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ANALYSIS OF PAVEMENT RADIATION LOADING THROUGH PAVEMENT TEMPERATURE

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1. INTRODUCTION

Pavement temperature forecasts are a critical component in the performance of pavement condition modeling and are most often driven from the solution of the conservation of mass, energy, and momentum. The fluxes of radiation, sensible heat, latent heat, and ground heat comprise the surface energy balance with the sensible, latent, and ground heat fluxes considered responses to net radiation forcing (Arya 2001). Of pertinent importance to pavement temperature prediction is the response in pavement temperature to diurnal cycles and variations of radiative flux. An analysis of pavement radiation loading investigates the relationship between radiative energy and pavement temperature.

The presence of cloud layers in particular are responsible for large variations in the net radiation received by the surface and introduce challenges to pavement temperature prediction. Cloud contribution to the surface energy balance is complicated in it being both an energy source for longwave radiation emission received at the surface while obstructing and altering the solar radiation received by the surface during daylight hours (Sass 1992). This study presents an analysis of the effect of variations in cloud cover on pavement temperature by employing a pavement temperature model to control and simulate atmospheric and surface conditions.

By assuming pavement temperature model output realistically resolves pavement temperature; the sensitivity of modeled pavement temperature to net radiation is used to characterize pavement radiation loading. Magnitudes and time characteristics of forecast radiation error are provided from net radiometer validation of radiation forecasts from numerical weather prediction output. Pavement temperature model sensitivity to various types of forecast radiation error is used to assess the ability of pavement temperature forecasting when employing forecast radiation values. This analysis illustrates how the performance of pavement temperature prediction is critically reliant on the resolved accuracy of the net radiation flux at the surface.

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2. BACKGROUND

Heat and fluid flow that dictate pavement temperature are governed by the conservation of mass, momentum, and energy (Jordan 1991). The conservation of energy for a finite volume is subject to mass flux, conduction, and radiative flux components. The surface energy balance at the air interface is subject to the fluxes of sensible heat, latent heat, ground heat, and net radiation (Jordan 1991, Arya 2001). The capability to predict pavement temperature is inherent on the approach in determining these fluxes most accurately (Sass 1992). The diurnal cycle of the surface energy budget illustrates the dependence of the direction of the fluxes of sensible and latent heat on the diurnal cycle of net radiation. The net radiation is considered an external force on the surface energy budget with the sensible, latent, and ground heat fluxes considered responsive to net radiation (Arya 2001). Net radiation is determined through the sum of the net shortwave and net longwave radiation fluxes, each calculated by subtracting the outgoing component from the incident at the surface component. The net radiation for a pavement surface is dependent on the albedo and emissivity of the pavement. The albedo determines the proportion of shortwave radiation being reflected by the pavement and the emissivity and surface temperature dictate the amount of the energy emitted by the pavement as stated by the Stefan-Boltzmann law.

Pavement temperature models are supplied with atmospheric, surface, and subsurface data used to solve the energy flux equations to determine the temperature of the pavement being studied. SNTHERM-RT is a one-dimensional mass and energy balance model derived from the surface temperature model SNTHERM.89, which forecasts temperature profiles within snow and soil layers, developed by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (Jordan 1991). The model produces a solution by vertically subdividing layers into horizontal homogeneous control volumes, and solving each of these layers for the equations of mass and energy balance. The mass balance equations of SNTHERM.89 do not feature the mass balance considerations necessary for pavement condition modeling, thus the solution of pavement temperatures through SNTHERM-RT is driven through the solution of the energy balance.

SNTHERM-RT obtains its pavement temperature solution for a given time step through the estimation of the top boundary fluxes and solving the mass and energy balance equations of each layer through a tridiagonal-matrix algorithm (Jordan 1991). The top node surface energy equation takes the sum of the net radiation, turbulent fluxes of sensible and latent heat, and any additional heat from rain or falling snow. The rate of change in stored heat for a given layer takes the energy contributions from water flow, diffusive vapor flux, conduction, and radiative flux (Jordan 1991). Net longwave radiation extinction is assumed to be in the top node only, and solar energy contribution is calculated for the top node and interior nodes. The bulk extinction coefficient for longwave radiation is input to the model while the bulk extinction coefficient for shortwave radiation is defined as the asymptotic bulk extinction coefficient (Jordan 1991).

