 0.5 h are considered "short events," which are counted as being either partial hits or partial false alarms. These predictions are separated because they often do not have sufficient time to form deep frost or to be observed.

Conventional measures of forecast skill for binary events include the false-alarm rate (FAR), probability of detection (POD), miss rate (MISS), rate at which the model will correctly reject the possibility of frost (CR), and threat score (TS) (Greenfield 2004). The average absolute error and bias of the predicted frost start and end time were compiled for each frost event. Because of the method of observation, 0500 LST was always the observed "start" time, although frost was usually present on the bridge by this time.

2) TEMPERATURE

Forecast bridge temperatures were analyzed by comparing RWIS observations with the BridgeT forecasts valid only at the time of the RWIS observation. Statistics [e.g., bias, root-mean-square error (rmse)] are computed for each model run. Individual model runs were averaged to produce a summary measure of the model's overall performance.

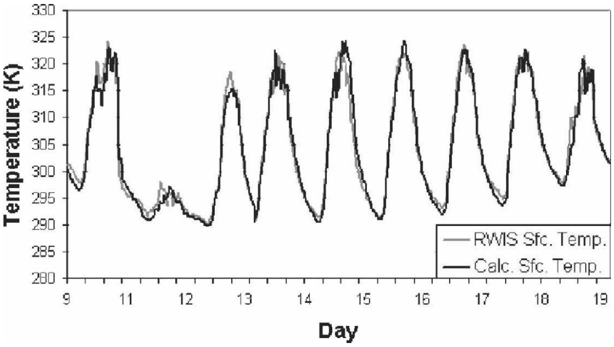

FIG. 3. Observed (RWIS) and calculated bridge surface temperature for a 10-day period in July 2002.

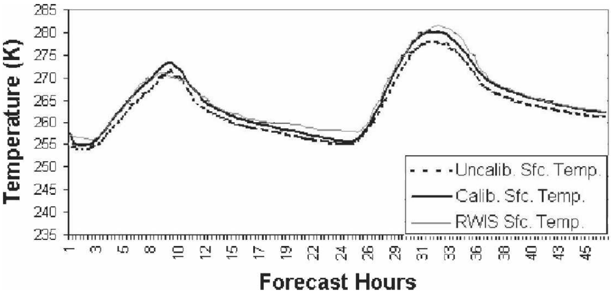

FIG. 4. The RWFS BridgeT results before and after calibration compared with the observed bridge temperature. Uncalibrated rmse was 2.28 K, and calibrated rmse was 1.17 K.

4. Results

a. BridgeT validation

The objective of BridgeT is to produce an accurate value of the bridge deck temperature. In operational applications, BridgeT obtains its input from a weather forecast model, which has its own error characteristics. To evaluate errors produced by BridgeT alone we used weather observations taken near an RWIS site as input for BridgeT. Radiation observations were taken from a site located about 19 km from the RWIS site, so errors resulting from spatial separation are included in BridgeT's calculations.

For the observing period from 9 July and 11 through 19 July 2002, BridgeT surface temperatures (at approximately 25-min intervals) were on average 0.20 K cooler than the RWIS ESS temperatures, with an rmse of 1.90 K (Fig. 3).

Errors frequently occurred during the peak daytime temperature range when the temperature is highly influenced by solar radiation. Small clouds episodically block a portion of the solar radiation from the RWIS bridge surface and radiometers at different times and for different durations because of the physical separation of the two observing sites. Daytime differences occasionally exceeded 5 K, with a peak difference of 7.75 K. The morning and evening temperature errors were typically small, thereby providing a measure of confidence in the ability of BridgeT to give accurate temperatures for times of the diurnal period when frost is likely.

b. Calibration and validation of coupled models

1) RWFS INPUT

Four hundred fifty-five 48-h RWFS model runs (new run every 3 h) were used to drive BridgeT valid for the period from 3 February 2003 through 8 April 2003 for the Ames RWIS ESS. The RWFS BridgeT produced forecasts that were cold biased, which were evident especially through recurring errors in nighttime cooling rates. BridgeT was recalibrated for use with this particular model to account for systematic biases in the model input. Corrections to the wind speed and longwave radiation yielded the most accurate calculations.

Wind speed errors from the first 100 RWFS runs were used to calculate the wind speed correction to be used with RWFS runs. During the first 100 RWFS runs, the wind speed was on average 1.37 m s^{-1} higher than observed at the RWIS ESS. The RWFS BridgeT forecasts improved when that bias was subtracted from all RWFS runs before convection calculations were performed, thus decreasing the convective fluxes. The longwave radiation values of the first 100 runs and all of the following runs were increased by a factor of 1.16 to help to counterbalance the steep nighttime cooling rates. Figure 4 shows a specific forecast before and after calibration.

Statistical analysis of the 48-h forecasts of the RWFS BridgeT model runs in comparison with the Ames RWIS observations showed that the average bias and average rmse of uncalibrated RWFS BridgeT bridge temperatures for 48-h forecasts for the entire period were 2.03 and 3.20 K, respectively. After calibration, the RWFS BridgeT cold bias was 0.09 K with an rmse of 2.64 K.

