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INDIANA DEPARTMENT OF TRANSPORTATION
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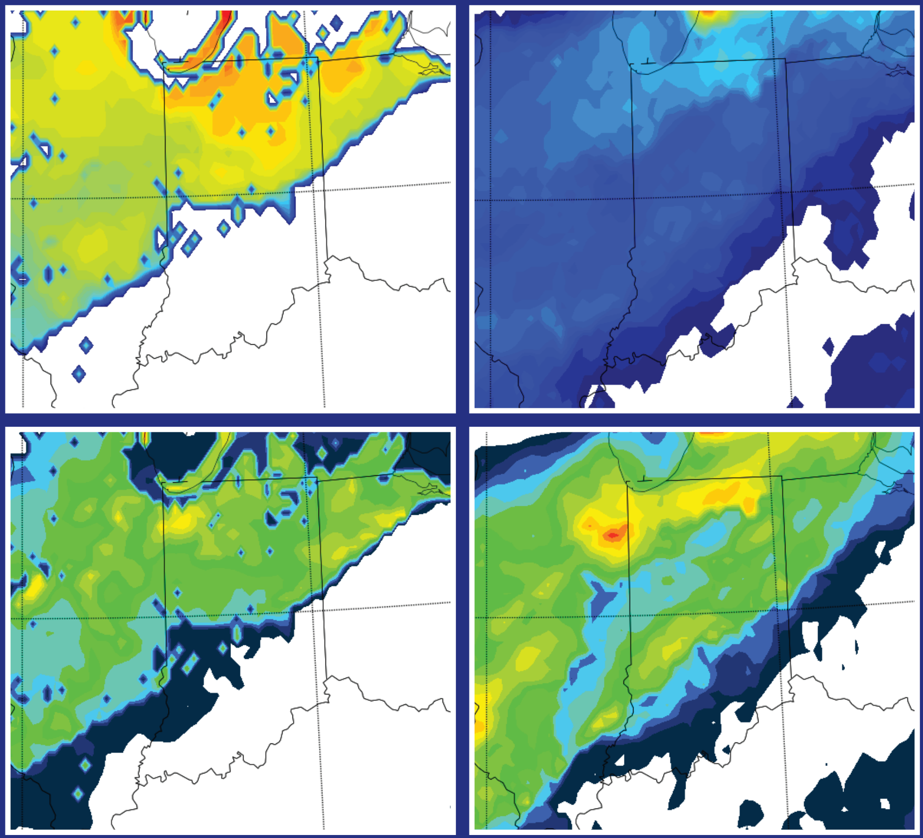
Road Weather Severity Based on Environmental Energy



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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract

Effective and efficient removal of snow and ice from public roadways is a key outcome for winter road maintenance operations. This outcome depends on the severity of the wintry weather as well as the quality and quantity of resources used to treat the roadways. Wintry weather conditions vary substantially from hour-to-hour, storm-to-storm, and season-to-season. Many different transportation departments have used empirical statistical models and machine learning methods based upon weather parameters to develop indices to estimate the severity of winter weather. Many of these previous studies used summary statistics, such as the number of days with certain events (snowfall, freezing rain, frost), to provide a seasonal index of winter severity. While summarizing the winter severity for the entire season is quite useful, providing information over shorter time periods will allow for more precise evaluation of maintenance performance during a winter season. A winter weather severity index has been developed that can be used to evaluate the performance of winter weather maintenance. This project involves the development of a physically-based analysis of winter severity, using estimates of the hourly rate of deposition of new snow/ice and the energy required melt it. The “Road Weather Severity Based on Environmental Energy” (RWSBEE) index can be considered an accumulation of energy, beyond that which is available from the environment, needed to melt snow/ice that has been deposited on the road surface on an hourly basis. The energy not provided by the environment that would be required to melt new snow can be thought of as a measure of the work required to remove the new snow from the road surface. We expect that RWSBEE will provide a clearer understanding of the severity of the weather, allowing INDOT to better evaluate their performance, assist with after-action review of recent storms, and improve the reaction to future weather events. Measurable improvements in the winter maintenance decision-making process are expected as a result.

Winter weather conditions that occur across different regions vary substantially from hour-to-hour, storm-to-storm, and season-to-season. The methods of road maintenance for fighting snow and ice can also vary between different maintenance units. It is important for organizations that perform road maintenance to be able to quantify the severity of the winter weather conditions, for purposes of monitoring, planning, and evaluating their performance. The Indiana Department of Transportation (INDOT) currently uses estimates of winter weather hours to quantify the severity of winter weather. The definition of a “weather hour” is fairly straightforward: any hour when wintry precipitation (snow, ice pellets, freezing rain) is falling with air temperatures below 35 °F. While this definition is reasonable, it does not take into account numerous factors that can strongly affect road conditions and subsequent efforts needed for road treatment, such as: precipitation rate, wind speed, and availability of sunshine. Consequently, INDOT has determined that the information provided by the weather hour estimates result in wide variations in roadway treatment expenses across Indiana. In order to more accurately and effectively evaluate the performance of winter maintenance, it is important to have detailed data related to winter weather conditions that provide useful information regarding the impact of winter weather on road conditions. State-of-the-art weather information can provide a clearer understanding of the severity of the weather, allowing INDOT to better evaluate their performance, assist with after-action review of recent storms, and improve the reaction to future weather events.

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EXECUTIVE SUMMARY

ROAD WEATHER SEVERITY BASED ON ENVIRONMENTAL ENERGY

Introduction

Winter weather conditions that occur across different regions vary substantially from hour to hour, storm to storm, and season to season. The methods of road maintenance for fighting snow and ice can also vary between different maintenance units. It is important for organizations that perform road maintenance to be able to quantify the severity of the winter weather conditions for the purposes of monitoring, planning, and evaluating their performance.

The Indiana Department of Transportation (INDOT) currently uses estimates of winter weather hours to quantify the severity of winter weather. The definition of *weather hour* is fairly straightforward: any hour when wintry precipitation (snow, ice pellets, freezing rain) is falling with air temperatures below 35°F. While this definition is reasonable, it does not take into account numerous factors that can strongly affect road conditions and subsequent efforts needed for road treatment, such as precipitation rate, wind speed, and availability of sunshine. Consequently, INDOT has determined that the information provided by the weather hour estimates results in wide variations in roadway treatment expenses across Indiana.

To more accurately and effectively evaluate the performance of winter maintenance, it is important to have detailed data related to winter weather conditions that provide useful information regarding the impact of winter weather on road conditions. State-of-the-art weather information can provide a clearer understanding of the severity of the weather, allowing INDOT to better evaluate its performance, assist with after-action review of recent storms, and improve its reaction to future weather events.

Findings

- Energy is required to remove snow and ice from road surfaces. This energy could be in the form of mechanical energy to plow snowfall off the surface or spread salt across the roadway. Energy could also be in the form of heat from the sun, air, or road surface that is transferred to the snow and ice by a variety of physical processes. Each of these sources of energy have different degrees of economic costs associated with them, some of which are quite difficult to estimate, while energy from the environment is available at no cost. The Road Weather Severity Based on Environmental Energy (RWSBEE) index is based upon the idea that winter severity can be derived by finding the additional energy required to melt snow and ice that has been deposited on the surface beyond the energy that is freely available from the environment. This additional energy can be considered an amount of work that is required to maintain the road surfaces.
- The amount of energy needed to raise the temperature of the mass of new snow or ice that has fallen (or has been deposited by blowing snow) onto a square meter of road surface during the past hour to the melting point, and then change the phase of that snow or ice from solid to liquid, can be computed. This will be a positive number, larger for greater values of snowfall and also for colder surface temperatures. The amount of energy available from the environment to warm the surface can also be computed. This will be either a positive or a negative value, depending on whether the environmental conditions are acting to warm or to cool the surface. Calculating the difference between these two energy values yields the additional energy required to melt the snow and ice that has accumulated on the road surface over the past hour. This energy value can be thought of as the additional work necessary to remove this new snow or ice from the roadway and is the defined in this work as the Road Weather Severity Based on Environmental Energy (RWSBEE) index, expressed in units of MJ/m^2.
- Examining the normalized change in the difference in cost between each area versus the statewide average value, nearly half of the areas moved closer to the state average when viewed in terms of costs per lane mile per RWSBEE than costs per lane mile per weather hour. Nearly 75% of the areas across the state were either closer to the state average or within $\pm$5% (minor difference) of the value when viewed in terms of costs per RWSBEE instead of costs per lane mile. Roughly 25% of the areas were viewed as significantly further away (more than 5%) from the state average when analyzed as cost per RWSBEE instead of cost per weather hour. Although the overall variation across the state increased more when doing the cost analysis per RWSBEE than per weather hour, the majority of the areas across the state were viewed as either closer to the state average or only slightly worse ($\pm$5%).
- Non-weather-related factors are also important in determining the maintenance costs, such as salt usage, at the unit, sub-district, and district levels. These factors cannot be accounted for using a severity index that is based solely on weather information.

Implementation

New spatially detailed datasets for analyzing winter weather severity across the state will be provided to INDOT in a form that will allow easy implementation into INDOT operations. We recommend that INDOT begin using the more detailed analysis datasets to analyze the performance of maintenance operations for upcoming and previous winter seasons.

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1. INTRODUCTION

Winter weather conditions that occur across different regions vary substantially from hour-to-hour, storm-to-storm, and season-to-season. The methods of road maintenance for fighting snow and ice can also vary between different maintenance units. It is important for organizations that perform road maintenance to be able to quantify the severity of the winter weather conditions, for purposes of monitoring, planning, and evaluating their performance. Many different transportation departments have developed empirical statistical models (e.g., Hulme, 1982; Jensen, Koeberlein, Bala, & Bridge, 2013; Kwon, Fu, & Jiang, 2013; Qui, 2008) and machine learning methods (Carmichael, Gallus, Temeyer, & Bryden, 2004) with weather parameters to develop indices that estimate the severity of winter weather. The Indiana Department of Transportation (INDOT) currently uses estimates of winter weather hours to quantify the severity of winter weather. The definition of a weather hour is fairly straightforward: any hour when wintry precipitation (snow, ice pellets, freezing rain) is falling with air temperatures below 35°F. While this definition is reasonable, it does not take into account numerous factors that can strongly affect road conditions and subsequent efforts needed for road treatment, such as precipitation rate, wind speed, and availability of sunshine. Consequently, INDOT has determined that the information provided by the weather hour estimates result in wide variations in roadway treatment expenses across Indiana. To more accurately and effectively evaluate the performance of winter maintenance, it is important to have detailed data related to winter weather conditions that provide useful information regarding the impact of winter weather on road conditions. State-of-the-art weather information from observing sensors, radar, and meteorological data analysis systems can provide a clearer understanding of the severity of the weather, allowing INDOT to better evaluate its performance, assist with after-action review of recent storms, and improve the reaction to future weather events. Eventually, measurable improvements in the winter maintenance decision-making process are expected as a result.

1.1 Current Winter Severity Estimates

Currently, INDOT uses analyses of winter weather hours to determine the impact of weather on the maintenance operations across the state. A weather hour is counted whenever wintry precipitation is observed during an hour where the air temperature is 35°F or below. In a previous JTRP project (Baldwin, Hoogewind, Snyder, Price, & Trapp, 2013), several alternate weather hour analyses were developed, utilizing additional surface weather observation stations, high-resolution radar estimates of precipitation from the National Weather Service, and three-dimensional analyses of atmospheric conditions from data assimilation systems. In general, each of these weather hour analysis systems provided similar types of information regarding the timing and location of winter weather, without information regarding the severity of winter weather.

