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Weather Severity Indices – Key Issues and Potential Paths Forward

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Aurora Project 2020-03

White Paper
January 2021

About Aurora

The Aurora program is a partnership of highway agencies that collaborate on research, development, and deployment of road weather information to improve the efficiency, safety, and reliability of surface transportation. The program is administered by the Center for Weather Impacts on Mobility and Safety (CWIMS), which is housed under the Institute for Transportation at Iowa State University. The mission of Aurora and its members is to seek to implement advanced road weather information systems (RWIS) that fully integrate state-of-the-art roadway and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures.

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16. Abstract

With a focus on WSIs used to describe the severity of winter storms, this white paper identifies the key challenges regarding the use and development of WSIs and discusses ways to further develop and improve WSIs going forward. The paper first discusses challenges facing users of WSIs developed to date, the key issues involved in modeling WSIs, and the challenges in capturing and modeling certain weather phenomena. The paper the identifies current research and other efforts that may address the challenges and issues identified and emphasizes the need to work closely with transportation agencies to implement WSIs effectively.

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WEATHER SEVERITY INDICES – KEY ISSUES AND POTENTIAL PATHS FORWARD

White Paper
January 2021

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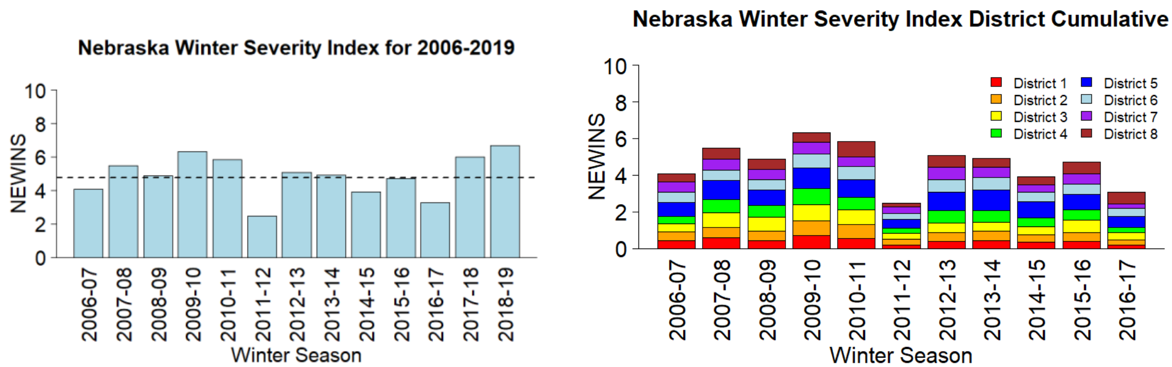
BACKGROUND

Weather severity indices (WSIs), severe weather indices (SWIs), and storm severity indices (SSIs), hereafter generally referred to as WSIs, are tools intended to describe the severity of a storm and are most often associated with winter storms. Describing the severity of a storm allows for a better understanding of the relationship between that severity and the resources used to address the storm-related impacts; the use of the first WSI to be developed revealed a "strong relationship between snow- and ice-control costs and the value of th[e] index" (Walker et al. 2019a). WSIs can also be used to guide incident management efforts by relating storm severity to events that impact mobility such as vehicular crashes and road closures. WSIs are most often used by state departments of transportation (DOTs), although these tools have the potential to be used by metropolitan planning associations (MPOs) or local agencies (e.g., cities, counties).

With a focus on WSIs used to describe the severity of winter storms, this white paper identifies the key challenges regarding the use and development of WSIs and discusses ways to further develop and improve WSIs going forward.

WSIs often combine meteorological parameters, and occasionally mobility data, to characterize and quantify the impacts and severity of weather conditions (Strong et al. 2005, Walker et al. 2019a). These parameters are often combined in a model using a set of variables with appropriate weighting functions applied to meet the specific needs or desires of a given agency (e.g., the WSIs used by the Wisconsin, Pennsylvania, Nebraska, and Maryland DOTs). Occasionally, WSIs are developed by computing a statistical regression relationship between weather parameters and mobility or safety data such as average annual daily traffic or crash rate, respectively (e.g., the WSIs used by the California, Montana, and Oregon DOTs), or road pavement friction measurements (e.g., the WSIs used by the Colorado and Idaho DOTs). More unique approaches include producing a storm-specific severity classification (e.g., the WSI used by the Nebraska DOT) with consideration of conditions before and after the storm (e.g., the WSI used by the Iowa DOT).

