Toward the Development of an Impact-Based Decision Support Tool for Surface-Transportation Hazards. Part II: An Hourly Winter Storm Severity Index

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ABSTRACT: In line with the continued focus of the National Weather Service (NWS) to provide impact-based decision support services (IDSS) and effectively communicate potential impacts, a new IDSS forecasting tool for surface-transportation hazards is in development at the Weather Prediction Center: the hourly winter storm severity index (WSSI-H). This second part of the series outlines the current algorithms and thresholds for the components of the WSSI-H, which has been developed in line with the approach and considerations discussed in Part I of this series. These components—snow amount, ice accumulation, snow rate, liquid rate, and blowing and drifting snow—each address a specific hazard for motorists. The inclusion of metrics related to driving conditions for untreated road surfaces and time-of-day factoring for active precipitation types helps directly tie forecasted weather conditions to transportation impacts. Impact severity level thresholds are approximately in line with thresholds used by transportation agencies when considering various mitigation strategies (e.g., imposing speed restrictions or closing roadways). Whereas the product is not meant to forecast specific impacts (e.g., road closure or pileup), impact severity levels are designed to scale with increasingly poor travel conditions, which can prompt various mitigation efforts from motorists or transportation agencies to maintain safety. WSSI-H outputs for three winter events are discussed in depth to highlight the potential utility of the product. Overall, the WSSI-H is intended to provide high-resolution situational awareness of potential surface-transportation-related impacts and aid in enhanced collaborations between NWS forecasters and stakeholders like transportation agencies to improve motorist safety.

SIGNIFICANCE STATEMENT: A new impact-based forecast product designed to aid in situational awareness of potential impacts from surface-transportation-related hazards is in development. In this second part of the series, we outline the algorithms and thresholds for the various components of the product, where each component addresses a unique hazard. Product outputs for three winter events are presented to highlight the potential utility of the product in an operational forecast setting. Ultimately, enhanced collaboration between forecasters and transportation agencies alongside guidance from this product will bolster consistent messaging to motorists and improve safety and mobility on roads.

KEYWORDS: Winter/cool season; Operational forecasting; Decision support; Societal impacts; Transportation meteorology

1. Introduction

Tobin et al. (2024, hereafter Part I) motivated the desire for an impact-based forecast product for precipitation-related surface-transportation hazards and outlined the intent and development considerations for such a product to meet these needs. Here, we outline the development of a new National Weather Service (NWS) Weather Prediction Center (WPC) forecasting tool as part of the winter storm severity index (WSSI; WPC 2022, 2024; Kastman et al. 2023, manuscript submitted to *Wea. Forecasting*) suite of products: the hourly WSSI (WSSI-H).

The WSSI was developed to complement a shifting focus of the NWS to provide impact-based decision support services (IDSS). Its algorithms combine official NWS forecast data with climatological and nonmeteorological data using geographic information systems (GISs) to output a forecast of the severity of societal impacts. Impacts are categorized on a four-tiered potential impacts scale of minor, moderate, major, and extreme for a variety of components that each address a specific hazard (e.g., snow amount, ice accumulation, and blowing snow). A "winter weather area" is also displayed for areas where winter weather conditions are anticipated but where impacts are not expected to occur. The product is thus able to spatially communicate potential impacts for all winter weather conditions—including those that do not meet NWS winter storm warning (WSW) criteria—and indicate which specific winter hazard the impacts are coming from (e.g., snow vs ice).

The WSSI is a decision support tool to help forecasters, stakeholders, and the public maintain situational awareness of impending winter conditions and has been used extensively by the NWS and media to effectively communicate potential impacts to the public. The product output is intended to scale with the severity of impacts on daily life, with impacts including, but not limited to, traffic disruptions; road, school, or

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business closures; power or other utility service disruptions or outages; and damage to tree limbs or built infrastructure from the weight of snow or ice. Social-science-based feedback revealed that most professional WSSI users are primarily concerned with impacts on surface transportation (Semmens et al. 2023). However, the current operational WSSI lacks the capability to adequately resolve all transportation-related impacts, as it is based on 6-h forecast data from the National Digital Forecast Database (NDFD), and displays impact classifications in 24-h increments. These 6-h forecasts are too coarse for short-duration, high-impact events such as snow squalls, whose total snowfall accumulations are often too low to trigger higher impact levels in the WSSI algorithms. Further, the 24-h breakouts are too coarse to resolve time-of-day-based impacts such as snowfall during peak travel times versus overnight hours.

Whereas the overall framework of the WSSI—ingesting forecast data and combining it with climatological and nonmeteorological data to inform impact levels—is ideal for surface-transportation applications, a separate product with higher temporal resolution is necessary to address and communicate surface-transportation-related impacts. Part I of this series discussed a novel approach to scale weather forecast data to transportation impacts using a metric for driving conditions and time-of-day factors for active precipitation. The former incorporates existing research on the influence of weather on vehicle free-flow speeds, and the latter are based on new research on the hourly influences of precipitation on crash risk and crash severity. Impact severity levels are then informed with the help of transportation agency guidelines for imposing specific travel restrictions (e.g., speed limit restrictions, vehicle bans, lane or road closures, and chain controls). In this way, the WSSI-H is intended to scale with increasingly poor driving conditions, which can necessitate enhanced mitigation efforts by motorists or transportation agencies. Impacts intended to be captured by the WSSI-H include disruptions to transportation, which can range from increased travel times and delays to extended road closures or impassable roads.

This second part of the series details specifics on the forecast data and algorithms of the WSSI-H. This includes more information on the formulation of the driving conditions metric and time-of-day factors that were introduced in Part I and the current algorithms and thresholds for each of the WSSI-H components. Finally, output for three recent events during which winter weather adversely impacted surface transportation is shown to demonstrate how the algorithms arrive at a final impact rating and highlight the potential utility of the product.

2. Framework of WSSI-H

WSSI-H algorithms ingest forecast data from the High-Resolution Rapid Refresh (HRRR; Dowell et al. 2022; James et al. 2022). The HRRR features a 3-km horizontal resolution and produces hourly output out to 48 h every 6 h [i.e., 0000, 0600, 1200, and 1800 UTC)] and out to 18 h for all other hours. The hourly temporal resolution and high spatial resolution of the HRRR make it ideal for WSSI-H development, as the data can be used to identify potential impacts to surface transportation on a much finer spatiotemporal scale than the NDFD-based operational WSSI (WPC 2022; Kastman et al. 2023, manuscript submitted to *Wea. Forecasting*). The HRRR has predictive skill for winter precipitation systems that has been documented in previous studies (e.g., Ikeda et al. 2013, 2017; James et al. 2022). Of note, there is higher performance skill for larger, synoptically forced systems than smaller weather systems, and lower performance skill for mixed-phase precipitation compared to rain and snow (Ikeda et al. 2013). In areas of mixed precipitation, the HRRR represents the vertical thermodynamic structure well, yet precipitation phase errors are often due to surface temperature biases (Ikeda et al. 2017).

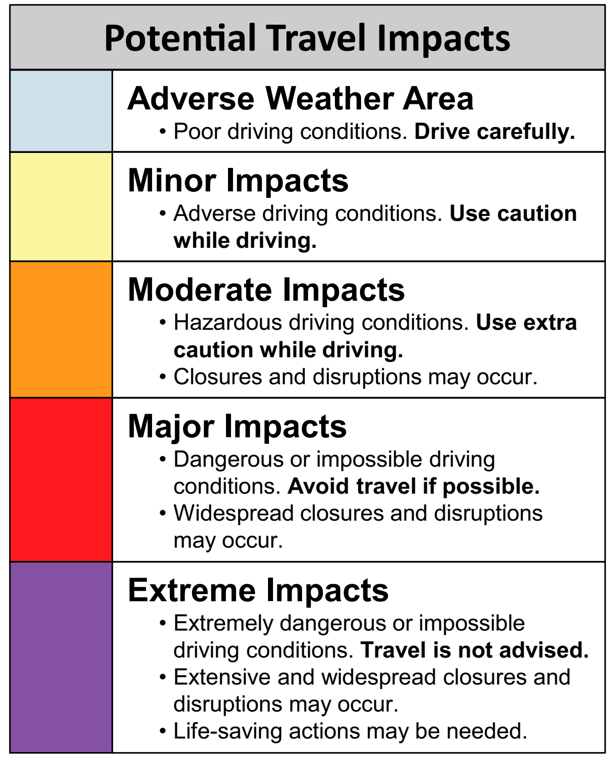

FIG. 1. WSSI-H legend, including impact categories and definitions.