For example, Figure 1.1 shows an estimate of winter weather hours across the state during March 25, 2013. This was based upon the hourly Rapid Refresh (RAP) data obtained by Purdue researchers as part of our previous JTRP study. This event shows that the entire state was affected by winter weather for several hours during this day, with the central portion of the state affected for the entire day. However, the weather hour estimates alone do not tell the entire story. Information regarding the intensity and type of wintry precipitation is missing from this analysis. Figure 1.2 shows the daily snowfall totals across the state (obtained from the National Weather Service) for this date. This analysis shows that the north-central portion of the state received 9–11″ of snowfall, with other regions that received 20+ weather hours also observed significantly less snowfall (4–6″ range). This example clearly demonstrates one basic shortcoming with using weather hours to estimate the severity of a winter weather event: the lack of information related to precipitation rate.

1.2 Alternate Winter Severity Indices

Several previous studies have attempted to develop indices to estimate the severity of winter weather (e.g., Carmichael et al., 2004; Hulme 1982; Jensen et al., 2013; Qui, 2008). As summarized by Strong, Shvetsov, and Sharp (2005), many of these studies use summary statistics such as the number of days with certain events (snowfall, freezing rain, frost) to provide a seasonal index of winter severity (e.g., Hulme 1982; McCullouch, Belter, Konieczny, & McClellan, 2004). While summarizing the winter severity for the entire season is quite useful, providing information over shorter time periods allows for more precise evaluation of performance throughout a winter season. By providing information on an hourly basis, summary severity statistics can be aggregated over any user-defined time period for subsequent analysis.

Previous studies (e.g., Juga, Nurmi, & Hippy, 2013; Kwon et al., 2013) have shown that road condition/friction is directly related to the amount of snow and/or ice sitting on the road surface. The depth of snow/ice remaining on the road surface is difficult to estimate since these parameters depend upon several factors that can vary considerably, such as precipitation rate, road treatment options, traffic, and surface temperatures. However, it is reasonable to assume that the amount of snow/ice on the road surface will be proportional to the precipitation rate. For example, Kwon et al. (2013) showed that snowfall rate was linearly related to the percent reduction in free flow speed. In addition, the mass of frozen precipitation is also expected to be an important factor. While fluffy, dendritic snowflakes will accumulate quickly and increase the depth of the snowfall much faster than dense ice pellets/graupel,

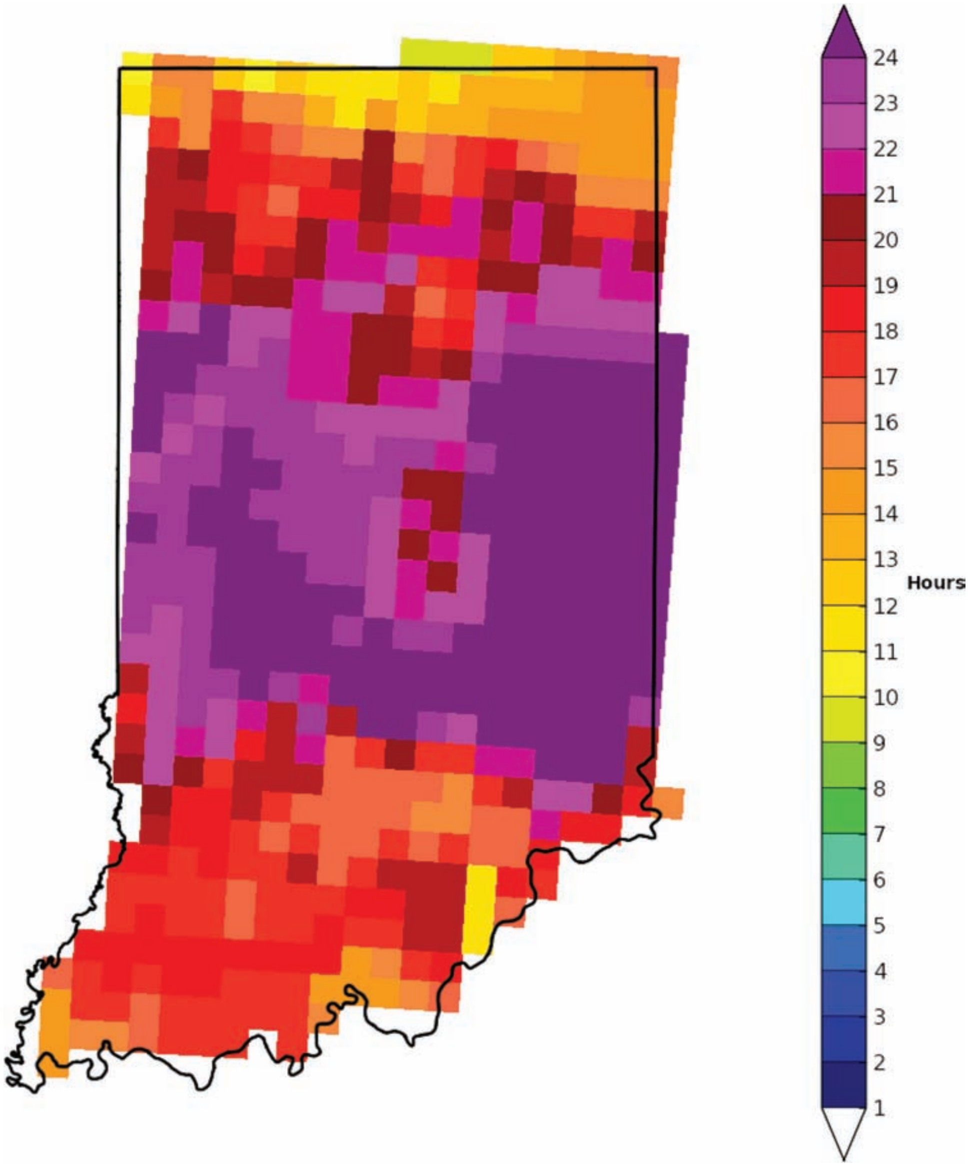

Figure 1.1 Winter weather hours during March 25, 2013, based on Rapid Refresh data. Obtained from http://weather.eaps.purdue.edu/INDOT/.

the amount of water contained in one inch of dendritic snowflakes is considerably less than for one inch depth of ice pellets/graupel. All other conditions being equal, dendritic-type snow will melt faster and leave less residual water behind on the road surface than denser winter precipitation types (ice pellets, rimed snow, graupel).

1.2.1 Local Winter Storm Scale (LWSS)

Previous work has focused on summary measures of the severity for a particular storm giving the storm total snowfall, maximum wind speed, minimum air temperature, and so forth (e.g., Hulme 1982; Jensen et al., 2013; Kwon et al., 2013; Qui, 2008). For example, the Local Winter Storm Scale (LWSS) was developed by Cerruti and Decker (2011) to classify winter storms on a scale from 0 to 5, in a similar fashion as other weather hazards such as hurricanes (Saffir-Simpson scale) and tornadoes (Enhanced Fujita scale). LWSS weighs storm elements such as maximum wind gust, snowfall, ice accumulation, and visibility to produce an overall storm rating. The weight factors were determined to be quite similar to those found by Qui (2008) to measure the impact of winter weather on highway maintenance. For this project, we proposed using daily values of LWSS as an initial index to provide a baseline for comparison purposes. Cerruti and Decker (2011) pointed out that their index does not take the duration of the precipitation into account, while speculating that this factor is important in determining the societal impact of the winter weather. In addition, LWSS does not use precipitation rate directly, visibility is used instead as a proxy to precipitation rate. Cerruti and

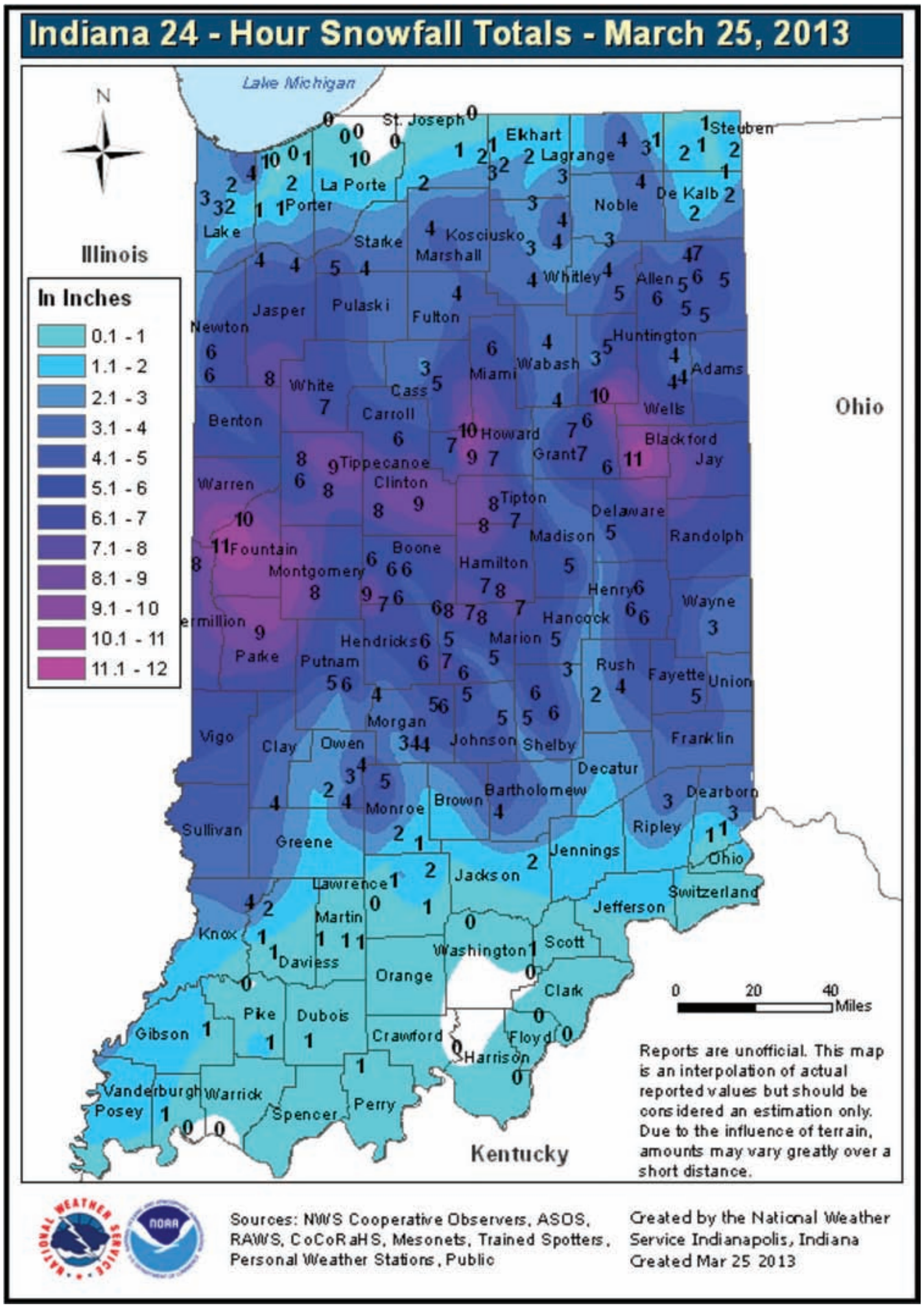

Figure 1.2 National Weather Service analysis of daily snowfall totals for March 25, 2013. Obtained from http://www.crh.noaa.gov/ind/?n=mar242013snow.