3. APPROACH

This pavement radiation loading analysis utilizes atmospheric and surface observations and numerical weather prediction model incident shortwave and longwave radiation output. The Road Weather Field Research Facility of the University of North Dakota (UND) Surface Transportation Weather Research Center provides the net shortwave and longwave radiation, two-meter temperature and relative humidity, two-meter wind speed and precipitation data required by the SNTHERM-RT pavement temperature model. Pavement radiation loading is defined as the response behavior of pavement temperature from changes in net radiation. Particular attention is paid to the influence of clouds on pavement temperature and the effect of errors in forecast incident shortwave and longwave radiation on the resulting pavement temperature.

Pavement temperature response to changes in net radiation is first identified via pavement temperature observations provided through the Lufft Intelligent Pavement Temperature Sensor installed in the asphalt road surface at the Road Weather Field Research Facility. A Kipp & Zonen CNR1 Net Radiometer is installed overhead the pavement temperature sensor to correlate changes in pavement temperature in time to changes in net radiation in time. The fluxes of sensible, latent, and ground heat can also be monitored indirectly through the temperature, wind, relative humidity, and subsurface temperature sensors installed at the Road Weather Field Research Facility. With consideration to the responsive fluxes, case study analyses are identified from events where changes in net radiation may have contributed to a response in pavement temperature. Cloud forcing events are identified in time periods where the net longwave radiation approaches zero Watts per meter-squared and negligible or minimal cloud forcing events are identified by a substantial net longwave radiation surface deficit.

Pavement temperature model sensitivity to radiation forecast errors can be simulated through the introduction or removal of cloud forcing in the radiation data used by SNTHERM-RT. By illustrating the difference in pavement temperature from cloud or non-cloud atmospheres, an assessment of the magnitude of pavement temperature error from radiation forecast errors of incorrectly-forecasted cloud forcing is made. The case study pavement temperature model analyses demonstrate the effect of an incorrect radiation forecast on the resulting pavement temperature by altering the net radiation flux and analyzing the difference in pavement temperature and subsurface temperature.

An ongoing analysis of the magnitude of error from radiation forecasts generated from numerical weather prediction output is performed through validation by the net radiometer. Time series and statistical analysis of these errors provide observations on the expected accuracy of radiation forecasts generated from numerical weather prediction model output. The error observations offer additional insight into the pavement radiation loading analyses relative to the expected accuracy of pavement temperature forecast from forecast radiation errors. Further investigation into the certainty of pavement temperature forecasts is performed through analysis of the magnitude of error in net radiation and pavement temperature from one-hour and three-hour forecast radiation time steps. Through the validation of radiation forecasts and subsequent pavement radiation loading analysis, conclusions on the certainty of pavement temperature forecasts are made.

4. DATA & DISCUSSION

A preliminary pavement radiation loading analysis is shown for the case study of March 26, 2006, in Figures 1 through 4. Figure 1 illustrates hourly unaltered net radiation components as observed and calculated. The incident shortwave and longwave radiation observations were provided from the Kipp & Zonen net radiometer at the UND Road Weather Field Research Facility. The reflected shortwave radiation was calculated for the asphalt pavement surface with an albedo of 0.10. The emitted longwave radiation was calculated with the asphalt pavement surface emissivity of 0.94 and with the generated pavement temperature values from SNTHERM-RT. The pavement temperature model was initialized with seven days of atmospheric observations before the case study date of March 26, and the two-meter temperature, relative humidity, wind speed and precipitation data were from hourly observations at the Road Weather Field Research Facility.

As illustrated in Figure 1, the net longwave radiation from 00 UTC through 06 UTC on March 26, 2006, indicate a cloud presence with the net longwave radiation approaching zero Watts per meter-squared. An additional cloud influence is seen at 09 UTC where the deficit approaches zero for one hour. The deficits during the daylight hours in combination with the incident shortwave radiation profile indicate minimal cloud presence during the daylight hours.