The outputs of most WSIs are quantitative in nature, with some qualitative exceptions. These numerical outputs can be interpreted as either a storm-specific severity value or a total seasonal severity value. Spatially, most WSI outputs define conditions either in the specific region impacted by a storm (e.g., climate zone or maintenance district) or statewide (Figure 1).



Walker et al. 2019b

Figure 1. WSI outputs showing seasonal severity in Nebraska from 2006 to 2019 (left) on a scale of 1 to 10 and severity at the district level from 2006 to 2017 (right)

CHALLENGES IN USING WSIS DEVELOPED TO DATE

A significant challenge regarding WSIs developed to date is the wide variety of methodologies used in their development, which limits comparisons of results. Methodologies can vary in terms of the chosen data source(s) used to develop the tool, the modeling or simulation approach employed, or the output values. Often, the chosen data source(s) or modeling/simulation approach may reflect the expertise or training of the lead developer. For example, meteorologists may emphasize atmospheric data sources, while transportation engineers and researchers may emphasize road-specific data sources.

While this variety of methodologies allows for innovation, the WSIs currently in use lack flexibility and transferability to other DOTs. WSIs often cannot be applied outside the specific set of conditions or the area for which they were developed, and individual WSIs are not broadly useful for consideration or implementation by other agencies (Walker et al. 2019a). This results in an inconsistent set of definitions for WSIs and an irregular, irreproducible set of WSIs that inhibit cross-region coordination.

Challenges in the use of WSIs can also arise if the data used, for example, road weather information system (RWIS) data, are of insufficient quality or quantity (Fay et al. 2020). For example, if a sensor is found to be providing odd readings mid-season and is not fixed immediately, the quantity of data produced by that source and the quality of those data may come into question. Additionally, comparing data across data vendors or among varying sensor types may also present challenges.

One of the most common, and critical, data challenges is the use and combination of meteorological data with road-specific data. For example, many WSIs do not take road pavement temperature and condition information into account, despite the relevance of these data to winter weather severity and winter maintenance operations and performance. WSI developers often cite unreliability or poor spatial resolution as reasons to exclude these data. However, methods to incorporate the broad spectrum of road weather data and the development of data quality control methods to remove erroneous observations will be imperative going forward.

Another challenge regarding WSIs developed to date has been limited adoption. One justification given for not using a WSI is that doing so is too complicated. The complexity may be due to the following:

- The collection and processing of the data needed to run the WSI
- The collection and processing of the data needed to ensure that the tool improves over time
- The calculation or modeling used to derive the WSI value
- The possibility that conditions that are common in one location are not common in another and may render the WSI output less than ideal in the second location
- A WSI user interface that is either too complex or not well suited for its intended use

Interestingly, the more complex WSIs often better represent the winter weather data they are intended to describe, whereas simpler tools may have a higher level of adoption but do not describe winter weather severity as effectively relative to winter maintenance operations.

Another challenge in the use of WSIs developed to date is establishing the ground truth of the output (Fay et al. 2020). In other words, how does the output from the tool (e.g., severe or mild storm severity) relate to on-the-ground conditions? Developing that a tool can accurately depict conditions experienced in the field (e.g., in terms of maintenance personnel needed, level of service [LOS] achieved, and the costs of addressing a storm’s impacts) can ensure buy-in from those using and evaluating the tool. WSIs that include freezing rain are among some of the most egregious in terms of validation and verification due to the lack of road-specific verification of ice accretion from freezing rain. However, some recent and promising advancements have improved ice accretion modeling and verification (Sanders and Barjenbruch 2016).

While WSIs have been around since the 1980s, this field of study has grown significantly in the last 20 years, indicating that this is both a fairly new field and one that is growing rapidly to support the needs of transportation agencies. Figure 2 provides a timeline of WSI publications.

1981	Cohen
1982	Hulme
1983	
1984	
1985	
1986	
1987	
1988	
1989	
1990	
1991	
1992	
1993	Boselly et al.
1994	
1995	
1996	
1997	
1998	
1999	
2000	
2001	Andrey et al.
2002	
2003	
2004	McCullouch et al., Carmichael et al.
2005	Nixon & Qiu, Strong et al.
2006	
2007	
2008	Qui & Nixon
2009	Marquis
2010	
2011	DePondecca et al.
2012	Farr & Sturges, Mass DOT,
	Balasundaram et al., NHDOT
2013	Kipp and Sanborn
2014	Chien et al.
2015	Jensen & Koeberlein
	Boustead et al., Mahoney et al.
2016	Walsh, Sanders & Barjenbruch
2017	
2018	Opperman & Williams
2019	Dao et al., Walker et al.
2020	Fay et al.