Decker (2011) also point out that precipitation type and density are not used in their index, while mentioning the importance of the type of snow (dry or wet) on the societal disruption. The score and weight factors for each of the five different weather variables in the LWSS are shown in Table 1.1. In general, the components of this index increase linearly as the weather variables increase in severity, with the overall index being a weighted sum of the individual factors.

1.2.2 MDSS Equation

For this project, another approach was developed to estimate winter weather severity using data and tools available within the Maintenance Decision Support System (MDSS) provided by INDOT's weather vendor (Iteris). This method utilized weather variables that are available via MDSS and an equation that can be included in the "Management Reports" tool. This equation expands upon the LWSS approach while

TABLE 1.1
LWSS score and weight factors for five different weather parameters, from Cerruti and Decker (2011). Wind speed and gust are the maximum values during a storm event. Snow and ice are the storm-total accumulations. Visibility is the minimum value during a storm event.

Score	Wind speed (kt)	Wind gust (kt)	Snow (inch)	Ice (inch)	Visibility (miles)
Weight factor	20%	15%	50%	30%	15%
1 (moderate)	7	13	2	Trace	3
2 (significant)	11	17	4	0.1	1
3 (major)	17	22	10	0.25	1/2
4 (crippling)	22	30	15	0.5	1/4
5 (extreme)	27	41	20	0.75	1/8
6 (catastrophic)	34	48	25	1.0	0

utilizing the information available in MDSS. This equation was developed in collaboration with Phil Ivy and Jason Jones of INDOT. In general, there are four weather-related processes that are included in the MDSS equation: ice accumulation, snowfall, blowing snow, and pavement temperature. The equation is intended for time periods of two weeks in length, since that is routinely used by INDOT for maintenance reporting. The equation can be easily modified for other time aggregation periods, such as daily. For this equation, a scale from 0 to 10 was created. The full MDSS equation is provided in Equation 1.1 in the format used by the Iteris software:

$$\begin{aligned} MDSS = {} & (0.3 * \sqrt{(ICEACC)} * 10 \\ & + 0.5 * (HRSNOWFL)/336 * (SNOWACC)/2 \\ & + 0.2 * (HRBLSN)/336 * ((WNDSPEED) * 0.5)^{(3)} \\ & /500) * (1.5 - 0.2 * ((PAVETEMP) - 20)/ \\ & (1 + \sqrt{(0.2 * ((PAVETEMP) - 20))^{(2)}})) \quad \text{(Equation 1.1)} \end{aligned}$$

using the following variable definitions for this equation:

ICEACC = total ice accumulation (inches) during two-week period
HRSNOWFL = number of hours of snowfall during two-week period
SNOWACC = total snow accumulation (inches) during two-week period
HRBLSN = number of hours of blowing snow during two-week period
WNDSPEED = average wind speed (mph) during two-week period
PAVETEMP = average pavement temperature (deg F) during two-week period

The square root of total ice accumulation is used, since those values are typically less than 1.0 inch, the square root enhances small values. Total snow accumulation was divided by 2 and multiplied by the fraction of hours of snowfall during the two-week period. The blowing snow factor is related to the wind speed raised to the third power. This is multiplied by the fraction of hours of blowing snow during the two-week period. Weights are applied to each of these factors as follows: 50% for snow, 30% for ice, and 20% for blowing snow. This weighted sum is then multiplied by a function of the pavement temperature, which is designed to ramp up quickly as the surface temperature falls from 25 to 15 degrees Fahrenheit, to indicate the increased difficulty in dealing with snow/ice on the road surfaces at colder temperatures. We will refer to this as the MDSS equation for the remainder of this report.

1.2.3 Meridian Index

A third alternate winter weather severity index was originally developed by Meridian (now Iteris) through the Clear Roads project (Mewes, 2012), it was determined that it would be beneficial to include it in this project for comparison purposes. The "Meridian index" consists of a weighted sum of accumulated snowfall and weather hours, with freezing rain weather hours weighted more heavily due to the increased difficulty with road maintenance during icing conditions. The equation for the Meridian index is provided in Equation 1.2:

$$MERIDIAN = snow * 0.5 + snowhr * 0.05 + blwsnowhr * 0.05 + frzrainhr * 0.1 \quad \text{(Equation 1.2)}$$

1.2.4 Road Weather Severity Based on Environmental Energy (RWSBEE)

For this project, INDOT specifically requested that the severity index should be based solely on weather/environmental information, in order to provide information that is independent of specific road treatment actions and traffic patterns. Therefore, a physically-based analysis of winter severity was developed, using estimates of the hourly rate of deposition of new snow/ice and the energy required melt it. Here, we propose the "Road Weather Severity Based on Environmental Energy" (RWSBEE) index, which is defined as the amount of energy, beyond that which is freely available from the environment, needed to melt new snow/ice that has been deposited on the road surface on an hourly basis. Weather conditions can make snow removal easier or more difficult as a result of several factors (i.e., sunshine, warm air temperatures). The additional energy beyond that freely available from the environment that is required to melt new snow/ice can be thought of as a measure of the work required to remove the new snow from the road surface. Since melting is not the primary method of snow/ice removal from road surfaces, a modified version of this index (RWSBEE2) was developed to limit the effect of precipitation rate, based on the assumption that the amount of work required to plow a road surface is generally the same, regardless of the amount of new snow accumulation. Additional details regarding the calculation of the RWSBEE index are provided in section 2. It was expected that the RWSBEE index would provide a clear physical understanding of the severity of the weather, allowing INDOT to better evaluate their performance, assist with after-action review of recent storms, and improve the reaction to future weather events. The remaining sections of this report will explain the physical basis for using this energy-based index, provide information regarding the sources of weather information used, discuss an example case in detail, and provide a seasonal summary of the 2013–14 winter season.

2. PHYSICAL BASIS

2.1 Energy Methodology

Work, or energy, is required to remove snow and ice from road surfaces. This energy could be in the form of mechanical energy to plow snowfall off of the surface or spread salt across the roadway. Energy could also be in the form of heat from the sun, air, or road surface that is transferred to the snow and ice by a variety of physical processes. Each of these sources of energy have different degrees of economic costs associated with them, some of which are quite difficult to estimate, while energy from the environment is available at no cost. The "Road Weather Severity Based on Environmental Energy" (RWSBEE) index is based upon the idea that winter severity can be derived by finding the additional energy required to melt snow and ice that has been deposited on the surface, beyond the energy that is freely available from the environment. This additional energy can be considered an amount of work that INDOT must perform in order to maintain the road surfaces.

In general, heat flows from hot to cold. For example, heat will flow from a warm surface towards colder air situated above it. The loss of heat will lower the temperature of the surface, and the absorption of heat will warm the air above. In meteorology, we call this transfer of heat a "flux" of energy. Snow and ice can be deposited on the surface via precipitation or blowing snow. Environmental conditions can either assist with melting, or make snow/ice removal more difficult. In order to find the extra energy needed to melt the mass of new snow and ice that has accumulated over the past hour, both the amount of energy available from the environment and the amount of energy required to warm and melt the snow and ice deposited on the road surface need to be estimated.

2.1.1 Energy Available from the Environment

Energy available from the environment to warm the surface can be obtained from several sources. Radiation from the sun reaching the surface is a primary source of energy. Some of that solar or "shortwave" radiation gets reflected by the surface, especially when the surface is covered with fresh snow. Energy is also radiated upward from the Earth's surface at a rate proportional to the surface temperature raised to the 4^{th} power. Greenhouse gases (H_2O vapor, CO_2, N_2O, CH_4, etc.) and clouds are quite effective at both absorbing and emitting this terrestrial or "longwave" radiation (i.e., the "greenhouse effect"). The sum of all of these radiation components reaching the surface is known as the "net radiation," which is typically a source of energy during the daytime hours, and an energy sink at night. Energy can also flow between the surface and the air above it through turbulent mixing processes. The "sensible heat flux" represents a flow of temperature from warm to cold, and is a function of the wind as well as the magnitude of the difference in temperature between the air and the surface. The sensible heat flux can act either to warm or cool the surface, depending on whether the air temperature is warmer or colder than the surface temperature. The "latent heat flux" represents a flow of energy due to moisture transports between the surface and atmosphere, such as evaporation of water from the surface.

The net radiation is the primary source of energy at the surface during the daytime. Some of this energy typically is "spent" though the sensible heat flux, and another portion goes into the latent heat flux. The remaining energy is typically known as the ground heat flux, and will be absorbed in the ground (or emitted from the ground often when the net radiation is negative) to affect the temperature of the surface, and the deeper soil below. For this project, we assume that the conduction of energy through the deep soil to/from the road surface occurs on a time scale much longer than 1h, and that the temperature of the new snow/ice deposited on the road will immediately be equal to the surface temperature (the mass of the new snow/ice being much smaller than the mass of the roadway). We assume that any available energy from the environment can assist with warming any new snow and ice that has been deposited on the road, if there is a positive amount of this extra energy available. Conditions can also result in cooling of the snow/ice on the surface, such as during the nighttime hours or when cold air blows across a relatively warm surface. In this case, the available energy term will be negative, indicating that environmental conditions are making snow removal more difficult. This term can be found by summing the surface heat fluxes and net radiation (Equation 2.1):

$$Q_N + Q_H + Q_E = Q_{avail} \qquad \text{(Equation 2.1)}$$

Q_N is then net radiation, Q_H is the sensible heat flux, Q_E is the latent heat flux, and Q_{avail} is the energy available from the environment to warm (or cool) the new snow/ice on the surface. These energy flux variables are typically provided in units of W/m^2, multiplying these by 3600s over the course of 1h will express these in terms of energy per unit area, or J/m^2.

2.1.2 Energy Required to Melt Snow and Ice

The total amount of energy required to melt the new snow and ice that has been deposited on the road surface during the past hour can be found by adding the energy required to warm the mass of snow/ice to the melting point (0°C, assuming pure water) and the energy required to change the phase of the snow/ice from solid to liquid. The amount of energy needed to warm the snow and ice to freezing can be found by multiplying the mass of snow/ice on the ground by the specific heat of snow and the number of degrees that needed to warm the snowpack to the melting point. Shown mathematically in Equation 2.2:

$$Q_{warm} = m * C_p * \Delta T \qquad \text{(Equation 2.2)}$$

where Q_{warm} is the energy required to warm the snow/ice to 0°C (J/m^2), m is the mass of new snow/ice deposited on the ground over a square meter (kg/m^2), C_p is the specific heat of snow (2097 $Jkg^{-1}\ K^{-1}$), and ΔT is the number of degrees needed to warm the surface to the melting point (degrees *K, equivalent to degrees Celsius*).

The amount of energy required to melt the mass of newly deposited snow and ice, once it reaches the melting point, can be calculated by multiplying the mass of snow/ice on the surface by the latent heat of fusion (Equation 2.3):

$$Q_{melt} = H * m \qquad \text{(Equation 2.3)}$$

where Q_{melt} is the energy required to melt the newly deposited snow and ice on the ground (J/m^2), m is the mass of snow that has been deposited in the past hour onto the road surface over a square meter (kg/m^2), and H is the latent heat of fusion ($3.34 \times 10^5\ Jkg^{-1}$).

$$Q_{totalmelt} = Q_{warm} + Q_{melt} \qquad \text{(Equation 2.4)}$$

Adding Q_{warm} and Q_{melt} yields $Q_{totalmelt}$ (Equation 2.4), the total amount of energy required to warm the snow/ice mass to the melting point and change the phase (solid-to-liquid) of the new snow/ice on the surface. The number of degrees needed to warm the surface to freezing (ΔT) was found by subtracting the surface temperature from the melting point (273.15 K). Q_{warm} and Q_{melt} are typically expressed in megaJoules (MJ) or $10^6\ J$ per square meter.