Figures 2 and 3 show altered net radiation component profiles investigating radiation forecast error. Figure 2 represents an incorrectly-forecasted cloudless atmosphere and Figure 3 represents an incorrectly-forecasted cloudy atmosphere. The net radiation environment of Figure 2 investigates the removal of cloud influence from 00 UTC through 10 UTC, and the net radiation environment of Figure 3 introduces cloud influence from 13 UTC through 23 UTC. Cloud influence was removed in Figure 2 by altering the incident longwave radiation value for each of the hours from 00 UTC through 10 UTC to an average incident longwave radiation value from when the sky was considered to have cloudless influence. The added cloud influence in the environment in Figure 3 restricted the incident shortwave radiation received by the surface while receiving greater magnitudes of incident longwave radiation.

The cloud influence of Figure 3 was present on March 25, 2006, where clouds were observed throughout the daylight hours. The incident and reflected shortwave radiation values of March 25 were used to represent altered shortwave radiation on March 26. The two-meter air and pavement temperatures throughout March 26, 2006 were higher than the day prior so incident longwave radiation values were calculated instead of taken from March 25. The incident longwave radiation was calculated by first using the hourly air temperature and the Stefan-Boltzmann law for a first-guess hourly incident longwave radiation value. SNTHERM-RT then produced pavement temperatures from the first-guess incident longwave radiation values. A correction to the incident longwave radiation was then performed by using the hourly pavement temperature and the Stefan-Boltzmann law with the asphalt emissivity of 0.94. SNTHERM-RT was then run again with the corrected longwave radiation values resulting in a net longwave radiation flux that was approximately zero Watts per meter-squared throughout the period of cloud influence. Additional approaches to restricting net shortwave radiation and increasing incident longwave radiation will be necessary in increasing the confidence in this pavement radiation loading error analysis.

Figure 4 shows the pavement temperatures as determined by SNTHERM-RT for each of the three net radiation environments. When the cloud influence is removed during the overnight hours of March 26, a higher rate of pavement temperature change with respect to time initially occurs, causing pavement temperatures to fall below freezing before the unaltered, clouded overnight environment. The pavement temperatures of the cloudless environment were cooler throughout the entire period of adjustment where temperatures approached the unaltered temperatures in the following two hours.

The cloud influence introduced to the environment on March 26 resulted in pavement temperatures colder than the unaltered environment with the maximum time of pavement temperature difference also occurring during the hour of maximum incident shortwave radiation. The clouded environment forces the pavement temperature to have a lower rate of change with respect to time than the unaltered, cloudless atmosphere promotes. Generally, the results of Figure 4 indicate what would be expected as the two altered environments were each altered to reduce net radiation values.

5. CONCLUDING REMARKS

The performance of pavement radiation loading analysis remains inherent on the approach and techniques used to isolate and study the effect of the radiative flux on pavement temperature. Though pavement temperature models provide an approach to studying pavement radiation loading, the limitations of the input of accurate future atmospheric variables must be considered when considering the capabilities of these pavement temperature models. Case study analyses and consideration of the characteristics of radiation forecast error provide the framework to assess the predictability of pavement temperature. Ultimately the predictability of pavement temperature remains inherent on the quality of resolution of net radiation at the pavement location being studied.

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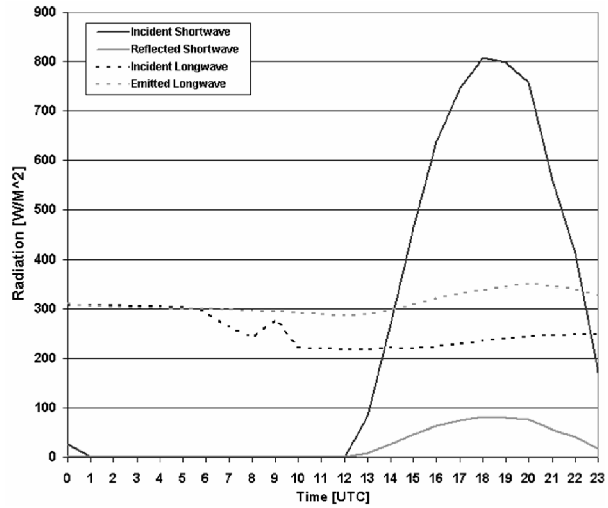

Figure 1. Series 1: Unaltered Net Radiation components from March 26, 2006. Incident shortwave (solid-black line) and incident longwave radiation (dashed-black line) from net radiometer, reflected shortwave (solid-grey line) and emitted longwave (dashed-grey line) calculated with 0.10 albedo and 0.94 emissivity, respectively.