The HRRR model variables used in the WSSI-H algorithms include variable density snow accumulation, visibility, wind speed, 2-m surface temperature, 1-h total liquid-equivalent precipitation, ice accumulation, and categorical precipitation types of rain, snow, ice pellets, and freezing rain. Hourly snow rates for forecast hours beyond 1 h are approximated as the difference between the snow accumulation of the current forecast hour and the prior forecast hour. Hourly ice accumulation rates are also computed in the same manner.

Anticipated impacts are categorized on a four-tiered scale of minor, moderate, major, and extreme. An "adverse weather area" is also included to denote areas where adverse weather conditions are anticipated but are not expected to impact surface transportation. Corresponding definitions for each category are shown in Fig. 1. These definitions include descriptions of the driving conditions (e.g., hazardous driving conditions), include precautionary action statements for drivers (e.g., use caution while driving), and describe the extent of possible closures or disruptions, if applicable. The language used in these definitions follows updated definitions of the operational WSSI based on social science–led feedback (Semmens et al. 2023) and existing language used by the NWS for adverse weather conditions (Tobin et al. 2022). These impact levels and definitions closely mirror those of the operational WSSI product yet are specifically tailored to transportation applications.

Output from the WSSI-H is intended to aid NWS forecasters in providing IDSS by keeping forecasters aware of potential anticipated impacts to surface transportation if no mitigation efforts are taken by transportation agencies (e.g., no spreading treatments are applied to the roads and roads are not cleared of accumulating precipitation). For example, forecasted impacts due to snow accumulation do not take into consideration whether snow has actually accumulated on roadways (e.g., as opposed to melting on treated roadways) or if transportation agencies have cleared roadways of accumulated snow. As a result, the WSSI-H implies a "worst-case scenario" of anticipated severity based solely on the forecasted meteorological conditions. This is in line with the NWS directives of providing IDSS for meteorological conditions and hazards that affect travel on roadways, including timing, uncertainty, precipitation amounts, and the potential for adverse travel conditions (NWS 2019). It also supports the role of the NWS in collaborating with transportation agencies and their in-house meteorologists or contracted private sector providers "to ensure consistent, effective, and actionable messaging related to anticipated impacts" (NWS 2019).

Forecasted impact levels are not meant to forecast specific impacts such as delays, crashes, and road closures but, rather, are intended to provide a general sense of impacts that scale with increasingly poor driving conditions. For example, minor impacts may include travel delays and isolated crashes, whereas moderate impacts may include more widespread or severe crashes or the imposition of speed restrictions. Major impacts may include extensive crashes that require more time to clear, road closures, or other travel restrictions. Last, extreme impacts may include impassable roads or widespread road closures.

a. *WSSI disruption factors*

At the core of the WSSI-H are WSSI disruption factors, which are the metric representative of driving conditions introduced in Part I. These factors provide a base measure for how disruptive the forecasted weather and road conditions are to motor vehicle free-flow speeds, which can correspond to increased travel times. Free-flow speeds are the mean speed of passenger cars under low flow rates (i.e., no traffic). WSSI disruption factors are based on free-flow factor values reported in Maze et al. (2006) for various weather conditions (e.g., precipitation type and rate, visibility, temperature, and wind) and in Ye et al. (2009) for pavement conditions (e.g., wet, snowy, icy, slushy, and dry), as defined in Table 1. Pavement conditions are parameterized for untreated roadways based on precipitation type, precipitation rate, snow–liquid ratio, ice accumulation, wind speed, and whether roads are subfreezing (i.e., <0°C). This logic is defined in Table 2. For simplicity—and as a starting point for development—roads are assumed to be subfreezing if ambient 2-m temperatures are <0°C. Ultimately, however, this logic will be replaced with a more sophisticated model, such as through the integration of a machine learning algorithm that outputs the probability that roads are subfreezing (ProbSR; Handler et al. 2020; Baldwin et al. 2023). This integration will require additional work to identify which probability thresholds are ideal for determining whether roads are subfreezing, as these thresholds may be dependent on geography, time of day, or season.

Untreated road surface conditions are parameterized separately for areas with active snowfall and areas with active liquid precipitation. Areas with overlapping snow and liquid precipitation are assumed to have whichever road condition is worse (i.e., the higher WSSI disruption factor). "Lingering"

TABLE 1. Free-flow factors and corresponding WSSI disruption factors for various weather conditions within the WSSI-H.

Weather condition	Free-flow factor	WSSI disruption factor: 1.0 + (1.0 − free-flow factor)
Pavement conditions		
Dry	1.00	1.00
Wet	0.96	1.04
Lightly slushy	0.90	1.10
Slushy	0.87	1.13
Deep slushy	0.84	1.16
Dusting of snow	0.96	1.04
Frost	0.94	1.06
Lightly icy	0.94	1.06
Icy	0.85	1.15
Very icy	0.83	1.17
Lightly snow covered	0.89	1.11
Snow covered	0.84	1.16
Precipitation conditions		
No precipitation	1.00	1.00
Rain ≤ 0.01 in. h^{-1}	0.98	1.02
Rain ≤ 0.25 in. h^{-1}	0.96	1.04
Rain > 0.25 in. h^{-1}	0.94	1.06
Snow ≤ 0.05 in. h^{-1}	0.96	1.04
Snow ≤ 0.1 in. h^{-1}	0.92	1.08
Snow ≤ 0.5 in. h^{-1}	0.91	1.09
Snow > 0.5 in. h^{-1}	0.87	1.13
Visibility conditions		
Visibility > 1 mi	1.00	1.00
Visibility ≤ 1 mi	0.93	1.07
Visibility ≤ 0.5 mi	0.93	1.07
Visibility < 0.25 mi	0.88	1.12
Temperature conditions		
$T > 50$°F (10°C)	1.00	1.00
$T \leq 50$°F (10°C)	0.99	1.01
$T \leq 32$°F (0°C)	0.99	1.01
$T \leq -4$°F (−20°C)	0.98	1.02
Wind conditions		
Wind < 10 mph (4.47 m s^{-1})	1.00	1.00
Wind ≥ 10 mph (4.47 m s^{-1})	0.99	1.01
Wind > 20 mph (8.94 m s^{-1})	0.99	1.01

TABLE 2. Weather and road temperature conditions corresponding to the various parameterized untreated road surface conditions.

	Weather and road temperature conditions	
Pavement condition	Snow rate > 0 (in. h^{-1})	Liquid rate > 0 (in. h^{-1})
Dry	Snow rate < 0.25 in. h^{-1}, subfreezing roads, SLR > 20:1, and wind > 5 m s^{-1}	—
Wet	Snow rate < 0.5 in. h^{-1} and above-freezing roads	Above-freezing roads
Lightly slushy	Snow rate 0.5–1 in. h^{-1} and above-freezing roads or SLR < 5:1	—
Slushy	Snow rate 1–1.5 in. h^{-1} and above-freezing roads or SLR < 5:1	—
Deep slushy	Snow rate ≥ 1.5 in. h^{-1} and above-freezing roads or SLR < 5:1	—
Frost	—	—
Lightly icy	—	Subfreezing roads and ice accumulation < 0.01 in. h^{-1}
Icy	—	Subfreezing roads and ice accumulation 0.01–0.05 in. h^{-1}
Very icy	—	Subfreezing roads and ice accumulation ≥ 0.05 in. h^{-1}
Dusting of snow	Snow rate < 0.5 in. h^{-1} and subfreezing roads	—
Lightly snow covered	Snow rate 0.5–1 in. h^{-1} and subfreezing roads	—
Snow covered	Snow rate ≥ 1 in. h^{-1} and subfreezing roads	—

road surface conditions are assumed where the worse road surface condition between the current and previous forecast hour (for forecast hours > 1) is used for the current forecast hour. For example, if the previous hour had "icy" untreated road conditions and the current forecast hour has "snowy" untreated road conditions, the current forecast hour's WSSI disruption factor for pavement will be set to that of the icy roads. If the following hour has "slushy" untreated road conditions, the WSSI disruption factor for pavement will then be set to that of snowy roads.

