OSU LSM	0 UTC	12 UTC
Bias (°F)	5.76	1.47
Average error (°F)	6.32	5.29
Standard dev (°F)	5.72	6.53
Max error (°F)	20.44	12.94
Min error (°F)	-3.80	-10.48

Table 4: 0 and 12 UTC surface temperature errors with the OSULSM .

by five to ten degrees. The 12 UTC has a much smaller warm bias and its average error is about a degree less than the 0 UTC run (Table 4). It is interesting to note that the 12 UTC run overestimated the temperature by at least five degrees whenever frost was present. At no other time did this run overestimate the surface temperature by so many degrees. The MM5's surface temperature performance with the OSULSM is statistically worse when compared to the runs with the old LSM. The average error and standard deviation for each run increased. The 12 UTC bias improved by 1.15 degrees (Table 5).

New – Old difference	0 UTC	12 UTC
Bias (°F)	1.25	-1.15
Average error (°F)	5.85	0.70
Standard dev. (°F)	0.53	1.32
Max error (°F)	6.12	0.77
Min error (°F)	3.77	-0.53

Table 5: Difference between runs with OSULSM (New) and the original LSM (Old) surface temperature performance. Values are in degrees Fahrenheit

b. Determining surface temperature inconsistency

The MM5 assumes a combined ground-vegetation surface when it calculates surface temperature because at the 20 km resolution, that is the best approximation of the land surface for the Ames area. Thus the MM5 outputs the surface temperature for a ground-vegetation surface. The frost model is assuming a pavement temperature for its calculations, as it had received through RWIS in the past. Now, however, the MM5 is supplying the frost model with a temperature for a different surface instead.

MM5 skin temperature predictions were compared with RWIS observations collected from the southbound I-35 overpass just East of Ames, within the fine resolution used by the MM5. The RWIS observations studied were from 01 September, 2001 to 06 November, 2001. Both RWIS and MM5 surface temperatures were compared with the corresponding air temperature observations to explore how each surface type correlates to atmospheric changes.

Pavement temperatures tend to get very warm during the day from solar heating, which can keep the concrete well above air temperature for many hours. During the period from 01 September, 2001 to 24 October, 2001, the RWIS pavement temperature averaged 9.4 degrees warmer than the air temperature, and could reach over twenty degrees warmer than the air temperature. Fig. 1A illustrates the general differences between observed air temperature and RWIS surface temperature for the period studied. For hourly resolution, a one-day illustration of these trends is shown in Fig. 2A.

The most important difference between the pavement surface and the MM5 surface is the different heating patterns. There is evidence of this through the comparison of the changes in the two different surface temperatures with changes air temperature. The different surfaces began heating at approximately the same time; however, the bridge surface heats much faster. When the two surface temperatures peak, the RWIS surface tends to be much warmer than the MM5 surface. The MM5 surface temperatures that were studied never got more than ten degrees warmer than the forecasted air temperature, and on average were two degrees cooler than the MM5 air temperature. Fig. 3A shows the differences in temperatures between the MM5 surface, RWIS surface and the two-meter air temperature. Fig. 4A is the same comparison as in Fig. 3A, but over a time span of 125 hours. For the period of Fig. 4A, the RWIS pavement temperature averaged 10.8 degrees warmer than the MM5 surface temperature.

3. Conclusions

Model errors are expected, and the users of this frost model should be aware of what the errors can do to the frost forecast. The errors will affect the rate of deposition as well as the timing of frost development or dissipation.

There are three critical conditions for frost to develop. For frost to form on a roadway, the pavement temperature must be below freezing, the dewpoint and air temperature must be above pavement temperature, and for significant accumulation the dewpoint must be near freezing or well above the pavement temperature for a extended period of time. (Takle 1990). Especially for these critical conditions, a few degrees of model error can mean the difference between forecasting frost or not. If the dewpoint was erroneously calculated a degree colder than the pavement when it was in fact above the pavement temperature, the model might result in a false zero frost forecast for that time. For each run, the average dewpoint error was greater than 2.5 degrees, which is enough to alter the frost forecast when dewpoint temperature and pavement temperature are very close.