Figure 2. Growth in literature on WSIs over time

The challenges in using WSIs developed to date can be summarized as follows:

- Data of insufficient quality and/or quantity
- Wide variety of data sources used
- Wide variety of parameters used
- Influence of the developer’s background on the resulting WSI
- Complexity of WSIs
- Limited adoption of WSIs
- Establishing the ground truth of the WSI’s output
- Validation of sensor data

KEY ISSUES IN DEVELOPING WSIS

Some of the most severe storms are, thankfully, some of the most infrequently occurring events. Meteorologists, state DOT maintenance personnel, and others often note that one winter season may be more severe than the next. As a result, using data from one or two storm seasons to capture winter weather phenomena can miss the most severe events. However, using data exclusively from some of the most severe storms would tend to result in excessive resource use because winter storms would, on average, be less severe than the most extreme events.

Therefore, a robust dataset that spans several seasons is necessary, but the question remains as to how many years of data should be used in the development of a WSI. The number of years of data necessary to develop a model depends on the model type chosen, the quality of the data available, and the number of data sources (e.g., the number of RWIS or weather stations) within a state or region, among other considerations. For high-quality, high-density data, 5 years may be sufficient, but ideally 10 or more winter seasons of data should be used to develop a WSI. This, however, is not an absolute or always feasible recommendation. A better understanding of recommended number of years of data needed to develop a WSI may emerge as more are developed using more consistent approaches.

Topography (e.g., mountains, density of tree coverage) and geography (e.g., whether an area is close to an ocean or lakes or is inland) can cause variations in winter weather that affect winter maintenance needs. As a result, it is important to acquire data that can account for these variations. Accurate sensors must be situated appropriately to record the various weather types and road conditions. While states affected by winter weather have typically developed state-level WSIs (though exceptions are identified in Mewes 2011 and Strong et al. 2005), winter weather does not discriminate by state. On the other hand, the challenge with interstate or regional development of WSIs is that data sources and accuracy also vary by state (e.g., RWIS stations are funded and maintained independently in each state). Regional WSI development may be more feasible in eastern states, which tend to cover much less area than Midwest and western states. Narrow sections of a state (e.g., western Maryland) can potentially take advantage of data collected in neighboring states that are in close proximity. There are opportunities for collaboration in the future if a better understanding of the relationships among data sources can be established.

To compensate for the spatial and temporal limitations in observations, many agencies have adopted methods to spatially interpolate and temporally average data to build their WSIs. An important limitation of these techniques is that it diminishes location-specific information in favor of a broader understanding of storm severity. This may be acceptable for some applications (e.g., anticipated maintenance costs, salt usage) but is inappropriate for more specific analyses (e.g., vehicular crash severity, road closures). When developing a WSI, it is essential for an agency to balance the data available with the desired outcomes. As such, appropriate discussions should take place prior to development and implementation of a WSI to avoid issues of overextension and, therefore, lack of adoption of a WSI.

Few, if any, WSIs provide a predictive forecasting capability. Nearly all are developed as a retrospective tool to assess the performance of winter maintenance operations, inform after-action reviews, or justify resource allocations and expenditures. A predictive WSI based on forecast information can be a powerful tool for stakeholder communication and coordination, preparedness and planning activities, and preemptive road safety closure efforts. An important caveat with a predictive approach, however, is that the best possible data quality and fidelity must be ensured for such applications to be enacted.

The key issues in developing WSIs can be summarized as follows:

- Spatial and temporal limitations in the application of a WSI
- Impacts/Influence of topography and geography on the accuracy of a WSI
- Need for a sufficient density of sensors
- Existing sensor locations in problematic areas
- Determining the appropriate resolution of a WSI
- Determining the appropriate number of years of historical data on which to base the WSI
- Use of a WSI as a retrospective or forecasting tool