The individual WSSI disruption factors for temperature, wind speed, visibility, precipitation type, precipitation intensity, and parameterized untreated road surface condition are each taken and multiplied together for a combined WSSI disruption factor. For example, 1.0 in. h^{-1} snowfall on snow-covered roads with 0.5-mi visibility, a temperature of 0°C, and wind speed of 15 mph would have a combined WSSI disruption factor of 1.43 (1.13 × 1.16 × 1.07 × 1.01 × 1.01; Table 1). The combined WSSI disruption factors ultimately help to regulate impact ratings based on the totality of weather and road conditions. For example, 0.25 in. h^{-1} of snow with otherwise decent driving conditions (e.g., warm temperatures, low wind speeds, high visibility, and wet roads) will have a lower impact than 0.25 in. h^{-1} of snow with poor driving conditions (e.g., cold temperatures, high wind speeds, low visibility, and snowy, slushy, or icy roads).

b. *Components of WSSI-H*

The WSSI-H currently addresses the following winter weather hazards that pose a threat to surface transportation: accumulations of snow and ice, precipitation rate, and blowing snow. Accumulations of snow and ice can create slick conditions on roadways, whereas actively falling snow and liquid precipitation can reduce visibility. Similarly, visibility reductions can occur if falling or previously fallen snow is blown or resuspended to the height of the driver's eye level. These hazards can each be extremely hazardous to motorists and can increase the risk of a crash, increase travel times, or prompt transportation agencies to impose restrictions, including vehicle restrictions, chain controls, and lane or road closures. Within the WSSI-H, anticipated impacts are computed for several individual components, so users can visualize and identify the specific hazard that is forecasted. Currently, these components are snow amount, ice accumulation, snow rate, liquid rate, and blowing and drifting snow. A flowchart depicting which of the HRRR input variables and other computed variables go into each component is included in Fig. 2 for reference.

1) PRECIPITATION ACCUMULATION

The snow amount and ice accumulation components denote the impacts associated with the total accumulations of snow and ice, respectively, since the model runs initialization. We adjust these accumulations by incorporating a normalized version of the combined WSSI disruption factor so that the impacts associated with the accumulations can appropriately scale to driving conditions. For example, 4.0 in. of snow accumulation while it is still snowing heavily is more impactful than 4.0 in. of snow accumulation after the weather has improved. For this, the combined WSSI disruption factor (with a value between 1.0 and 1.53) is normalized to a value between 0.9 and 1.25, which is then multiplied by the modeled depth of snow or ice accumulations (in inches) for the respective component to obtain an effective snow amount or an effective ice accumulation. This means that these effective accumulations are anywhere from 10% lower to 25% higher than modeled accumulations based on parameterized driving conditions. These final values are then used

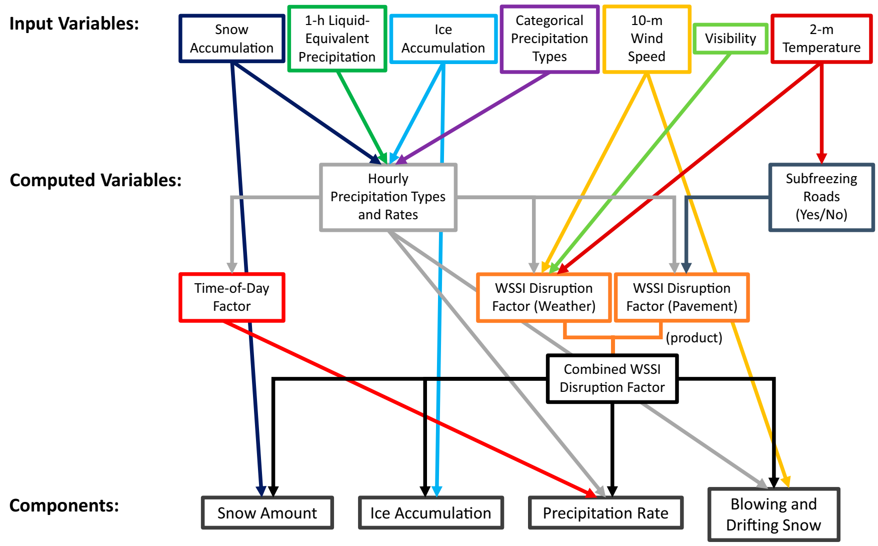

FIG. 2. Flowchart of the HRRR input variables and computed variables that go into each component of the WSSI-H.

to determine the corresponding impact category. The thresholds for the snow amount component are identical to those used for the current operational WSSI (Fig. 3), and the thresholds for the ice accumulation component are shown in Table 3. The snow amount thresholds are based on a climatology developed exclusively for the WSSI based on observed 2-day station-based snowfall data (Kastman et al. 2023, manuscript submitted to *Wea. Forecasting*). The threshold for adverse weather area is any snow or ice accumulations >0 in.

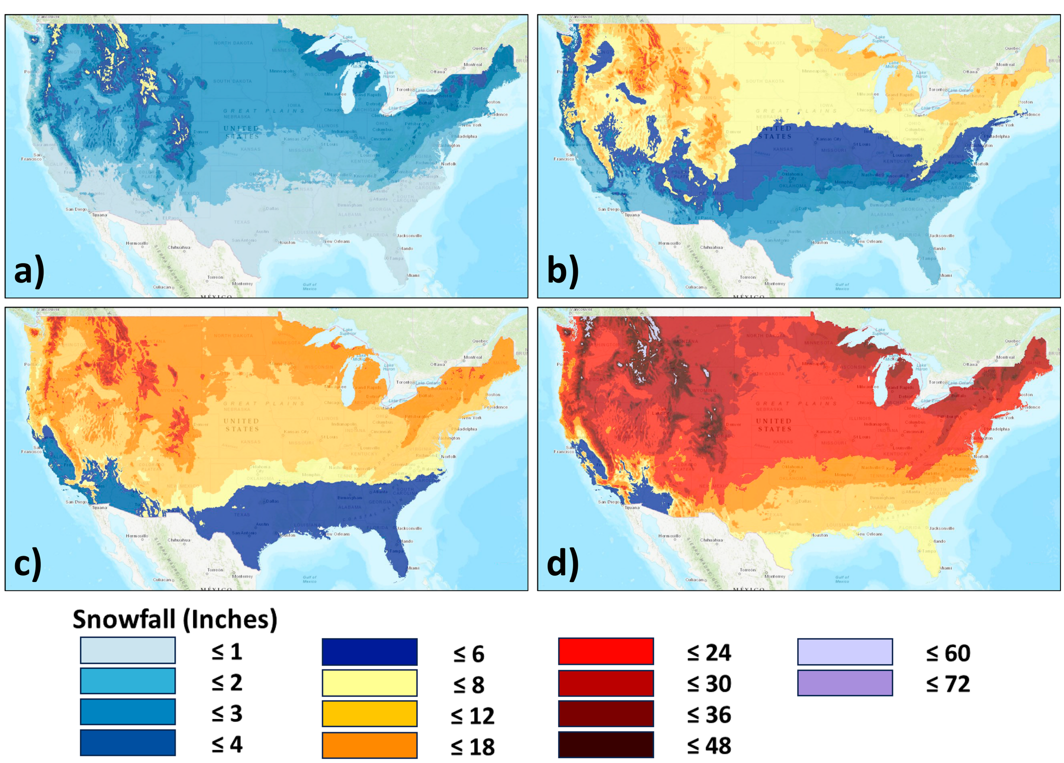

FIG. 3. WSSI snow amount component thresholds for both operational WSSI and WSSI-H for the (a) minor, (b) moderate, (c) major, and (d) extreme impact levels.