Windspeed, air temperature, dewpoint temperature, and pavement temperature all affect the rate of deposition. According to Knollhoff (2001), the governing equation to determine the frost accumulation rate, R(t) can be found by:

$$R(t) = (\frac{1}{\rho_f})e * (\frac{1}{R_d}) * C_e(D\frac{U}{T_a}) \ , \qquad (1)$$

where U is the windspeed in m s^{-1} and T_a is the air temperature in Kelvin. D is the difference between the exponential functions of the saturation vapor pressures for the dewpoint and pavement temperatures (Appendix B). The equation for D is:

$$D = e_s(T_o)\{\exp(\frac{L_d}{R_v}(\frac{1}{T_f} - \frac{1}{T_d})) - \exp(\frac{L_d}{R_v}(\frac{1}{T_f} - \frac{1}{T_p}))\} \ , \qquad (2)$$

where T_f is the freezing temperature, T_d is the dewpoint temperature, and T_p is the pavement temperature (Appendix B). In Eq. (2), the larger the difference between the pavement and dewpoint temperature, the greater the rate of deposition or dissipation.

The 0 UTC run had a warm bias in dewpoint. Such a bias suggests the frost model may more frequently overestimate the rate of frost accumulation, because in Eq. (2), a larger dewpoint increases the value of *D*, which in turn increases the rate of deposition, *R(t)*. By the same equation, when the bridge and dewpoint temperature are near freezing, one degree in error effects *D* by nearly a factor of two. The 0 UTC run also has a fast bias in its windspeed that may also increase the predicted rate of accumulation. The 12 UTC run is different from the 0 UTC run, but its biases also work toward increasing the rate of deposition. It has a small negative bias in its dewpoint, but a large negative bias in its temperature. Temperature is inversely related to *R(t)*, so a smaller temperature will increase the rate of deposition. This run also has a fast bias in windspeed, which may frequently inflate the value of *R(t)*. MM5's overall performance with air temperature, dewpoint temperature and windspeed would overestimate the rate of frost accumulation.

One of the most critical variables for frost development is pavement temperature. Frost will only form when the pavement temperature is below freezing; when pavement temperature is above freezing, existing frost will melt. Because of this, predicting when frost can develop or dissipate depends largely on knowing when the pavement reaches the freezing point. The pavement must also be colder than the dewpoint temperature for frost to form, so calculating accurate pavement temperatures becomes even more important for a good frost forecast. There are significant differences between the MM5 and RWIS surface temperatures. The RWIS temperatures were over 10 degrees warmer than the MM5 surface temperatures during the period studied, due to differences in heating and cooling. In the morning hours, the two surface temperatures get closer after nighttime cooling, but still adhere to their own unique cooling rates. If the MM5 surface temperature is used in place of pavement temperature the timing of frost onset or disappearance will be off because of different cooling or heating behavior. Due to the accuracy required for a reliable frost forecast, it is necessary to invent a new method to predict pavement temperatures.

A program can be designed to calculate the temperature of the bridge surface based on the thermal properties of the bridge and its interaction with environmental conditions. The surface temperature of concrete can be found by using a set of equations as found in a Road Surface Model written by Shao and Lister (1996). With the help of the MM5, we can use modifications of these equations to find pavement temperature. The MM5 calculates much of the information needed for the road surface model in its usual calculations. We can adjust these equations for use on a bridge, and calculate them through time using the parameters forecasted by the MM5.

The heat conduction equation is:

$$C_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\kappa \frac{\partial T}{\partial z}), \qquad (3)$$

where C_m is the heat capacity, and κ is the conductivity of the concrete. T is the temperature at time t and depth z. Typical values for C_m are usually between 840 to 1 170 J K Kg^{-1} for a concrete bridge. κ depends on the composition of the concrete, and ranges from 1.4 to 3.6 J $(m^2 s)^{-1}$ K m^{-1} (Neville, 1996, 374-378). This equation must be modified for a bridge surface rather than for pavement on solid ground. For our purposes, z can only go down the thickness of the bridge, and there are two surfaces that experience heat changes; the top and the underside of the bridge. The top of the bridge will experience heating by the sun, heating and cooling by the surrounding air, and most of the latent heat effects. The underside will receive negligible solar heating and latent heat effects, but will be effected by changes in air temperature. The upper boundary condition can be expressed by the energy balance equation

$$\begin{aligned}(1-\alpha_s)S + L'(T_s) + H(T_s) \\ + LE(T_s) + G(T_s) = 0,\end{aligned} \qquad (4)$$

where S is the solar irradiance, α_s is the surface albedo, L' is the net longwave irradiance, H and LE are the sensible and latent heat flux densities, G is the ground conductive heat flux density and T_s is the pavement surface temperature (Shao and Lister, 1996). The lower boundary condition can be found by the same method, or approximated to the ambient air temperature. Since the MM5 calculates values similar to these in its own calculation, it will be able to provide the necessary variables to the pavement model. The pavement model will use the appropriate modifications of Eqs. (3) and (4) for the physical aspects of the bridge using albedo, heat capacity, heat conductivity, and emissivity of a bridge. After the pavement temperatures have been calculated, they can be used by the frost model. The frost model would receive air temperature, dewpoint temperature, and windspeed straight from MM5, but the surface temperature it accepts would be from the pavement surface model.