CHALLENGES IN CAPTURING AND MODELING WEATHER PHENOMENA WITHIN WSIS

Air and pavement temperature, snow, wind, and freezing rain have been identified as the most common variables found in WSIs. However, these variables may be prevalent less because they are the best variables for describing winter weather and more because they can be supported by readily available, reliable data (Walker et al. 2019a). Most winter storms consist of snow, whose density and intensity has the potential to vary during a storm. However, winter storms consisting of snow may not be the most severe from a winter maintenance perspective. Rather, storms that start out with warmer temperatures (e.g., with some liquid precipitation or snow that initially melts on warmer surfaces) that then drop below freezing (e.g., turning the liquid to ice) are more concerning from a serviceability perspective. Furthermore, storms that result in significant snow over a short period or that result in blinding drifts or thin layers of snow on the road after the storm, thereby potentially causing black ice, are also problematic. Researchers have used several approaches to incorporate the states of a storm and the experience of blowing/drifting snow into models (Fay et al. 2020, Sturges et al. in review). National Weather Service (NWS) personnel in North Dakota are actively working on the development of a Blizzard Severity Index to more accurately model and capture the impacts of blowing/drifting snow events (Andrew Moore, weather forecaster, National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction/Storm Prediction Center, personal communication 2020). More opportunities lie in how to best incorporate blowing and drifting snow into WSI models.

Depending on the area in the United States, winter weather can start as early as September (e.g., in Alaska, Maine, Montana, or Colorado) and end as late as July (e.g., in the Rocky Mountains). The first storm may sometimes be a sudden indication that the winter weather season has arrived, and many motorists may not be prepared. For example, the lower elevations of Colorado experienced a winter snowstorm in early September 2020, when a day prior the temperatures had been near 90°F (Nelson 2020). Again, because of the infrequency with which such storms occur, these storms may not be well represented in the data used to develop WSIs, but they can provide important data points to help agencies better prepare for when they do occur.

The timing and location of winter storms can impact their severity. The presence of a winter storm in a large, dense urban area versus a rural area may also impact the severity of a storm, in that the impact on travel may be more significant in urban areas. Furthermore, a storm during the day, when there is some potential influence from thermal heat, may be less severe than a nighttime storm (Fay et al. 2020). However, if the storm is particularly severe during the morning and/or evening rush hour, the severity of its impacts could be increased. The length of a storm is also significant. A fast-moving, short-duration, heavy snow event may have more impact than a long-duration, light snow event because the former may impact how people behave and their travel decisions (and whether schools are open). Seasonality is an important consideration for storms as well, given the significant influence of the diurnal cycle and sun angle on whether snow accumulates on roadways; that is, the severities of daytime versus nighttime storms and early-season versus late-season storms differ due to the associated variability in pavement/soil temperatures throughout a winter season).

Snow squalls, defined as intense and localized bursts of snow that often result in fatal multivehicle crashes, present a unique weather regime that may be a challenge for WSIs to capture adequately. While these events may be commonly associated with regions that experience lake effect snow (e.g., Michigan, Ohio, Pennsylvania, and New York), they can occur anywhere. Snow squalls are often overlooked due to a combination of their localized nature and the poor spatial resolution of observations typically incorporated into WSIs. The National Weather Service has recently implemented a new product to its array of tools to communicate the occurrence of such events. Snow squall warnings (SQWs) are short-term warnings similar to tornado or severe thunderstorm warnings that are focused on distinct areas (NWS 2020). WSIs have generally not yet incorporated squall events.

Determining where blowing snow conditions are occurring remains an area where both models and observations struggle. The depth of the blowing snow layer can be the result of many factors, including the dryness of the snow, the strength of the wind, and the amount of time the snow has been on the ground. Blowing snow conditions can be further complicated when snow is actively falling in conjunction with snow being picked up off the ground by strong, gusty winds. In some cases, a thin layer of snow blowing over the road surface can lead to the formation of black ice, while snow lofted to heights above vehicles can contribute to reduced visibility. The impacts of blowing snow can be difficult to quantify due to the microscale conditions that can create it. Examples of these conditions include the topography on each side of the road (the presence of berms, trees, and the like) and the direction the wind is blowing with respect to roadside features. Capturing these conditions can be difficult due to the spacing of sensors.

Freezing drizzle is an often overlooked and undermeasured precipitation type that can cause significant interruptions to surface transportation. The Journal North Report (2018) highlighted a case where freezing drizzle was occurring in eastern New Mexico along the I-25 corridor but none of the automated weather stations were reporting these conditions. Two people died amid the 20-car pileup resulting from the ice that accumulated on the road surface. Unlike freezing rain and snow, which are precipitation types that can be reported in an automated manner from many surface observation stations, freezing drizzle often falls below the detection thresholds of many of the sensors used by these stations. Reporting freezing drizzle conditions is therefore difficult, though the latest generation of weather sensors now claim to have this capability.