TABLE 3. WSSI-H impact level thresholds for each component.

WSSI impact category	Snow rate component Effective snow rate	Liquid rate component Effective liquid rate	Ice accumulation component Effective ice accumulation	Blowing and drifting snow component Effective visibility
Adverse weather area	0.00 in. h^{-1}	0.00 in. h^{-1}	0.00 in.	1.0 mi
Minor	0.50 in. h^{-1}	0.25 in. h^{-1}	0.01 in.	0.5 mi
Moderate	1.00 in. h^{-1}	0.50 in. h^{-1}	0.10 in.	0.25 mi
Major	2.00 in. h^{-1}	1.00 in. h^{-1}	0.64 in.	0.0625 mi
Extreme	3.00 in. h^{-1}	2.00 in. h^{-1}	1.28 in.	0.031 25 mi

2) PRECIPITATION RATE

The snow rate and liquid rate components denote impacts associated with hourly precipitation rates of snow and/or ice pellets (for snow rate) and rain and/or freezing precipitation (for liquid rate). Similar to what was done for precipitation accumulations, we wish to compute an effective precipitation rate that adjusts the modeled precipitation rates based on driving conditions. However, we also wish to adjust precipitation rates based on the time of day at which the precipitation is occurring. In Part I of this series, the influence of precipitation type on transportation throughout the day was defined in the form of time-of-day factors. These factors were created by analyzing transportation data (i.e., crash and traffic volume data) from several Great Lakes states and are based on a combination of 1) crash relative risk estimates, 2) crash severity and vehicles involved, and 3) average traffic volumes. These factors help to scale impacts based on local time of day and day of the week. For example, 1.0 in. h^{-1} of snow will have a higher impact during midday versus overnight hours, and snow during weekday morning rush hours will have a higher impact than the same time on a weekend. These time-of-day factors are defined for each precipitation type (snow, ice pellets, freezing rain, and rain) for each local hour of the day for weekdays, weekends, and holidays (Thanksgiving, Christmas Eve, Christmas, New Year's Eve, and New Year's Day). These factors are applied across the entire United States based on the local time of day within each respective time zone. Because the factors were derived using data from select years and four states in the Great Lakes region and smoothed to preserve only the prominent diurnal influences of precipitation on transportation (e.g., midday vs overnight periods), they may not appropriately capture more localized diurnal influences, diurnal influences for other regions of the United States, or the magnitude of rush hour influences. The inclusion of these more specific influences would require additional research.

The product of the combined WSSI disruption factor and the appropriate time-of-day factor (Part I) is normalized to a value between 0.9 and 1.25 based on the minimum and maximum potential value for snow (for snow rate) and for rain (for liquid rate). This normalized value is then multiplied by the modeled hourly precipitation rate to obtain an effective precipitation rate. This means that these effective precipitation rates for snow and rain are anywhere from 10% lower to 25% higher than modeled rates. Effective precipitation rates for ice pellets and freezing rain can exceed the 25% increase because of their higher time-of-day factoring. This is done to ensure that the impacts associated with ice pellets exceed those for snow of the same rate and that the impacts associated with freezing rain exceed those for rain of the same rate, consistent with observed impacts (e.g., Part I; Tobin et al. 2021). However, in order to ensure that the effective precipitation rates do not drastically exceed the raw precipitation rates, especially for higher precipitation rates, we cap the effective precipitation rates at 0.25 in. h^{-1} greater than the raw precipitation rates. For example, 2.0 in. h^{-1} of snow will only ever adjust to an effective precipitation rate of 1.8–2.25 in. h^{-1}.

Impact thresholds for the snow rate and liquid rate components are based on the respective effective precipitation rates shown in Table 3, with the threshold for adverse weather area as any effective precipitation rate > 0 in. h^{-1}. These thresholds are based on Pennsylvania Turnpike guidelines that trigger different "event levels" in their "Weather Event Management Playbook," which may include various potential travel restrictions, as introduced in Part I. These thresholds are applied across the United States as a starting point, but these thresholds—particularly the snow rate thresholds—will need to be adjusted in the future to introduce appropriate regionality. For example, snow rate thresholds in the southern region should be lowered, whereas thresholds in mountainous areas of the western United States may need to be increased. However, as discussed in Part I, our knowledge of appropriate thresholds for other states and regions is currently limited due to such thresholds being poorly defined or unknown. Knowledge of these thresholds or research into precipitation rate climatology across the United States is necessary to help inform which thresholds should be used.

3) BLOWING AND DRIFTING SNOW

The blowing and drifting snow component denotes impacts associated with the combination of wind and falling and/or resuspended snow. This component calculates the snow transport rate—the mass of blowing snow particles passing through a unit width per unit time—and then computes corresponding visibility at driver eye level (~1.2 m). Table 4 includes the relevant symbols, definitions, and equations necessary for determining the conditions under which blowing and/or drifting snow occur (Table 5). These conditions follow from Takechi et al. (2016), which were presented in English in Harada et al. (2022).

TABLE 4. Definitions and equations for symbols used in the WSSI-H blowing and drifting snow algorithms.

Symbol	Definition	Equation (if applicable)
ASNOW	Variable-density snow accumulation	
D_1	Drifting snow conditional for $t < 12$	$-0.59U_{10} + 0.2T - 0.08\text{ASNOW} + 0.477$
D_2	Drifting snow conditional for $t \geq 12$	$-1.18U_{10} + 0.16T + 0.09t + 0.03U_{\text{sum}} + 4.93$
P	Liquid-equivalent snowfall rate (mm h^{-1})	
T	Air temperature (°C)	
$T_{\max}$	Maximum temperature after the end of snowfall (°C)	
t	Elapsed time after the end of snowfall (h)	
U_{10}	Wind speed at 10 m (m s^{-1})	
U_7	Wind speed at 7 m (m s^{-1})	$U_7 = U_{10}\dfrac{\log\left(\dfrac{7}{z_0}\right)}{\log\left(\dfrac{10}{z_0}\right)}$
U_{sum}	Integrated value of the fourth power of hourly wind speed since snowfall ended (m^4 s^{-4})	
z_0	Roughness length of snow surface (m)	0.000 15

After identifying the conditions in which blowing and/or drifting snow occur, the snow transport rate Q (in kg m^{-1} h^{-1}) is computed as follows:

$$Q = 1.47PU_7 + 0.00053U_7^{4.0}, \quad (1)$$

where the first part of the equation is the snow transport rate due to falling snow with wind and the second part is the snow transport rate due to drifting snow. As a note, the 4.0 in the exponent for the drifting snow portion of the equation was reduced from 4.6 in Harada et al. (2022) to provide a better estimation for the WSSI-H and to be in line with Takechi et al. (2016) taking the fourth power of hourly wind speed for U_{sum}. The snow transport rate is then converted to visibility at driver eye level following Harada et al. (2022), assuming that there exists no snow bank:

$$\text{vis}_{1.2\text{m}} = 8438Q^{-0.891}. \quad (2)$$

Because the impacts from blowing and drifting snow are primarily derived from reductions in visibility, the lower HRRR visibility and the calculated visibility at driver eye level are used to ensure proper representation of impacts in areas identified as having blowing and drifting snow. Although the calculated visibility is often lower than the HRRR visibility (see section 3), the ability to use the forecasted visibility when it is lower is beneficial if winter visibility forecasts are improved through blowing snow parameterization schemes (Letcher et al. 2021). We again wish to adjust this visibility based on the totality of driving conditions. For example, low visibility with snow-covered roads can be more impactful than the same visibility conditions with dry roads. As was done for precipitation accumulations, we normalized the combined WSSI disruption factors to a value between 0.9 and 1.25. Effective visibility is obtained by multiplying the calculated visibility at driver eye level in blowing and drifting snow by 2.0 minus the normalized value (i.e., 1.0 minus the absolute difference between 1.0 and the normalized value). This means that the effective visibility can be anywhere from 25% lower to 10% higher than the calculated visibility in blowing and drifting snow based on parameterized driving conditions. Impact thresholds based on the effective visibility are shown in Table 3, including the 1.0-mi threshold for adverse weather area. These thresholds were chosen specifically to highlight when blowing and drifting snow decrease visibility below 1.0 mi, which is when visibility begins to appreciably affect transportation (e.g., Maze et al. 2006).