2.1.3 RWSBEE Index

The amount of energy needed to raise the temperature of the mass of new snow/ice that has fallen (or deposited by blowing snow) onto a square meter of road surface during the past hour to 0°C, and then change the phase of that snow/ice from solid to liquid, has been computed ($Q_{totalmelt}$). This will be a positive number, larger for greater values of snowfall and also for colder surface temperatures. The amount of energy available from the environment to warm the surface has also been computed (Q_{avail}). This will either be a positive or negative value, depending on whether the environmental conditions are acting either to warm ($Q_{avail} > 0$) or cool ($Q_{avail} < 0$) the surface. Calculating the difference between Q_{avail} and $Q_{totalmeltyields}$ the additional energy required to melt the snow and ice that has accumulated on the road surface over the past hour. This energy value can be thought of as the additional work necessary to remove this new snow/ice from the roadway, and is the defined here (Equation 2.5) as the Road Weather Severity Based on Environmental Energy (RWSBEE) index, expressed in units of MJ/m^2.

$$RWSBEE = Q_{totalmelt} - Q_{avail} \qquad \text{(Equation 2.5)}$$

It is possible that the energy available from the environment will exceed that required to melt the new snow/ice that has been deposited over the past hour. In this case, no additional effort is required to remove the snow, the environmental energy is sufficient to produce complete melting, and the RWSBEE index is set to zero.

2.1.4 Modified RWSBEE Index (RWSBEE2)

The RWSBEE index measures the amount of work required to melt new accumulations of snow and ice that have fallen during the past hour. However, since melting is not the primary method of snow/ice removal from road surfaces, this index will not be representative of the actions typically taken by a maintenance unit to clear snow/ice from road surfaces. Plowing is certainly the primary method used in situations with any substantial snowfall, and one can assume that the amount of work required to plow a given section of roadway is generally the same, regardless of the amount of new snow/ice accumulation. Given this, a modified version of this index (RWSBEE2) was developed to more accurately represent the work performed to maintain road surfaces during a winter storm, with a combination of melting and plowing processes acting to maintain road surfaces. In this modification, the effect of hourly precipitation deposition was capped at 1.0 kg/m^2, which for typical snow depth-to-liquid mass ratios converts to ½ inch of snowfall per hour. This modification caps the mass of new snow/ice deposition (which affects the variable m in equations 2.2 and 2.3 above) such that any value greater than 1.0 kg/m^2 will be set equal to 1.0 kg/m^2. This will limit the values of Q_{warm}, Q_{melt}, and $Q_{totalmelt}$ for each hour in the previous equations. We will call this modified index "RWSBEE2."

2.2 Blowing Snow

Blowing snow can be a very important factor when trying to quantify the mass of new snow deposited on roadways. Not only can blowing snow add to the total mass of snow/ice on the roadway, it can significantly decrease visibility, making travel very hazardous. The physical processes of blowing snow are summarized here, following the discussion of the Prairie Blowing Snow Model by Pomeroy, Gray, and Landline (1993).

2.2.1 Blowing Snow Physical Processes

As the wind flows over particles (such as dust, sand, or snow crystals) found on the surface that are loose enough to displace, those particles first start to vibrate, then are lofted into the air, if the force of the wind is large enough. In the case of snow, there are several factors that influence the "looseness" or "mobility" of the snow located on the top of the snowpack. The mobility of the snowpack is very difficult to assess, as the snowpack forms a cohesive matrix of crystals that are bonded together. The strength of that cohesion can vary considerably based upon temperature, age of the snow, and previous melting. Surface vegetation and other morphological characteristics of the ground surface also have the capacity to hold a certain depth of snow in place.

Snow can be transported by the wind primarily via three different physical processes. The first process is known as *creep:* when one particle is displaced and rolls across the surface. The particle can also bump into another particle causing that second particle to move. The next form of snow movement is called *saltation*. Saltation is where the snow particles jump across the surface. This normally occurs in the first 10–20 cm above the surface and can contribute to the snow deposition on roadways. For saltation to occur, the shear stress of the wind must exceed the stress that is necessary to shatter the bonds of the snow crystals to the surface. The final form of snow movement is called *suspension*, where snow particles lifted off the ground are transported by the turbulent wind. The suspension layer extends from the top of the saltation layer to several tens of meters above the surface.

Once a snow crystal is lifted off the ground, it will continue to be suspended until the force of gravity causes it to return to the ground, the snow crystal runs into an object, or the snow sublimates and is converted into water vapor by dry air. Evaporation/sublimation of blowing snow can be a considerable factor, especially within the suspension layer (Bowling, Pomeroy, & Lettenmaier, 2003). The distance that a snow crystal covers in the air is called the *fetch*. For areas with level terrain and minimal obstructions, snow can be transported many kilometers from the original source. The horizontal transport of blowing snow is represented by a transport flux term, which is basically equivalent to the mass of the blowing snow (per square meter) multiplied by the horizontal speed of its motion. Local deposition of snow or erosion of the snowpack due to blowing snow would generally be calculated via the difference between the transport flux *into* an area and the transport flux *out of* an area. If these terms are equal, there is no net change to the mass of snow on the surface. When the flux into an area is greater than the flux out of an area, there is a net increase of mass of snow/ice on the surface, which is known as *deposition*. *Erosion* occurs when there is a net decrease of mass, due to the transport out of the area being greater than the transport into the area.

The physical processes associated with blowing snow are quite complex, and there have been several numerical models developed to simulate those processes (e.g., Liston & Sturm, 1998; Pomeroy et al., 1993). Simulations require precise information about the condition of the snowpack, spatial variations in terrain and vegetation, detailed wind velocities, etc. For this project, we simulate those processes over spatial and temporal scales ($\sim$100 km^2, hourly) that are larger than those used by the sophisticated blowing snow models. As a result, we are using several concepts and equations that were developed for the simulation of these individual processes in models at scales similar to those that we are representing in this project.

Here we assume that once the blowing snow process has been initiated, it will quickly become "fully developed." This means that the saltation and suspension processes will be active across the entire area represented by a grid box within our domain. We need to calculate a deposition rate for blowing snow on a typical square meter of roadway *within* a grid box. Since a roadway represents a small fraction of the area represented by a grid box ($\sim$100 km^2), we assume that the only process impacted by the roadway is saltation, and the suspension of snow will have negligible change as the wind flows across the road. Therefore, in order to estimate the deposition rate of blowing snow on a roadway, the process that needs to be quantified numerically is saltation. This is the process that contains the connections between the surface and the $\sim$10 cm layer of blowing snow above the surface. We assume that any snow covering the road surface is not mobile, therefore the saltation rate will drop to zero as the wind flows across the roadway area. For purposes of calculating the divergence of the saltation rate, we assume that this occurs over a distance of 30 m.

To determine the rate of saltation for blowing snow, we first must determine the degree of *mobility* of the snowpack, or whether or not the snow on the ground can be lofted into the air by the wind. Since the last hour of snowfall, if the warmest temperature was less than the melting point (0°C) and no new liquid precipitation has fallen, the snowpack can be considered to be mobile. Otherwise, the snowpack is considered to be immobile, and no blowing snow can be produced. In order to take the holding capacity of the ground cover and terrain into account, the depth of the snowpack must also be at least **twice** the *roughness length* (Liston & Sturm, 1998). The roughness length (z_0) is a height above the surface at which the average wind speed goes to zero when extrapolated on a logarithmic profile. Values of roughness length are estimated based upon the dominant land-use/land-cover of a grid box area, and are allowed to vary over time to account for vegetation growth. A typical wintertime value for z_0 over cropland is 0.07m, which means that the snow depth must be greater than approximately 5.5 inches before it can be considered to be mobile. Roughness lengths in urban areas are closer to 0.25m, and in forested regions are on the order of 1m, so much deeper snow packs are required to be considered mobile snow in those regions. The specific roughness length data that were used were obtained from the NDLAS system, which will be described in more detail in section 3. Next, a threshold wind speed was determined for blowing snow initiation, based on the work of Li and Pomeroy (1997) who found that such a threshold varied as a function of air temperature. The threshold equation is based on the wind speed at 10m above ground and is given below in Equation 2.6:

$$U_t = 6.975 + 0.0033(T_a + 27.27)^2 \qquad \text{(Equation 2.6)}$$

where U_t is the threshold 10m wind speed (m/s) and T_a is the air temperature (°C). If the wind speed exceeds this threshold (for areas with mobile snowpack), the saltation rate is computed using the following formula from Pomeroy and Gray (1990) in Equation 2.7:

$$Q_{salt} = \frac{U^{1.295}}{2118} - \frac{1}{17.37U^{1.295}} \qquad \text{(Equation 2.7)}$$

where U is the 10m wind speed (m/s) and Q_{salt} is the saltation transport rate for blowing snow (kg/m/s). Using our assumption that the saltation transport drops to zero when the wind flows over a roadway, the deposition rate due to blowing snow ($D_{blowing}$) can be estimated (Equation 2.8):

$$D_{blowing} = \frac{Q_{salt}}{30m}\frac{3600s}{1h} \qquad \text{(Equation 2.8)}$$

where $D_{blowing}$ is in units of $\frac{kg}{m^2hr}$.

3. SOURCES OF WEATHER INFORMATION

In order to monitor the changing severity of winter weather conditions during the course of a storm, hourly information is required. For this project, we obtained the weather-related variables from a variety of sources. These are all freely available, generated routinely by the National Weather Service, and available in near real-time for continued monitoring. Each variable was remapped to a regular latitude/longitude grid across the lower 48 United States, using 1/8 degree grid spacing (approximately 12.5 km). This is the same geographic grid used by the North American Land Data Assimilation System (NLDAS) described in detail below. Parameters are considered to represent spatial averages across an area represented by a grid box, and either temporal accumulation or average over the previous 1h period, ending at the valid time of the analysis.

3.1 Rapid Refresh (RAP)

The Rapid Refresh (RAP; Benjamin et al., 2006) is an hourly, short-range weather prediction and data assimilation system was operationally implemented at the National Centers for Environmental Prediction (NCEP) on 1 May 2012. The RAP has horizontal grid spacing of 13 km with 50 vertical levels. Because new forecasts and analyses are available every hour, the RAP lends itself nicely for the use of estimating hourly weather conditions. Contained within the RAP dataset are four categorical precipitation type variables—rain, snow, ice pellets, and freezing—that were used to estimate winter weather hours. These classifications are based up on a series of logic that involve vertical thermal and moisture profiles and information derived from the cloud microphysics parameterization. However, the classifications are not mutually exclusive; that is, more than one precipitation type designation may exist for the same grid point location. A winter weather hour was counted if one of these classifications were designated while at the same time the observed precipitation (from the Stage IV analysis described below) amount exceeded 0.05 mm. More information about the RAP can be found at http://rapidrefresh.noaa.gov.