The average error of the first 24 h of the calibrated RWFS BridgeT runs was 0.03 K and the rmse was 2.45 K. There were 122 forecast runs out of 455 in which the calibrated calculation of bridge temperature was actually less accurate when compared with its uncalibrated forecast. The average errors in the first 24 h were smaller than the average errors in the entire 48 h, and the errors were reported to be less than 2 K over 60% of the time.

Bridge frost was observed twice during this period. RWFS BridgeT correctly forecast both events. When the forecast period was taken as the first 24 h of each run, RWFS BridgeT correctly forecast the only two observed frost events but predicted three false alarms for this period. There were two mornings on which brief frost was predicted to occur 1 h after observations were concluded. Table 1 contains the frost performance indices for the RWFS BridgeT runs. There were no partial hits. RWFS BridgeT correctly predicted 86% of the frost and no-frost mornings. Its high false-alarm and prediction rates correspond to RWFS BridgeT's cold bias in early morning bridge temperature. The RWFS BridgeT average frost start time for those two events was 2 h and 10 min earlier than the first observation. Its end times were on average 30 min different from the observations, but had zero bias.

2) MM5 INPUT

One hundred ninety-eight 48-h MM5 forecasts were used as input for BridgeT during the 2003–04 frost season from 11 November 2003 through 31 March 2004. Uncalibrated MM5 BridgeT surface temperature forecasts were on average 1.02 K too cool during this period, and its rmse was 2.73 K. The cold bias and rmse improved with calibration for longwave radiation, similar to the longwave calibration used with RWFS. Best results were obtained when longwave radiation was increased by a factor of 1.13. Wind speed calibration was performed by subtracting the wind speed bias (0.96 m s^{-1}) of the first 50 runs from the wind speed before convection calculations were made. After calibration, the surface temperature bias was reduced to 0.16 K too warm < and the rmse was reduced to 2.64 K. Sixty-nine of the 198 MM5 BridgeT forecast runs were actually less accurate after calibration. Figure 5 shows a specific MM5 BridgeT forecast before and after calibration.

Analysis of the first 24 h of the runs showed that the MM5 BridgeT was on average 0.13 K too warm and had an rmse of 2.40 K. Sixty percent of the 24-h MM5 BridgeT surface temperature calculations possessed errors of less than 2 K.

Frost observations were made on 68 mornings during the winter of 2003–04. Frost was positively observed on five mornings. Because MM5 forecasts were available only twice a day, the 1200 UTC run must correctly predict frost occurrence because it determines the frost treatment for that workday. The 0000 UTC run can only cause a partial hit because it is issued after the typical workday is concluded and will not influence treatment schedules, except for emergency late-night treatment for the upcoming morning. Thus, overall model effectiveness is largely determined by the quality of the 1200 UTC run.

TABLE 1. RWFS BridgeT frost performance during February and March 2003.

	FAR	POD	MISS	CR	POFD	TS
RWFS BridgeT	0.60	1.00	0.00	0.86	0.14	0.40

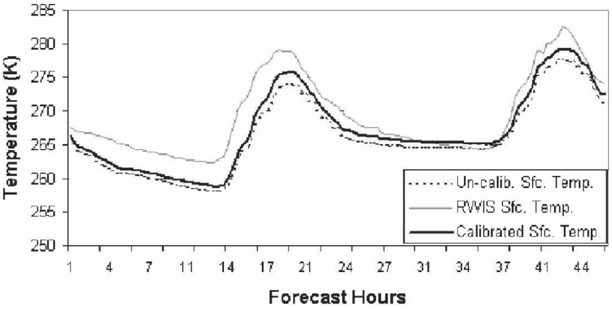

FIG. 5. The MM5 BridgeT results before and after calibration compared with the observed bridge temperature. Uncalibrated rmse was 3.67 K, and calibrated rmse was 2.82 K.

The MM5 BridgeT frost prediction performance was reasonable, but had a tendency for false alarms and partial hits. There were six false alarms, although one of which was a very short event, lasting less than 10 min. Only one of five frost events was predicted 24 h in advance because of missing forecasts and precipitation predictions during frost times in preceding forecasts. One frost event was not forecast at all because of the prediction of precipitation during that morning from all associated model forecasts. When light precipitation (less than 0.1 mm h^{-1}) was excluded in BridgeT, all frost events without missing model runs were predicted 24 h in advance. However, false alarms increased dramatically (20 false alarms). Table 2 shows the performance for standard (light precipitation allowed) and calibrated (light precipitation excluded) BridgeT settings. Despite a poorer prediction rate with BridgeT's standard settings (i.e., light precipitation allowed), predictions of precipitation instead of frost may still cause some response (albeit for precipitation, not for frost) from the IaDOT.