3. Retrospective WSSI-H examples

WSSI-H output is presented in this section for three winter events to provide examples of how the impact levels are determined and also to highlight the potential utility of the product. For the first case, we focus on the use of the product to identify the timing and location of transient winter hazards, such as snow squalls and banded snow. For the second case, we focus on the use of the product to inform impacts over a full 48-h period and introduce the ability to identify locations that are expected to experience prolonged durations of higher-tier impacts from snow rates and blowing snow. For the third case, we focus again on a full 48-h period but with an emphasis on ice-related impacts.

a. 1 March 2020: Fatal multicar pileups in Wyoming

Afternoon snow squalls in the Rock Springs to Laramie corridor of Interstate 80 in Wyoming resulted in two separate

TABLE 5. Conditions for blowing and/or drifting snow, based on Takechi et al. (2016).

	Conditions for blowing and/or drifting snow
	Active snowfall
Blowing and drifting snow	$(T \leq -3)$ and $(U_{10} \geq 5)$ or $(-3 < T \leq 2)$ and $[U_{10} \geq 5 + (3 + T)]$
Blowing snow (no drifting)	$(T \leq -3)$ and $U_{10} < 5$ or $(-3 < T \leq 2)$ and $[U_{10} < 5 + (3 + T)]$ or $2 < T < 2.5$
	Preexisting snow
Drifting snow only	$U_{10} > 3$, $T < 2$, $T_{\max} < 2$, and $t < 12$ and $D_1 < 0$ $t \geq 12$ and $D_2 < 0$

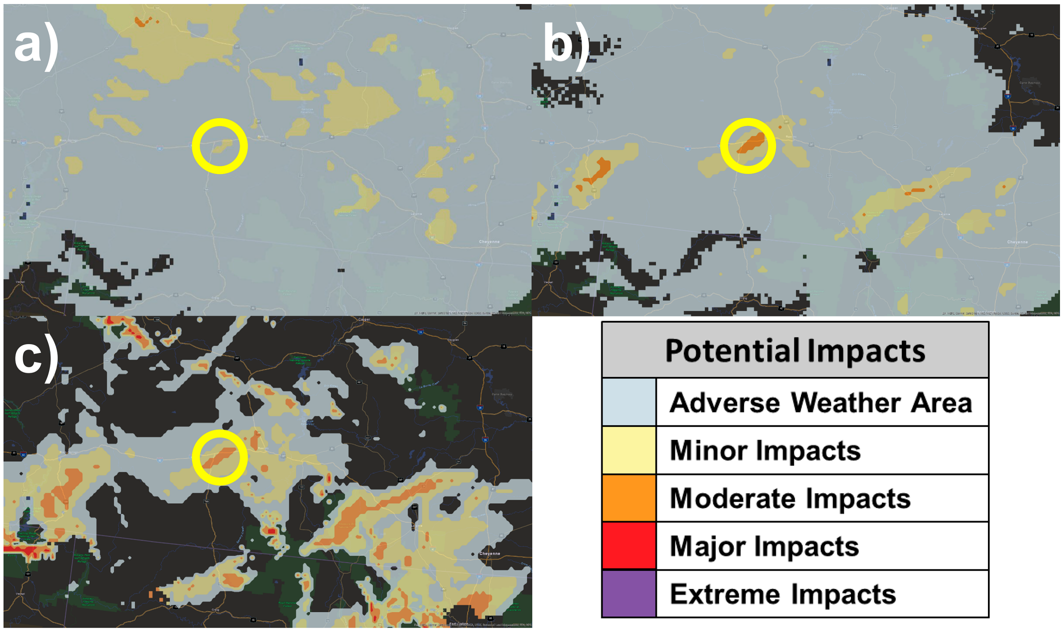

FIG. 4. WSSI-H output valid at forecast hour 11 from the 1200 UTC 1 Mar 2020 model run for (a) snow amount, (b) snow rate, and (c) blowing and drifting snow. The location of the fatal pileup is indicated by the yellow circle.

pileups—one fatal—at mile markers 181 and 184 around 0339 mountain time (2239 UTC). Thirty vehicles, consisting mostly of commercial vehicles, initiated the fatal pileup, with secondary crashes involving around 25 vehicles. The second, smaller pileup involved roughly 40 vehicles, again mostly commercial vehicles. Three people were killed in the first pileup, and 30 people were transported to the local hospital between the two pileups.

WSSI-H algorithms were run using data from the 1200 UTC 1 March 2020 HRRR model output. The resulting WSSI-H output for forecast hour 11 (Fig. 4) is valid around the time of the crash and shows that snow amounts do not quite meet the criteria for minor impacts, but both snow rate and blowing and drifting snow show moderate impacts at the crash location. The raw HRRR variables and the computed WSSI-H variables at the crash location for this forecast hour are included in Table 6 for reference as we walk through how impact levels were arrived at for this forecast hour.

At this forecast hour, there is no liquid precipitation or ice accumulation and thus no impacts for the liquid rate or ice accumulation components. With a snow rate of 1.00 in. h^{-1} and a temperature of -5.29°C, roads are assumed to be snow covered with a WSSI disruption factor for pavement of 1.16 (Tables 1 and 2). The product of this WSSI disruption factor for pavement (1.16) and the WSSI disruption factors for the other ambient weather conditions (Table 1 values in relation to the Table 6 values: 1.13 for precipitation, 1.07 for visibility, 1.01 for temperature, and 1.01 for wind) results in the combined WSSI disruption factor of 1.43 (i.e., $1.16 \times 1.13 \times 1.07 \times 1.01 \times 1.01$), indicating poor driving conditions. This value (with a range of possible values between 1.0 and 1.53) normalized between 0.9 and 1.25 is 1.18. This normalized value multiplied by the HRRR snow amount of 2.18 in. results in an effective snow amount of 2.58 in., which does not quite meet the minor threshold of 2.66 in for the snow amount component (Fig. 3).

For the snow rate component, the time-of-day factor for snow at that hour on a weekend (1.56) is multiplied by the combined WSSI disruption factor (1.43) for a value of 2.23. This resulting value (with a range of possible values between 1.0 and 2.46) is then normalized (between 0.9 and 1.25) to 1.20 and multiplied by the raw snow rate. This provides an effective snow rate of 1.2 in. h^{-1}, which exceeds the moderate impact threshold for snow rate.

For the blowing snow component, the computed visibility within blowing and drifting snow conditions is 0.29 mi. This computed visibility follows from Eq. (2) after computing the snow transport rate of both blowing and drifting snowfall [Eq. (1), in full], as the forecasted conditions favor both blowing and drifting snowfall during active snowfall (Table 4). This computed visibility is lower than the HRRR visibility (0.5 mi), highlighting the added value of computing visibility in conditions of blowing snow instead of relying on the model output. This lower visibility is then multiplied by 2.0 minus the normalized combined WSSI disruption factor (i.e., $2.0 - 1.18 = 0.81$) for a final WSSI-H blowing snow visibility of 0.23 mi, which is below the moderate threshold for blowing and drifting snow.

Overall, the output from the WSSI-H is consistent with whiteout conditions from heavy and blowing snowfall on snowy roads that contributed to the fatal pileup. The location of other snow squalls along Interstate 80 that also created dangerous driving conditions, yet did not result in deadly pileups, can also be identified in the WSSI-H output where there are narrow regions of higher impacts from both snow rate and blowing and drifting snow. At 1420 mountain standard time

TABLE 6. Raw HRRR values and computed WSSI-H values for the HRRR model runs and forecast hours discussed in sections 3a–c at the locations noted in Figs. 3–5, respectively. WSSI-H impact levels corresponding to the computed values are also denoted, if applicable.