3.2 North American Land Data Assimilation System (NLDAS)

The North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004) is a land-surface model dataset that is quality controlled, and spatially and temporally consistent. It supports modelling activities by using the best available observations and model output. NLDAS has horizontal grid spacing of ⅛° and a temporal resolution of one hour. The NLDAS dataset contains several of the primary variables that can be used to compute the winter severity index, such as energy fluxes, wind speed, and temperatures. More information about NLDAS can be found at http://ldas.gsfc.nasa.gov/nldas/NLDASgoals.php.

3.3 Snow Data Assimilation System (SNODAS)

The Snow Data Assimilation System (SNODAS; National Operational Hydrologic Remote Sensing Center, 2004) is a modelling and data assimilation system developed by the National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC). SNODAS provides a framework to integrate snow and ice cover data from satellites and aircraft with surface observations and numerical weather model estimates of snow and ice cover and depth. SNODAS is a gridded dataset with a spatial resolution of 1 km and a daily temporal resolution. Daily snow depths were interpolated in time to hourly values by factoring the accumulated Stage IV precipitation. Snow depths were linearly interpolated to hourly values if no precipitation was observed. More information about SNODAS can be found at http://nsidc.org/data/docs/noaa/g02158_snodas_snow_cover_model/.

3.4 NCEP Stage IV Precipitation Analysis

The NCEP Stage IV (Lin & Mitchell, 2005) precipitation analysis is an hourly mosaic of precipitation accumulation compiled using gauge and radar data. The data is compiled by each of the 12 River Forecast Centers (part of the National Weather Service) located across the country. Once the data are collected, they are sent to NCEP where a national mosaic is produced. Some of these data are manually quality controlled. Stage IV precipitation data are represented on a grid with spatial resolution of 4 km and have available temporal aggregations of one hour, six hours, or 24 hours. More information about the NCEP Stage IV precipitation analysis can be found at http://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/stage4/.

Precipitation type was determined using the RAP categorical precipitation type variables (snow, freezing rain, ice pellets, rain). When the precipitation type was diagnosed as snow, hourly snowfall was determined using the RAP vertical temperature profile at that location. The Kuchera/AFWA snow-to-liquid ratio formula ("snowratio"), assumes that the snowfall will depend upon the warmest temperature in the vertical profile ("T_{max}" in °C). This was used to convert the mass of precipitation (observed by Stage IV) to hourly snowfall. The snow-to-liquid ratio was capped at 40:1 for cold temperatures (occurs for $T_{max} \leq -28°C$) and at 0:1 for warm temperatures (for $T_{max} \geq 6°C$).

$$\begin{aligned} snowratio &= 12 - 2 * T_{max} \text{ if } T_{max} > 0^{\circ}C \\ snowratio &= 12 - T_{max} \text{ if } T_{max} \leqslant 0^{\circ}C \end{aligned} \qquad \text{(Equation 3.1)}$$

3.5 Summary of Weather-Related Variables and Data Sources

Table 3.1 lists the weather-related variables that were used in this project and the sources for those data.

TABLE 3.1
Weather-related variables and data sources.

Weather-related variable (units)	Data source
Roughness length (m)	NLDAS
2m air temperature (K)	NLDAS
10m wind speed (m/s)	NLDAS
Surface temperature (K)	NLDAS
Net surface shortwave and longwave radiation (W/m^2)	NLDAS
Sensible and latent heat fluxes (W/m^2)	NLDAS
Vertical temperature profile (K)	RAP
Categorical precipitation type (yes/no)	RAP
Visibility (m)	RAP
10m wind gusts (m/s)	RAP
Snow depth (m)	SNODAS
Hourly accumulated precipitation (kg/m^2)	Stage IV

4. EXAMPLE: JANUARY 5–7, 2014, WINTER STORM

See Figures. 4.1 through 4.8.

4.1 Weather Summary

The January 5–7, 2014, case was one of the most severe winter storms of the 2013–14 season. During this three-day period, Indiana experienced almost every type of weather that a large winter storm can produce, including heavy snow, high winds, frigid temperatures, and blowing snow. Total snowfall estimates for the state, shown in Figure 4.1, ranged from just a few inches around Vincennes and Seymour, to 10+ inches in the central regions of the state. Because of the many different extremes produced by this storm, it is an ideal test case for the proposed severity indices.

4.2 Winter Weather Hours

For this event, the winter weather hours were dominated by snow and/or blowing snow. The bulk of the snowfall occurred on January 5, as a low pressure system moved across the region. A rain-snow boundary had set up along a southwest-northeast oriented line cutting through the central part of the state. Areas to the south of this boundary received mostly rain, with a couple inches of snow towards the end of the event as colder air pushed southward. Areas to the north of this boundary received the heaviest snowfall, and a total number of winter weather hours due to snow in the 18- to 24-hour range (Figure 4.2). During the morning hours of January 6, strong winds brought in much colder (sub-zero °F) weather across the state, producing widespread blowing snow conditions over areas with fresh snowcover. At times, I-65 was shut down between Lafayette and I-94. The estimated number of hours of blowing snow (Figure 4.3) during the period following the snowfall exceeded the number of hours of snowfall over most of the state.

4.3 LWSS Performance

The Local Winter Storm Scale (LWSS, see section 1.2.1) index values for this event were accumulated over a three-day period by summing daily index values (see Figure 4.4). In this case, most of the state ended up in the range of LWSS values between 3 and 4, with maximum values near 6 in the northeast corner of the state. The peak values were due to a combination of locally higher snowfall as well as stronger maximum wind speeds. For this example, there is a small amount of variation in the LWSS values across the state, with the far southern tier of counties still reaching the 2–3 range of index values, even with minimal snowfall and no blowing snow estimated. Since the LWSS calculation does not take blowing snow into account explicitly, the combination of high wind speeds and light snowfall still produce relatively high LWSS values, even though no blowing snow was estimated in these areas.

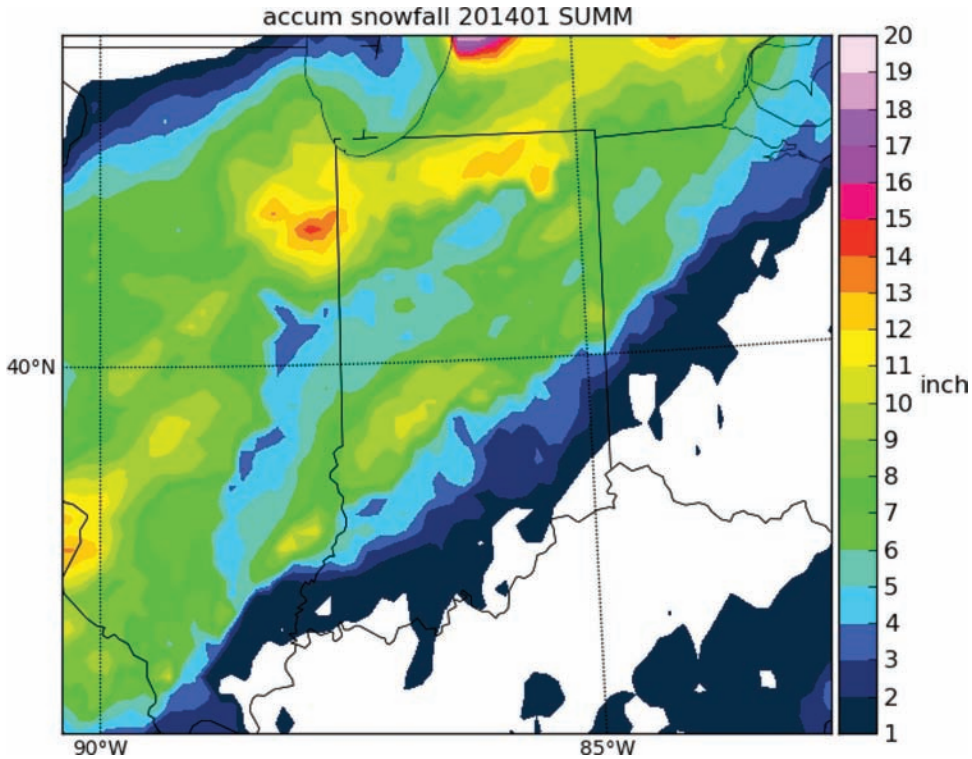

Figure 4.1 Estimated total snowfall (inches) during the January 5–7, 2014, period.

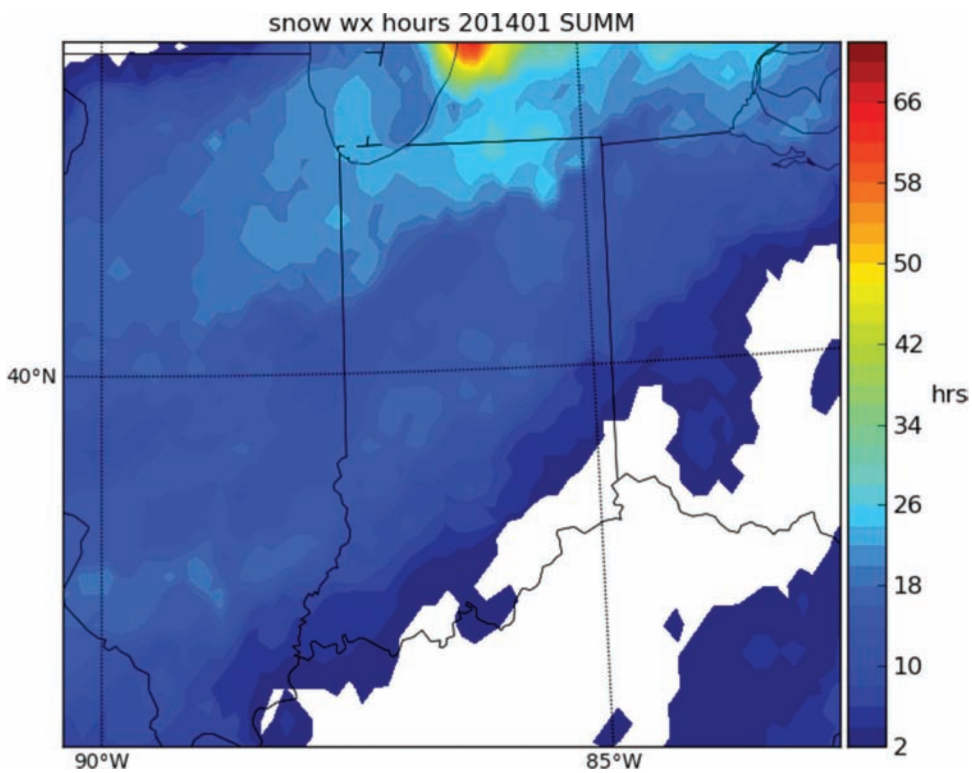

Figure 4.2 Estimated total hours of snow during the January 5–7, 2014, period.