4. Discussion

Since the ISU MM5 has only been running since August of 2001, it was not possible to study this model under winter conditions. This fall was also unusually warm for this region, so much of the data set that was studied was for more mild conditions than the average Iowa autumn. This study assumes that the MM5's biases and other characteristics will hold throughout the winter months, when it will be used for frost forecasts. The ISU MM5 may need to be periodically checked to ensure that its performance does not vary with seasonal changes.

Furthermore, the only archived RWIS observations available for this study were for this fall. The physical properties of the bridge don't change with the seasons, but it is likely that its diurnal heating patterns do change. Though a small data set was used, the surface temperature comparisons used in this paper were designed simply to show that significant differences between surface temperatures may plague the frost model. The pavement temperature model suggested above should give a better approximation of real pavement temperature independently of the season.

This study was performed early in the year, before the MM5 had made any winter forecasts. This winter, the frost model's performance will be studied, so it is important that possible problems solely within its input are found and fixed before much of the frost season has passed.

5. Summary

This paper addressed model error and surface temperature differences between RWIS observations and MM5 forecasts. The MM5 forecasted values are being used as input in a model that calculates the depth of frost on pavement. Model runs were analyzed against observations to find biases and errors. In early November the Oregon State Land Surface Model was adopted as the ISU MM5's surface physics model. Model performance was slightly improved for the three-week period after the switch. Observations for skin temperatures were too far apart to evaluate model cooling or heating rates or diurnal trends; however, the observations were able to test the model value at a certain point in time. The surface temperature performance worsened after the installation of the OSULSM.

The frost model calculates the depth of frost using the forecasted MM5 air temperature, dewpoint temperature, windspeed and surface temperature. The model outputs the total depth of frost for one-minute intervals through the end of the MM5 forecast time. Errors and biases for the MM5 forecasts were found to be sufficient to misrepresent the timing of frost, as well as the rate of deposition or dissipation. All significant MM5 model biases may lead towards overestimation of frost deposition rates.

The MM5 does not calculate the surface temperature of a bridge, but that is what the frost model was designed to receive. As of now, there is no correction for the difference. A study was performed that compared RWIS bridge surface temperature with MM5 surface temperature.

The differences between the MM5 surface temperature and RWIS pavement surface temperature were considerable. The temperature range experienced by the RWIS observations were typically much warmer than MM5 predictions. Furthermore they experienced different heating and cooling rates, thus different timing on their respective peak and minimum temperatures. These differences are very important to the timing and the thresholds of the development of frost. In order to increase the accuracy of the frost prediction model, a new method of calculating pavement surface temperature should be developed. Using energy balance and heat conduction equations modified for a bridge pavement surface, it will be possible to develop a model that will forecast pavement temperature from MM5 input. After the new surface temperatures are calculated, the frost model can be employed using the MM5 air temperatures, dewpoint temperatures, and windspeed, but with surface temperatures from the pavement model.

Acknowledgments. Special thanks to mentors Daryl Herzmann, David Flory, and Dr. Takle, to Caleb Huitt for the use of his computer, and to all who reviewed this paper.

REFERENCES

Chen, F. and J. Dudhia, 2001: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129,** 569-585.

Knollhoff, D. S., 2001: Analysis and interpretation of roadway weather data for winter highway maintenance. M. S. thesis, Dept. of Meteorology, Iowa State University, 74 pp.

Neville, A. M., 1996: *Properties of Concrete*. John Wiley & Sons, Inc., 844 pp.

Shao, J., and P.J. Lister, 1996: An automated nowcasting model of road surface temperature and state for winter road maintenance. *J. Appl. Meteor.*, **35,** 1352-1361.

Takle, E. S., 1990: Bridge and roadway frost: occurrence and prediction by use of an expert system. *J. Appl. Meteor*., **29,** 727-734.