WSSI-H model run and forecast hour	1200 UTC 1 Mar 2020, forecast hour 11	0600 UTC 3 Jan 2022, forecast hour 9	1200 UTC 31 Jan 2023, forecast hour 48
	Raw HRRR variables		
Snow amount	2.18 in.	5.81 in.	0.16 in.
Snow rate	1.00 in. h^{-1}	1.26 in. h^{-1}	0.00 in. h^{-1}
Ice accumulation	0.00 in.	0.00 in.	1.23 in.
Ice rate	0.00 in. h^{-1}	0.00 in. h^{-1}	0.01 in. h^{-1}
Liquid-equivalent precipitation rate	0.08 in. h^{-1}	0.18 in. h^{-1}	0.01 in. h^{-1}
Temperature	−5.29°C	−0.44°C	−0.23°C
Visibility	0.50 mi	0.25 mi	7.58 mi
Wind speed	16.22 m s^{-1}	9.93 m s^{-1}	3.19 m s^{-1}
	Computed WSSI-H variables (WSSI-H impact level, if applicable)		
Combined WSSI disruption factor	1.43	1.50	1.29
Effective snow amount	2.58 in. (adverse weather area)	7.14 in. (moderate)	0.17 in. (adverse weather area)
Time-of-day factor, snow	1.56	1.57	—
Effective snow rate	1.20 in. h^{-1} (moderate)	1.51 in. h^{-1} (moderate)	0.00 in. h^{-1} (no impacts)
Effective ice accumulation	0.00 in. (no impacts)	0.00 in. (no impacts)	1.34 in. (extreme)
Time-of-day factor, freezing rain	—	—	—
Effective liquid precipitation rate	0.00 in. h^{-1} (no impacts)	0.00 in. h^{-1} (no impacts)	0.01 in. h^{-1} (adverse weather area)
Visibility from blowing and drifting snow	0.29 mi	0.12 mi	—
Effective visibility	0.23 mi (moderate)	0.09 mi (moderate)	—

(MST) (2120 UTC), the NWS Cheyenne Weather Forecast Office (WFO) updated several WSWs for the area between Cheyenne and Rawlins. One WSW near Rawlins specifically mentioned "Interstate 80 northwest of Laramie towards Rawlins" and included the following for the impacts statement: "Transportation may be severely impacted with snow-covered roads, drifting snow and poor visibility. Plan on slippery road conditions. Patchy blowing snow could significantly reduce visibility at times." This is consistent with the location of the snow squall hazards and shows the potential for the WSSI-H to be used to aid in the identification of hazards to surface transportation and the issuance of WSWs or other NWS products. Future work should explore the utility of the WSSI-H for forecasting snow squalls and how the product can be used in relation to other forecasting tools (e.g., the snow squall parameter; Banacos et al. 2014) to differentiate squall-like blowing snow conditions from other blowing snow hazards (e.g., blizzards).

b. 3 January 2022: Interstate 95 shutdown in Virginia

A significant mid-Atlantic winter storm gridlocked traffic along a 50-mile stretch of Interstate 95 centered on Fredericksburg, Virginia. The backup of traffic due to poor weather conditions, disabled vehicles, and traffic crashes—several of which involved jackknifed tractor trailers that physically blocked multiple lanes of traffic—made it difficult for first responders and tow trucks to respond to and clear the incidents and also significantly hampered snowplow operations. Poor road conditions were further exacerbated by rain before the snow preventing effective pretreatment and high snow rates of over 3 in. h^{-1} that make snow-clearing operations difficult even under normal circumstances. After traffic came to a complete standstill, uncleared snow accumulations turned to ice overnight, with reports of up to 4 in of ice on the roadway. The cascading effects of higher-than-normal traffic volumes due to nearby flight cancelations, the inability to clear incidents and snow accumulations from roadways, and poor communication to motorists to avoid the interstate ultimately resulted in a complete shutdown of the interstate for over 30 h, stranding hundreds of motorists without food, water, or even gas.

The 48-h maximum WSSI-H impact output from the 0600 UTC 3 January 2022 HRRR model is shown in Fig. 5. This summary output initialized prior to the onset of the snowfall in the Fredericksburg area provides an event-level summary of the anticipated impacts and aids in highlighting areas of concern. Heavy snowfall—both in amount and rate—and reductions in visibility due to blowing and drifting snowfall are the primary drivers for impacts for the event, with moderate-to-major impacts in the region among these components. Although no specific timing information can be gained from this 48-h maximum perspective (e.g., when will peak impacts occur?), we introduce some timing information by outlining areas with four or more consecutive hours of at least moderate impacts of snow rate (Fig. 5b) and areas with six or more consecutive hours of at least moderate impacts of blowing and drifting snow (Fig. 5e). These extended durations of enhanced impacts aid in further highlighting areas of

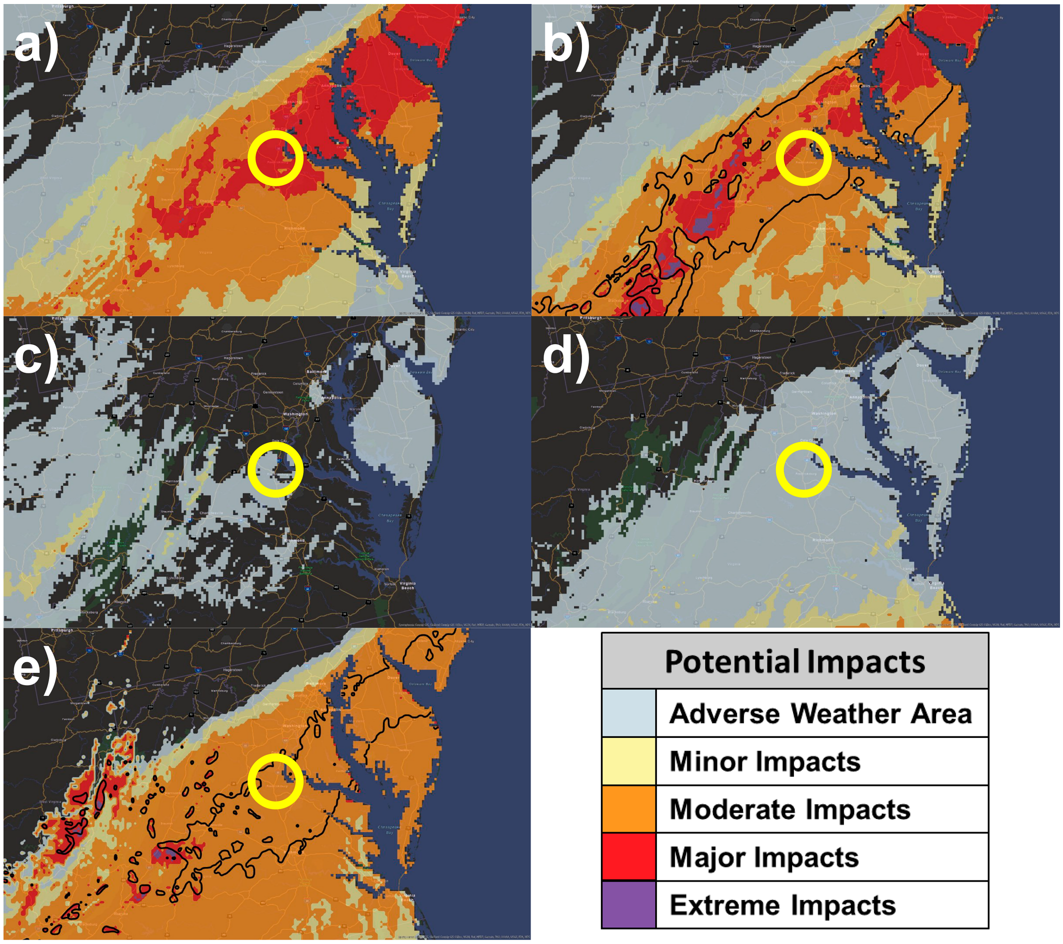

FIG. 5. The 48-h maximum WSSI-H output from the 0600 UTC 3 Jan 2022 model run for (a) snow amount, (b) snow rate, (c) ice accumulation, (d) liquid precipitation rate, and (e) blowing and drifting snow. The location of the initial point of the Interstate backup is indicated by the yellow circle. Black outlines in (b) denote areas with at least moderate impacts forecasted for four or more consecutive hours. Black outlines in (e) denote areas with at least moderate impacts forecasted for six or more consecutive hours.

concern embedded within the larger areas of major (or extreme) impacts. Inspection of the hourly WSSI-H output reveals that forecast hours 7–10 all exceeded the criteria for moderate snow rate impacts, corresponding to the hours ending at 0800–1100 eastern time. For blowing and drifting snow, forecast hours 5–11 exceeded the moderate impacts threshold.