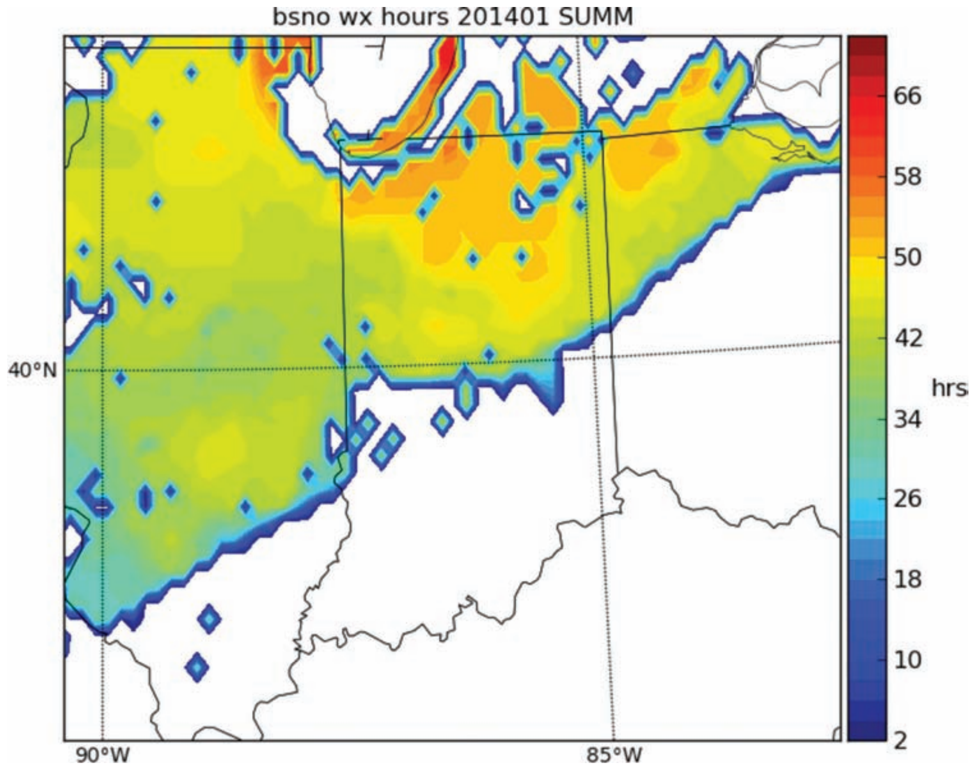

Figure 4.3 Estimated total hours of blowing snow during the January 5–7, 2014, period.

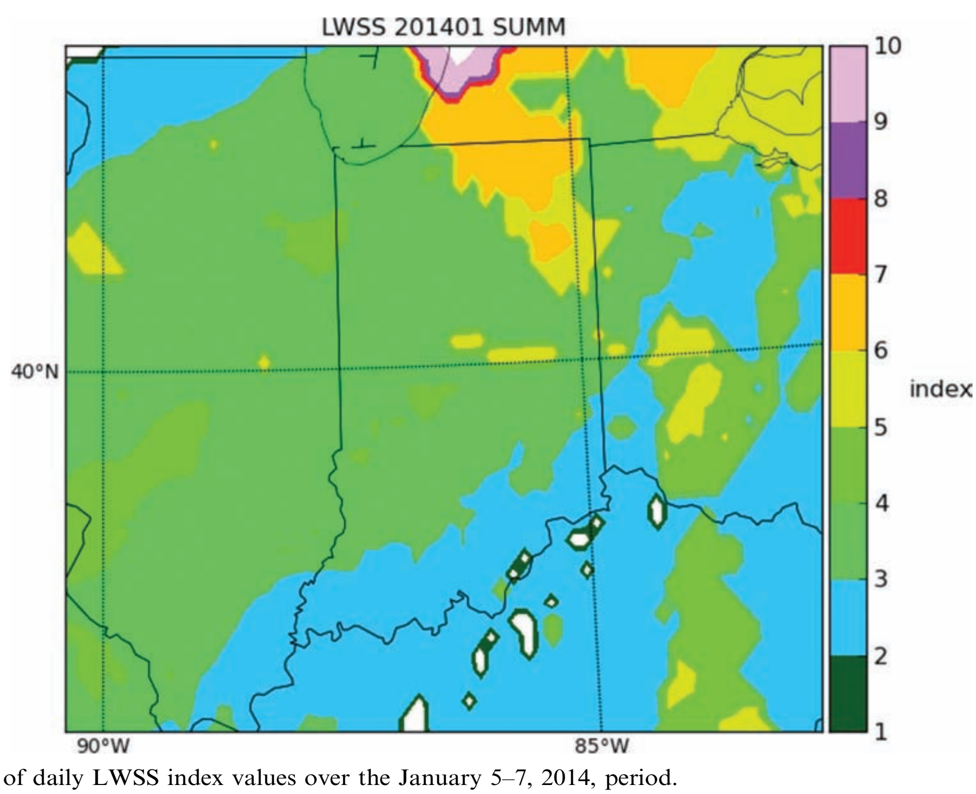

Figure 4.4 Sum of daily LWSS index values over the January 5–7, 2014, period.

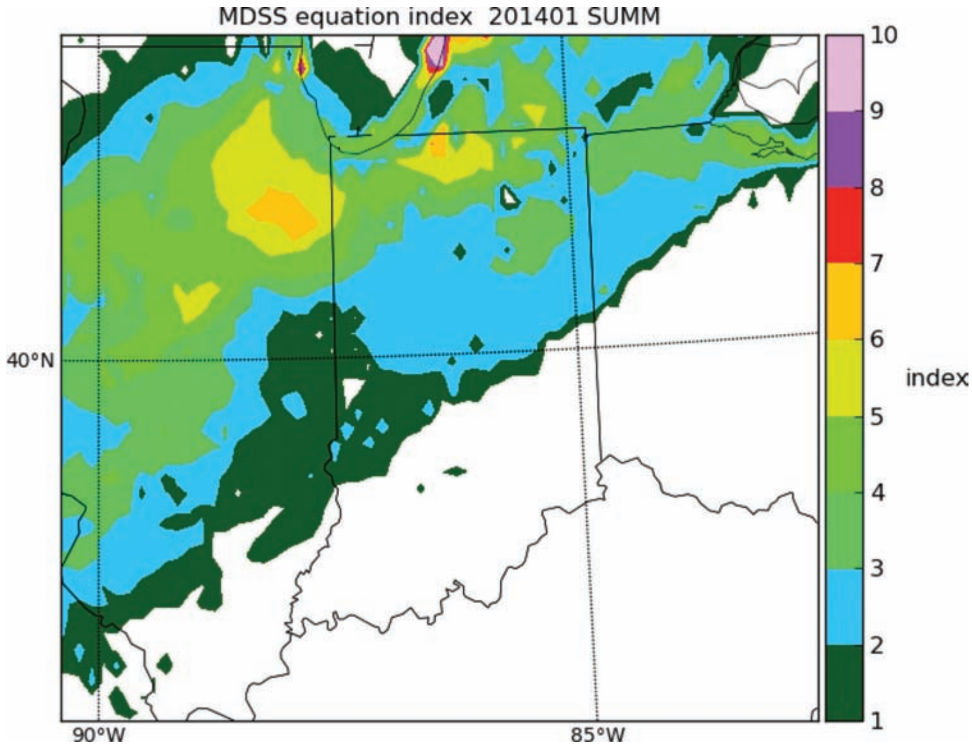

Figure 4.5 Accumulated MDSS equation values over the January 5–7, 2014, period.

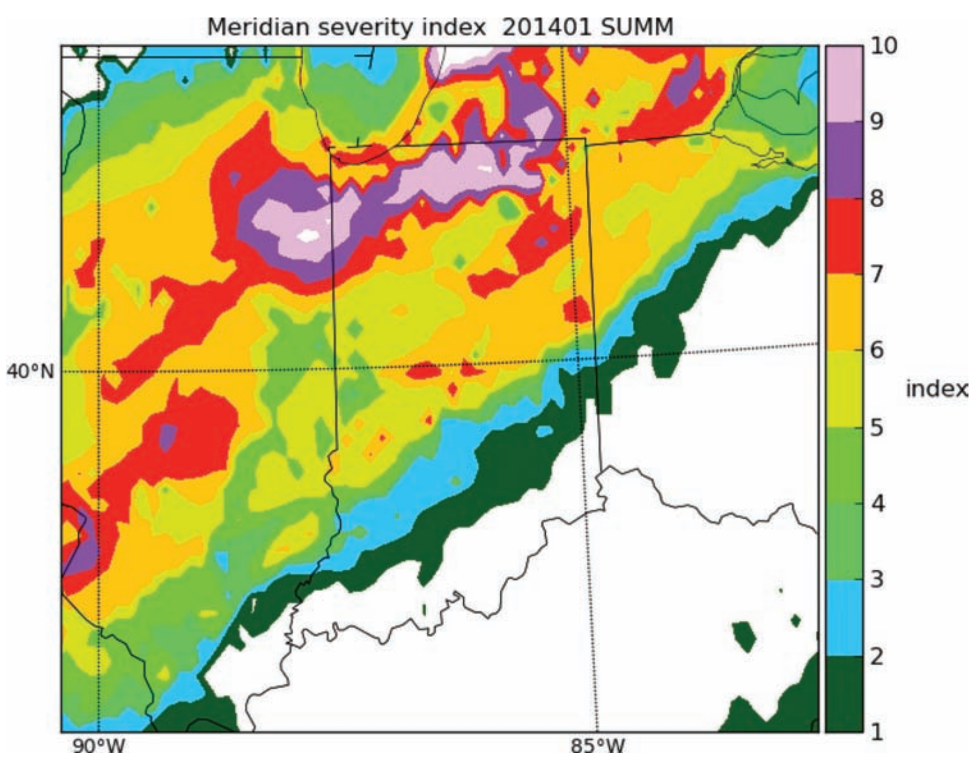

Figure 4.6 Accumulated values of the Meridian index during the January 5–7, 2014, period.

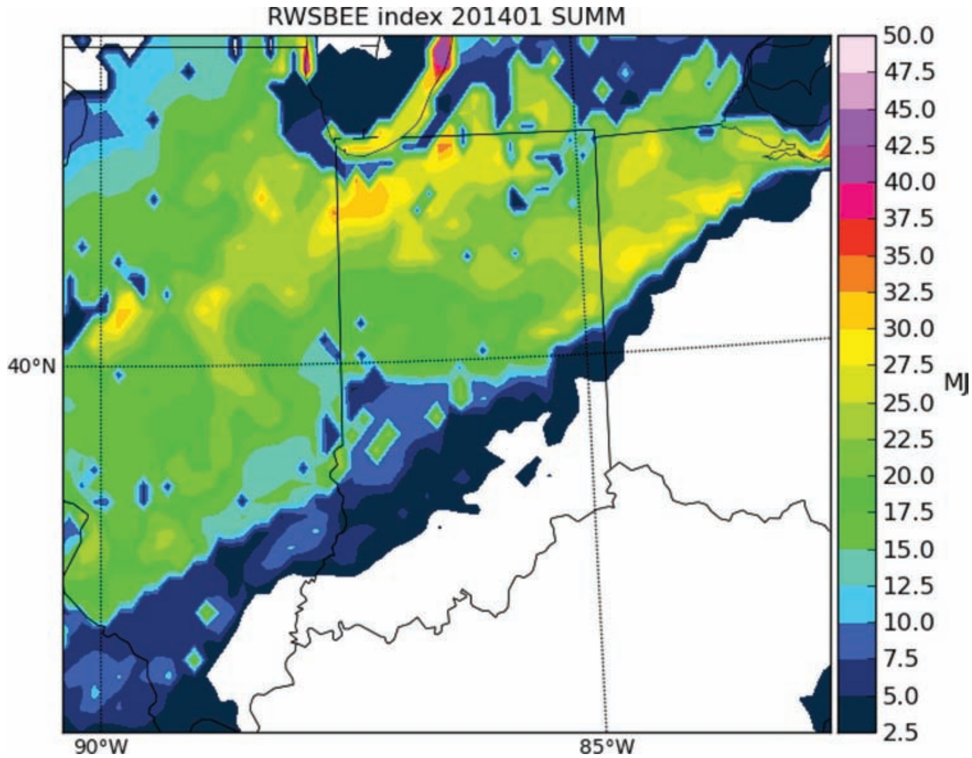

Figure 4.7 Accumulated RWSBEE index values during the January 5–7, 2014, period.