MM5 BridgeT predicted frost onset an average 3.9 h before observations began. Average frost demise was calculated to occur 23 min before observations ended.

c. *Sensitivity to forecast quality and bridge property specification*

Input data quality is crucial for accurate surface temperature calculations. Accurate forecasts of bridge condition (e.g., dry, wet, frosty) require not only accurate input for the calculation of bridge surface temperature, but also accurate meteorological conditions, such as humidity and precipitation. Humidity forecasts are diffi-

TABLE 2. MM5 BridgeT frost prediction performance during winter 2003–04. The "standard" setting includes light precipitation. The "− Precip." setting excludes precipitation of less than 0.1 mm h^{-1} from BridgeT calculations. A short event is a predicted frost event lasting less than 10 min. A partial hit is a correct prediction of frost that was issued less than 24 h in advance.

Setting	Events included	FAR	POD	MISS	CR	POFD	TS
− Precip.	No short events	0.79	1.00	0.00	0.69	0.31	0.21
− Precip.	Short events	0.80	1.00	0.00	0.67	0.33	0.20
Standard	No partial hits, no short events	0.83	0.20	0.80	0.92	0.08	0.10
Standard	Partial hits and short events	0.60	0.80	0.20	0.90	0.10	0.36
Standard	Partial hits, no short events	0.56	0.80	0.20	0.92	0.08	0.40

cult for models to accurately produce and verification is difficult because of sensor accuracy or representativeness (Takle and Greenfield 2002).

Differences in bridge properties can be expected because of design differences, use of bridge materials having a range of thermal and radiative properties, and variations resulting from differences in age, wear, and mixture composition. The bridge properties needed by BridgeT include solar absorptivity, longwave absorptivity, bridge thickness, density, specific heat, and thermal conductivity. From the range of plausible values, we found that the model performed best when we used the bridge properties listed in Table 3.

In principle, these properties may be specified for each individual bridge in a forecast region. It is important to note the impact these specifications have when varied within their usual ranges to investigate the possible effects of the incorrect assignment of bridge characteristics, or how different bridges will react under identical weather conditions. Our sensitivity studies revealed that surface temperature calculations are particularly sensitive to the possible variations of solar reflectivity and thermal conductivity and are least sensitive to differences in longwave absorptivity and bridge thickness.

5. Summary

BridgeT was designed to help forecasters to produce accurate forecasts of bridge frost and conditions. BridgeT is a numerical model for heat transfer in a concrete bridge that takes atmospheric values from a weather forecast model and calculates bridge surface temperature, frost depth, and bridge conditions. It accounts for heat fluxes resulting from solar and longwave radiation, conduction through the bridge, convection on the top and bottom surfaces, and latent heat effects through explicit forward-difference numerical methods.

TABLE 3. Bridge properties used by BridgeT for this study.

Bridge property	Value
Bridge thickness	0.21 m
Thermal conductivity	1.401 W m^{-1} K
Solar absorptivity	0.74
Longwave absorptivity	0.88
Density	2300 Kg^{-1} m^3
Thermal diffusivity	6.922×10^{-7} m^2 s^{-1}
Specific heat	880 J Kg^{-1} K

Comparisons of its results with measured surface temperatures from an RWIS station have demonstrated that BridgeT realistically represents early morning low temperatures and temperature trends when run with input from observations of air temperature, wind speed, and radiation. Some of the error can be attributed to the spatial separation (19 km) of the bridge temperature observation site and the radiation observation site.

BridgeT is capable of supplying surface temperatures within 1 K of the measured values over a 40-h forecast period if it is supplied with accurate weather forecasts. RWFS BridgeT has shown reasonable skill in surface temperature and frost prediction, although the nighttime cooling rate is typically too steep. RWFS BridgeT tends to overpredict frost, but also has a high probability of predicting all frost events. These traits are consistent with the steep nighttime temperature trends associated with RWFS BridgeT. MM5 BridgeT has shown slightly better skill in bridge temperature prediction; although calibration improved overall performance, calibration was not as effective at improving the forecast as was true for RWFS BridgeT. Frost predictions were prone to false alarms and partial hits, largely because of humidity and precipitation errors from MM5.

We believe that the main source of the nighttime cold bias was because of the weather forecast models and not BridgeT. We suspect the weather forecast models had a tendency to underestimate downward longwave radiation, but we could not verify this because no longwave radiation observations were available with which to analyze the available MM5 or RWFS longwave calculations. Other possible sources of the nighttime cold bias is misrepresentation of the longwave flux at the bridge bottom and improperly assigned bridge properties. Future analysis is needed to isolate the source(s) of the nighttime cold bias.

Future improvements to BridgeT may include fine-tuning and testing its pavement condition forecasts, expanding BridgeT for roadway use, and incorporating treatment recommendations for predicted pavement conditions. Because BridgeT cannot improve upon the quality of its input, it remains vulnerable to failure through input errors. Improvements in mesoscale forecast quality, especially humidity and radiation accuracy, are necessary for significant improvements to BridgeT frost and surface temperature forecasts.

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