We now focus on forecast hour 9 (1500 UTC; 1000 eastern time) to examine how impact levels were determined during this critical high-impact period when both snow rates and visibility reductions due to blowing and drifting snow were forecasted to impact transportation. At this forecast hour, there is no liquid precipitation or ice accumulation. The other raw HRRR and computed variables for the hourly WSSI at the interstate location noted in Fig. 5 are provided in Table 6. With a snow rate of 1.26 in. h^{-1} and a temperature of -0.44°C, roads are assumed to be snow covered with a WSSI disruption factor for pavement of 1.16 (Tables 1 and 2). Alongside the WSSI disruption factors for the other ambient weather conditions (Table 1 values in relation to the Table 6 values), the combined WSSI disruption factor is 1.50, indicating very poor driving conditions. This value is normalized to 1.23, which when multiplied by the HRRR snow amount of 5.81 in results in an effective snow amount of 7.14 in., which exceeds the moderate threshold of 4.65 in. for snow amount (Fig. 3).

The snow rate at this time is 1.26 in. h^{-1}, and the time-of-day factor for snow is 1.57. The product of the time-of-day factor and the combined WSSI disruption factor—normalized between 0.9 and 1.25—is 1.23, which results in an effective snow rate of 1.54 in. h^{-1} when multiplied by the snow rate. This effective snow rate is more than 0.25 in. h^{-1} greater than the raw snow rate, so it is adjusted down to 1.51 in. h^{-1}, which exceeds the moderate threshold of 1.0 in. h^{-1}.

Whereas the HRRR forecasted visibility at this time is 0.25 mi, the computed visibility from blowing and drifting snow is 0.12 mi. This computed visibility follows from Eq. (2) after computing the snow transport rate of both blowing and drifting snowfall [Eq. (1), in full], as the forecasted conditions favor both blowing and drifting snowfall during active snowfall (Table 4). This lower computed visibility again highlights the added value of computing visibility in conditions of blowing snow instead of relying solely on the model output. This lower computed visibility multiplied by 0.77 (i.e., 2.0, the normalized combined WSSI disruption factor of 1.23) results in an effective visibility of 0.09 mi, which is below the moderate threshold of 0.25 mi for blowing and drifting snow (Table 3).

Armed with impact forecasts at the event-level perspective (i.e., the 48-h maximum of impacts), a graphical depiction of the areas with a long duration of enhanced impacts (i.e., the outlines of several consecutive hours of at least moderate impacts), and knowledge of the specific hours meeting those enhanced impact criteria (i.e., forecast hours 7–10), it becomes evident that a highly impactful winter weather conditions is forecasted to occur in the Fredericksburg area of Interstate 95 for an extended period of time during the peak morning travel hours. Such a graphical depiction of a long duration of enhanced impacts, in addition to specific timing information and local knowledge of the road system and traffic demands on the Interstate, could potentially have been used to enhance the message for motorists to remain off roads for the entire morning until roads have been cleared and assist in allowing transportation officials, first responders, and the public to maintain situational awareness of the ongoing hazardous event.

c. 31 January–1 February 2023: Icing conditions in Texas and Arkansas

A winter storm with freezing precipitation significantly impacted surface transportation in the southern plains due to icy road conditions. Motorists were urged to stay off the roads unless necessary, and portions of Interstates 40, 35, 30, 20, and 10 were shut down due to crashes. Delivery services from DoorDash were suspended in central Arkansas and north Texas, and the U.S. Post Office suspended operations in north Texas, while Amazon, FedEx, and UPS were all operating under limited capacity. Hundreds of crashes across Texas, including two separate pileups involving at least a dozen vehicles, resulted in dozens of injuries and several fatalities. Motorists were also stranded on streets or highways due to icy road conditions.

Composite maximum WSSI-H output from the 1200 UTC 31 January 2023 model run valid for the next 48-h period (Fig. 6) forecasts adverse weather conditions with pockets of minor-to-moderate impacts from snow amount, snow rate, and liquid rate and extensive areas of major and extreme impacts from ice accumulations in Texas, Oklahoma, and Arkansas through Tennessee. This shows that while snow and snow accumulations were also forecasted as a hazard during this period, the primary hazard was significant ice accumulations from modest precipitation rates.

We focus on forecast hour 48 to examine how ice-based WSSI-H impacts are formulated for the Dallas/Fort Worth area location noted in Fig. 6. Freezing rain at this forecast hour is falling and accumulating ice at a rate of 0.01 in. h^{-1}. With no other active precipitation types and a temperature of −0.23°C, roads are assumed to be icy with a WSSI disruption factor for pavement of 1.15 (Tables 1 and 2). The combined WSSI disruption factor is 1.29, which normalizes to 1.09. This normalized value increases the 1.23 in. of ice accumulation up to an effective ice accumulation of 1.34 in., resulting in an extreme output for the ice accumulation component. For the liquid precipitation rate, the product of the combined WSSI disruption factor (1.29) and the time-of-day factor for freezing rain (1.81) is normalized to a value of 1.21, resulting in an effective liquid precipitation rate of 0.01 in. h^{-1}, which does not meet the minor impact threshold.

This event highlights the interconnection between the precipitation rate and accumulation components. Although the previous event (section 3b) had comparable impact levels from both the snow rate and snow amount components, this event shows how impacts from precipitation rates and accumulations do not necessarily go hand in hand. The precipitation rates for this event are not high enough to trigger enhanced impacts categories. However, the incremental ice accumulations from each hour added up considerably throughout the event, enough to trigger major and extreme impacts for the ice accumulation component in many areas. This highlights the need to examine each component of the WSSI-H to identify forecasted hazards.

4. Summary and discussion

The WSSI-H is a new NWS product in development at the Weather Prediction Center that is designed to aid in the forecasting of weather-related impacts on surface transportation. It is based on hourly high-resolution numerical weather prediction model data and accounts for several aspects of how weather affects surface transportation, including reduced vehicle speeds, increased crash risk and severity, and the potential for travel restrictions due to weather and road conditions. Currently, WSSI-H outputs four impact levels (minor, moderate, major, and extreme) for a series of weather hazards that affect surface transportation: snow amount, ice accumulation, precipitation rate (i.e., snow and liquid precipitation rates), and blowing and drifting snow. An adverse weather area is also output to denote areas in which a hazard is forecasted but is not expected to be impactful. Impact levels from each of the hazard types are meant to provide situational awareness of potential surface-transportation impacts to NWS forecasters, NWS partners (e.g., Department of Transportation and other transportation agencies, emergency managers), media, and the public.