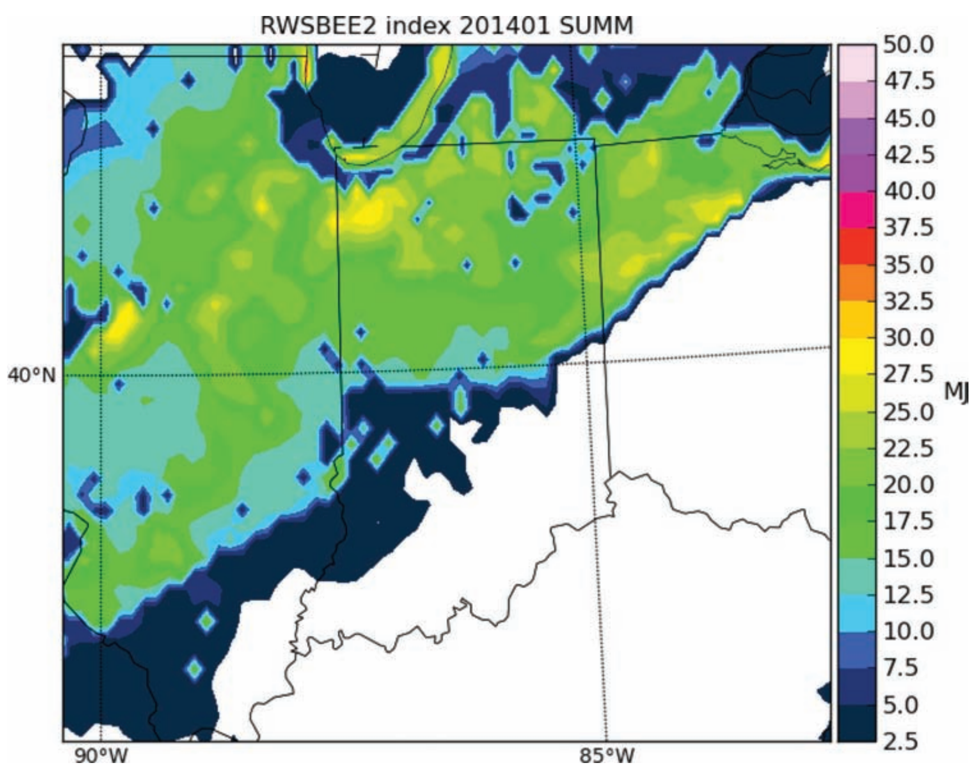

Figure 4.8 Accumulated RWSBEE2 index values during the January 5–7, 2014, period.

4.4 MDSS Equation Performance

The result of the custom equation developed for the MDSS (see section 1.2.2) values for this event were accumulated over a three-day period by summing hourly index values (see Figure 4.5). In this case, most of the state ended up in the range of MDSS values between 2 and 5, with maximum values near 6 in the northern portion of the state. The peak values were due to a combination of locally higher snowfall, cold surface temperatures, and long duration of blowing snow. For this example, the variation in the MDSS values across the state appear to be sensible, with the far southern tier of counties falling below an index value of 1, given the minimal snowfall and no blowing snow estimated.

4.5 Meridian Index Performance

The "Meridian" index (see section 1.2.3) values for this event were accumulated over a three-day period by summing daily index values (see Figure 4.6). In this case, most of the state ended up in the range of Meridian index values between 2 and 6, with maximum values near 10 in the northern portion of the state. The peak values were due to a combination of locally higher snowfall, and long durations of both snow and blowing snow. For this example, there are detailed variations in the Meridian values across the state, with the region just to the north of the rain-snow boundary showing local maxima in the index, given the relative maxima in snowfall there. The far southern tier of counties fell below an index value of 1, given the minimal snowfall and no blowing snow estimated.

4.6 RWSBEE Index Performance

The "RWSBEE" index (see section 2.1) values (in units of MJ) for this event were accumulated over a three-day period by summing hourly index values (see Figure 4.7). In this case, most of the state ended up in the range of RWSBEE index values between 10 and 20 MJ, with maximum values near 30 in the northern portion of the state. The peak values were due to a combination of locally higher snowfall, and relatively large amounts of blowing snow deposition, and a small amount of available energy from the environment due to the extreme cold. The available environmental energy did help to reduce the overall work (and final value of the RWSBEE index) by approximately 20%. For this example, there are detailed variations in the RWSBEE values across the state, with the region just to the north of the rain-snow boundary showing a sharp increase in values, and RWSBEE values tending to increase as you move northward. In many locations, blowing snow was nearly as big a factor with this winter storm as the snowfall. Across the northern tier, blowing snow approximately doubled the energy needed to remove the snow, while near Indianapolis the additional blowing snow was a minor factor for the energy calculation. The far southern tier of counties fell below a RWSBEE value of 1, given the minimal snowfall and lack of estimated blowing snow.

4.7 RWSBEE2 Index Performance

As in the previous section, the modified RWSBEE index (RWSBEE2, see section 2.1.4) values (in units of MJ) for this event were accumulated over a three-day period by summing hourly index values (see Figure 4.8). In this case, the pattern of RWSBEE2 values ended up being very similar to the original RWSBEE values, ranging between 10 and 20 MJ, with maximum values near 30 in the northern portion of the state. The highest peak values found in the original RWSBEE were reduced in the modified version, due to the capping of hourly deposition of snow/ice at 1 kg/m^2. It appears that in this case, most of the hourly precipitation and blowing snow accumulations were less than this value.

5. COMPARISON OF SEVERITY INDICES TO WINTER MAINTENANCE COSTS

5.1 Correlation between Proposed Winter Severity Indices

The various severity indices (see sections 1 and 2) were computed over the entire 2013–14 winter season. For each index, daily values were obtained from hourly weather data covering the midnight-midnight CST time period. The same 24h period was used regardless of local time zone (1am–1am EST). The LWSS, MDSS, and Meridian index calculations were based upon daily values of weather parameters, while the RWSBEE and RWSBEE2 index values were calculated hourly, with the sum of the 24 hourly RWSBEE /RWSBEE2 values stored as the daily index. Daily values of each index were simply summed across the entire winter season of 2013–14 (1 Nov 2013–29 Mar 2014) to produce a seasonal summary.

To support the creation of an index value weighted toward roadways under INDOT responsibility, a method was developed to estimate the number of INDOT lane miles within each 1/8th degree grid box of our final weather data analysis. Lane mileage was a provided attribute within the INDOT roadway shapefile (obtained from: http://maps.indiana.edu/download/Infrastructure/Interstates_Highways_INDOT.zip). For each road segment, the fraction of vertices of each road segment that fell within a single grid box was determined. The product of this fraction and the total lane mileage of the segment was used to define the number of lane miles within that particular grid box. If multiple road segments intersect a particular grid box, the fractional lane miles of each individual segment were summed and the total was assigned. While the estimates of lane mileage within each grid box are not considered to be exact, the results of this basic method allow for the general distribution of lane miles to be accounted for within final product. For each index value, the overall summary value for a particular INDOT "area" (unit, sub-district, or district) was calculated using a weighted average of the index values at 1/8th degree grid box locations within each INDOT area, weighted by the number of lane miles within each 1/8th degree grid box. This will ensure that the weather occurring in regions with greater lane mile density will be properly represented in the overall summary value for that INDOT area.

The various proposed severity indices were computed for each INDOT district, sub-district, and unit during the 2013–14 season. These values were compared with winter weather hour estimates obtained from INDOT, which were provided by their weather vendor, Iteris. Winter maintenance cost information and lane miles were also obtained from INDOT for this season. The overall state average of winter weather hours for the 2013–14 season was 275.5 hours, with an average of $6.73 spent on maintenance per lane mile per weather hour. The state average of LWSS for this season was 117.8. The statewide average value for the MDSS equation was 14.4, and the state average value for the Meridian index across this season was 50.1. The statewide average value of RWSBEE for this season was 74.7 MJ, while the modified RWSBEE2 statewide average was 63.7 MJ.

By examining the correlation between the various index calculations and the winter weather hours for all units, sub-districts, and districts, a high level of correlation was found for each of the proposed winter severity indices. Across all of the INDOT areas, LWSS had a correlation of 0.97 with winter weather hours during this season. MDSS showed a correlation of 0.96, and the Meridian index was nearly perfectly correlated with winter weather hours (0.99), likely due to the fact that the Meridian formula uses weather hour information directly. RWSBEE index values showed a correlation with weather hours of 0.94, still indicating a strong correlation with weather hour information, but providing slightly more independent information than the other proposed indices. The modified RWSBEE2 index had a slightly higher correlation with weather hours of 0.96. Since the RWSBEE and RWSBEE2 indices are based upon physical processes related to snow/ice melt, these will be used for further consideration in the analysis of the 2013–14 season.

5.2 Comparison of Maintenance Costs per Lane Mile per Index Value

The distribution of winter maintenance costs per lane mile per winter weather hour for each individual district, sub-district, and unit across the 2013–14 season is shown in Figure 5.1. The costs have been normalized by the state average for this season, and have been randomly shuffled to avoid identification of specific INDOT units. After normalizing these data (by dividing by the state average), the standard deviation of the statewide distribution is equal to 0.29. This can be considered the "coefficient of variation" for the costs per lane mile per weather hour for this season. As shown in Figure 5.1, there is considerable variability in the costs per lane mile per hour of winter weather across the state, with several areas below the state average, and many other areas above the state average.

The distribution of winter maintenance costs per lane mile per RWSBEE index value for each individual district, sub-district, and unit across the 2013–14 season is shown in Figure 5.2. As in the previous figure, these costs have been normalized by the state average for this season, and have been randomly shuffled in an identical manner, so that the areas are in the same order as in Figure 5.1. After normalizing these data (by dividing by the state average), the standard deviation of the statewide distribution is equal to 0.33. This can be considered the coefficient of variation for the costs per

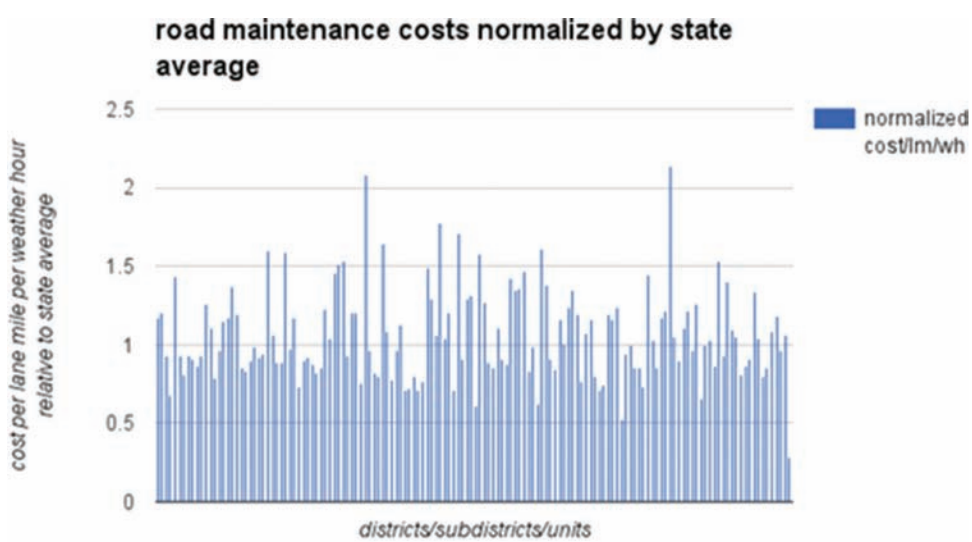

Figure 5.1 Normalized winter maintenance costs per lane mile per weather hour during 2013–14 season. A value of "1" on this chart indicates a cost per lane mile per weather hour equal to the state average value. Each bar indicates the value for a specific INDOT district, sub-district, or unit. These areas have been randomly shuffled on this chart to prevent identification.