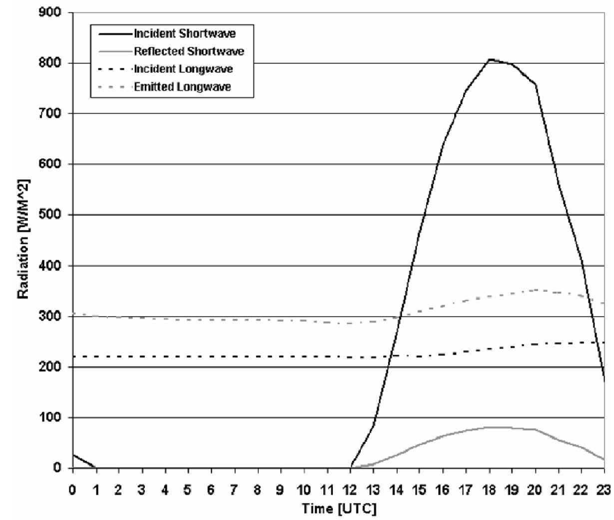

Figure 2. Series 2: Altered incident longwave radiation from 00 UTC through 10 UTC March 26, 2006. Incident shortwave (solid-black line) and incident longwave radiation (dashed-black line) from net radiometer, reflected shortwave (solid-grey line) and emitted longwave (dashed-grey line) calculated with 0.10 albedo and 0.94 emissivity, respectively.

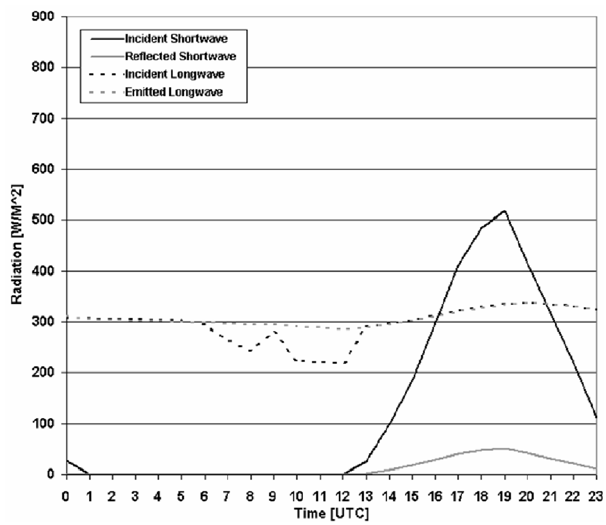

Figure 3. Series 3: Altered incident shortwave and longwave radiation from 13 UTC through 23 UTC March 26, 2006. Incident shortwave (solid-black line) and incident longwave radiation (dashed-black line) from net radiometer, reflected shortwave (solid-grey line) and emitted longwave (dashed-grey line) calculated with 0.10 albedo and 0.94 emissivity, respectively.

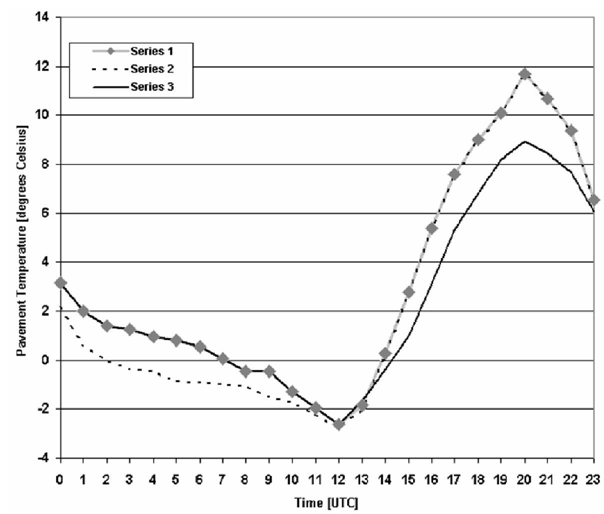

Figure 4. Pavement Temperatures from SNTHERM-RT for Series 1 unaltered net radiation (grey-diamond band), Series 2 altered overnight longwave radiation (dashed-black line), and Series 3 altered daylight hours incident shortwave and longwave radiation (solid-black line).