Impact levels for the WSSI-H are designed to scale with increasingly poor driving conditions that can become increasingly perilous for motorists. As the severity of these adverse driving conditions increases, so, too, does the need for mitigation efforts or strategies in response to the forecasted weather and road conditions. These can range from motorists needing to slow down or increase following distances to transportation agencies imposing restrictions or closing roadways. The product implies a worst-case scenario based on forecasted meteorological conditions to aid NWS forecasters in more effective collaboration with stakeholders like state Department of Transportation (DOT) and provide more targeted messaging

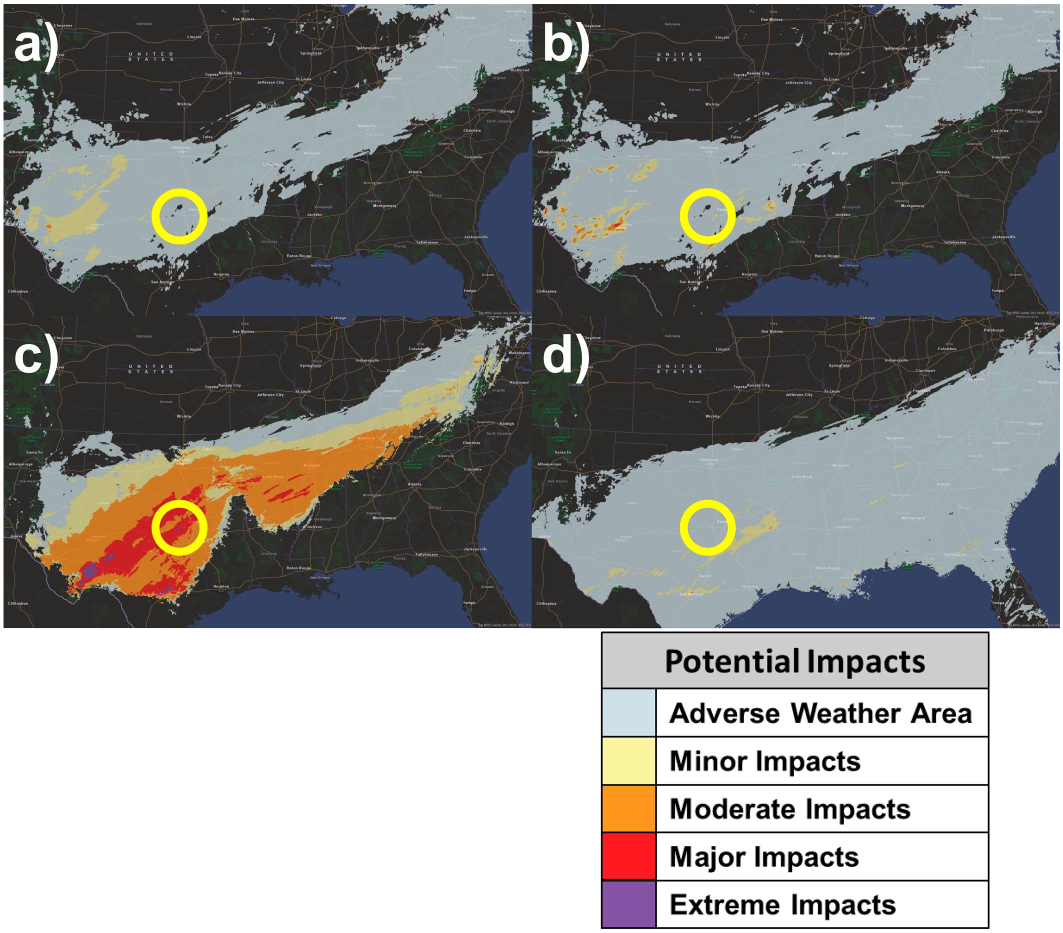

FIG. 6. The 48-h maximum WSSI-H output from the 1200 UTC 31 Jan 2023 model run for (a) snow amount, (b) snow rate, (c) ice accumulation, and (d) liquid precipitation rate. The location of interest for the discussion and values in Table 6 is indicated by the yellow circle.

to the public. It is not meant to predict specific impacts (e.g., a road closure or pileup) and does not serve as a replacement for official road condition guidance from local DOTs or other transportation agencies, nor does it supersede any other forecast information provided by the NWS. Users are encouraged to check official transportation sources for current road conditions, delays, closures, and other travel restrictions (e.g., speed restrictions, vehicle bans, and chain controls) and official NWS forecast conditions and warnings.

WSSI-H outputs from three winter events were presented to highlight the utility of the product to provide guidance on potential impacts on surface transportation, both at the hourly time scale and at a 48-h event-level time frame. These hourly outputs can help provide specific timing information for a variety of hazards with several hours of lead time. A 48-h maximum impact summary for each component provides easily digestible situational awareness and impact guidance in the short term. On these 48-h summary views, areas with several consecutive hours of enhanced impact levels can be outlined to highlight specific areas of interest that may be subject to prolonged impacts. These areas are more likely to become inundated by prolonged durations of adverse weather, which can result in cascading impacts stemming from an inability to "keep up" with weather conditions, delayed recovery efforts until conditions improve, or even life-threatening conditions for stranded motorists. The availability of hourly guidance in conjunction with these highlighted areas can then provide the necessary timing information of impacts. In an operational setting, such guidance at both the hourly and 48-h time scales is crucial for providing timely IDSS for surface transportation, which may help to mitigate adverse impacts and improve transportation safety.

The availability of several different components within the WSSI-H allows users to discriminate which specific hazard is forecasted and how severe that hazard is expected to be. The snow amount component provides climatologically driven guidance for impacts due to snow accumulations, with thresholds consistent with those for the operational WSSI product. The WSSI-H allows users to interrogate the time at which snow accumulations meet these critical thresholds—a capability that is not available with the 24-h time frames of the operational WSSI product. The ice accumulation component provides similar timing guidance for critical ice accumulations. These thresholds are specific to surface transportation and, as such, are notably lower than the thresholds used for the operational WSSI, which are designed to capture additional impacts such as damage to trees and utility disruptions. Damage to trees and overhead wires tends to occur with higher ice accumulations than those that can cripple surface transportation. The WSSI-H is the only WSSI product to include both snow and liquid precipitation rate components to provide guidance for impacts due to hourly precipitation rates. Precipitation rates address two distinct yet correlated hazards for surface transportation: visibility and inundation. Heavy snow rates, for example, can both limit visibility for motorists and overwhelm transportation agencies in their efforts to keep roadways clear of snow accumulations. Heavy liquid precipitation rates can similarly reduce visibility and may lead to dangerous hydroplaning conditions from water on roadways. However, the opacity of snow versus liquid precipitation means that these components must have different precipitation rate thresholds. Last, the blowing and drifting snow component specifically addresses visibility reductions owing to snow blowing through a driver's field of vision. In regions where heavy snow rates combine with strong winds, the snow rate and blowing and drifting snow components are highly correlated.

The WSSI-H is currently a prototype available internally to the NWS. The product will undergo further development to improve utility and ensure that the output is applicable for surface-transportation IDSS. For example, one limitation of the current algorithms that will be addressed in future updates is that there are no regional variations for impact level thresholds for most components. The snow amount component is the only component that is regionalized, as its thresholds follow from the operational WSSI version, whose thresholds are based on a snowfall climatology that accounts for both snow amount and frequency. Regionalization for snow rate and ice accumulation may similarly be introduced through future climatology-based efforts. At present, areas with higher traffic volumes such as interstates and major cities have the same impact thresholds as areas with fewer roads and traffic volumes. Future nonmeteorological factors such as traffic density or population density can be implemented to address these impact differences. Other components such as flash freeze are also considered for inclusion in the WSSI-H. Last, the WSSI-H algorithms are adaptable and can be used with other high-resolution forecast data (e.g., the Rapid Refresh Forecast System) as the science and availability of new operational models allow.

Currently, the WSSI is the only operational product available from the NWS that translates winter weather forecast data into an impact-based forecast product. It is used extensively to provide situational awareness and to help communicate the potential societal impacts of anticipated winter weather. However, as the NWS continues to emphasize IDSS and messaging of potential impacts, the introduction of the WSSI-H will provide critical forecast information in support of this mission for surface-transportation applications.

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Data availability statement. The NOAA High-Resolution Rapid Refresh (HRRR) model is available at https://registry.opendata.aws/noaa-hrrr-pds.

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