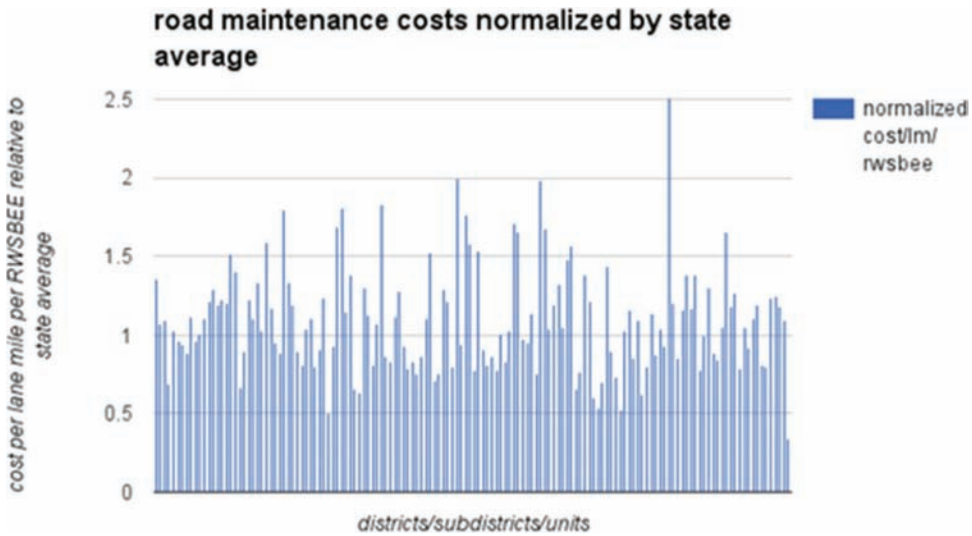

Figure 5.2 As in Figure 5.1, except for costs per lane mile per RWSBEE index. The random shuffling of individual areas is identical to Figure 5.1.

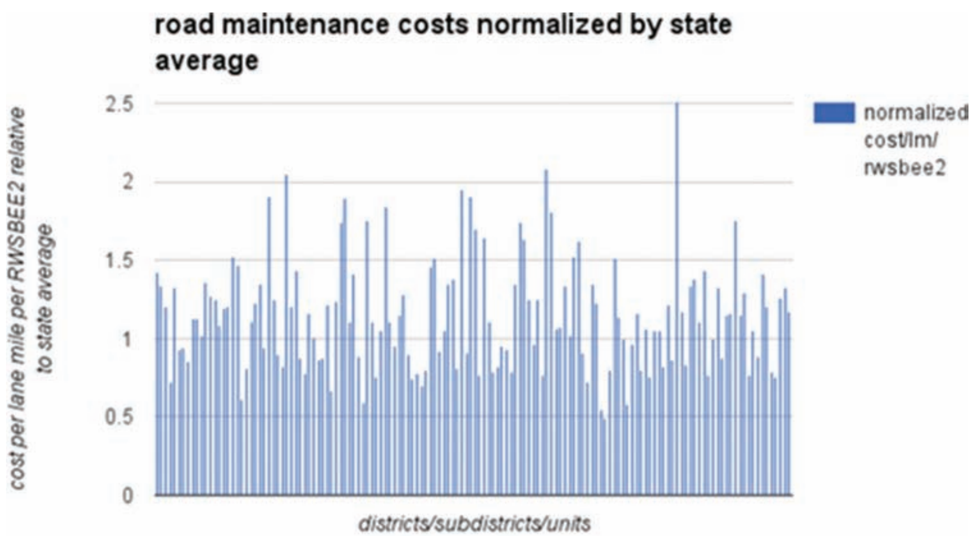

Figure 5.3 As in Figure 5.1, except for costs per lane mile per RWSBEE2 index. The random shuffling of individual areas is identical to Figure 5.1.

lane mile per weather hour for this season. This value is larger than the variation found in the costs per lane mile per weather hour, indicating an increase in the variability of the costs when analyzed per RWSBEE index value. Again, as in the previous figure, there is considerable variability in the costs per lane mile per RWSBEE index across the state, with several areas below the state average, and many other areas above the state average.

Similar results are found in the distribution of costs per lane mile per RWSBEE2 index value for each district, sub-district, and unit across the 2013–14 season (Figure 5.3). These costs have been normalized by the state average value for this season, and have been randomly shuffled in the same manner as in Figure 5.1, so there is a one-to-one correspondence to the order of district/sub-district/units as you move from left-to-right along each of these bar charts. In the case of the modified RWSBEE2 index, the standard deviation of the statewide deviation has increased slightly to 0.36. There remains considerable variability in the costs per lane mile per RWSBEE2 index across the state, with several areas above and below the state average.

Figures 5.4 and 5.5 display the relationship between individual cost (per lane mile) values per weather hour versus per RWSBEE (Figure 5.4) or RWSBEE2 (Figure 5.5) index values. Given the high degree of correlation found between these indices and the winter weather hour data, these results are not surprising. In particular, the most "expensive" area in terms of costs per weather hour is also the most expensive area when viewed in terms of costs per RWSBEE index. The least

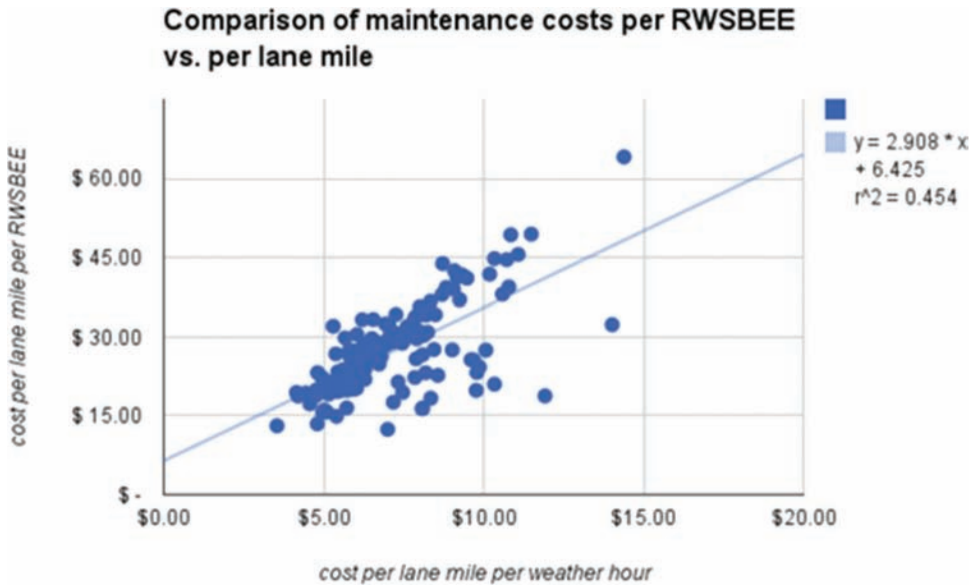

Figure 5.4 Scatter plot of INDOT area cost per lane mile per weather hour vs. cost per lane mile per RWSBEE. Linear trendline included.

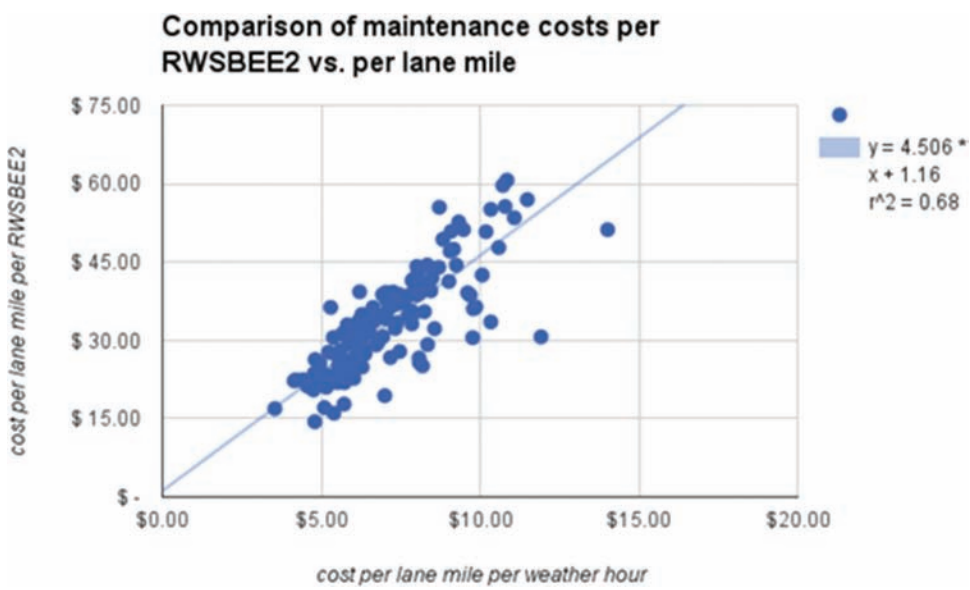

Figure 5.5 Scatter plot of INDOT area cost per lane mile per weather hour vs. cost per lane mile per RWSBEE2. Linear trendline included.

costly area in terms of cost per lane mile is the second least costly in term of cost per RWSBEE. In general, the cost per RWSBEE is approximately three times the cost per weather hour, and areas that are more costly in terms of weather hours are also more costly in term of RWSBEE index values. Similar results are found with the modified RWSBEE2 index, except the cost per RWSBEE2 is approximately 4.5 times the cost per weather hour.

Examining the normalized change in the difference in cost between each area versus the statewide average value, nearly half of the areas (67 out of 141) moved closer to the state average when viewed in terms of costs per lane mile per RWSBEE than costs per lane mile per weather hour. Nearly 75% of the areas (104 out of 141) across the state were either closer to the state average or within ±5% (minor differences) of the value when viewed in terms of costs per RWSBEE instead of costs per weather hour. These were the points scattered near the trendline in Figure 5.3. Roughly 25% of the areas (37 out of 141) were viewed as significantly further away (more than 5%) from the state average when analyzed as cost per RWSBEE instead of cost per weather hour. The modified RWSBEE2 index displayed nearly the same performance (105 out of 141 moved closer or stayed within ±5% of state average) when viewed in term of costs per RWSBEE2 instead of costs per weather hour. Although the overall variation across the state increased when doing the cost analysis per RWSBEE (or RWSBEE2) than per weather hour, the majority of the areas across the state were viewed either closer to the state average or only slightly worse ($\pm 5\%$). Therefore, the RWSBEE/RWSBEE2 indices appear to be including useful information regarding weather severity in the areal analysis of costs per lane mile.

Clearly, non-weather related factors are also important in determining the maintenance costs at the unit, sub-district, and district levels, such as salt usage. These factors cannot be accounted for using a severity index that is based solely on weather information.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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