Another unique regime of winter weather events includes high-impact, sub-advisory events (DeVoir 2004, Petr 2019). These are events where the meteorological conditions may be unremarkable (e.g., a light dusting of snow, nocturnal frost formation on roadways) but the resultant impacts are considerable (e.g., numerous vehicular crashes, significant travel disruptions). WSIs, forecasters, and agencies struggle to identify these events because of the disconnect between the weather conditions and the impacts. However, such events may have the greatest public relations and safety consequences, with potential for political fallout.

Aggregation of data helps bring stability to representations of weather phenomena in models (Mewes 2011). However, aggregation may not allow a model to produce a WSI at the preferred level of detail or resolution (e.g., storm severity at the maintenance shed level instead of at the district level).

The specific temporal resolution of a given WSI comes with advantages and disadvantages. Hourly, storm-specific severity metrics such as those used in Iowa and Colorado (Walsh 2016, Carmichael et al. 2004) provide a very high resolution to relate weather conditions to their resultant impacts. However, these metrics are data and computationally intensive, which may limit other agencies from utilizing a similar approach. Other agencies, such as the Minnesota, Wisconsin, and Pennsylvania DOTs, have taken a compromise approach to produce daily, monthly, or seasonal metrics (Strong et al. 2005). While these approaches lack storm-specific information, they are generally simpler to compute. Boustead et al. (2015) developed a WSI capable of calculating an accumulated winter severity throughout an entire season. This accumulated winter season severity approach provides better information for seasonal and climatological comparisons, but it does not capture how a single, early-season extreme event could significantly bias the overall seasonal severity. The Nebraska Winter Severity Index developed by Walker et al. (2019a) is unique in that it uses hourly storm-specific severity to compute daily, monthly, and seasonal WSI metrics at the level of both the individual maintenance district and the state. This hybrid approach may be of interest to agencies desiring a WSI that can operate across different time scales.

The key issues related to capturing and modeling weather phenomena within WSIs can be summarized as follows:

- Capturing elusive weather phenomena:
  - Blowing snow
  - Black ice, freezing rain, icing events, freezing drizzle, etc.
  - Snow squalls
- Detecting high-impact, sub-advisory conditions
- Modeling challenges:
  - Snow density changes
  - Changes in temperature and precipitation type during a storm
  - Duration and intensity of storm precipitation
  - WSI accuracy in shoulder months (September, October, November, March, April, May)
- Effects on the timing of a storm (e.g., day versus night)
- Effects of the location of a storm (e.g., urban versus rural)
- Ability of sensors to detect and accurately report freezing drizzle, the presence of ice, etc.
- Accurately scaling up a WSI
- Determining the appropriate level of resolution of a WSI

ADDRESSING THE IDENTIFIED ISSUES

One way to make WSIs more usable is to automate data collection and processing. The development of software to package the inputs and outputs in a user friendly format is an area of opportunity that would benefit from further investigation.

Initial work is being done to explore the integration of data from multiple sources: invasive and noninvasive, stationary and mobile, and so on. The results of this effort will help determine how soon data from multiple sources can be grouped to create more robust data sets for WSIs.

Potential areas of synergy that can be investigated to improve the usefulness of WSIs include existing and in-development warning system programs:

- Blizzard warning systems
- Snow squall warning systems
- Frost warning systems

Additionally, the application of spatial variability analysis techniques such as kriging can fill the gaps between sensor locations.

The following efforts outside of the field of WSI research could benefit the development of WSIs:

- North Dakota NWS-DOT Pathfinder Blizzard Severity Index

- New York Mesonet – Using different wind sensor types and snow accumulation to model drifting snow (Nick Bassill, meteorologist, Center of Excellence and New York State Mesonet, October 18. 2019, personal communication)
- Ice Accretion Model (Sanders and Barjenbruch 2016)

A variable that could be incorporated into WSIs is visibility. Visibility is a measurement that has become available relatively recently through data collected from sensors (Fay et al. 2020). Walker et al. (2019a) noted that visibility data can help determine the severity of a winter storm. However, Fay et al. (2020) observed numerous gaps in visibility data where the sensors providing the data indicated ERROR or observations were simply missing. If a device can provide information regarding visibility, there is a need to ensure that the device is functioning properly.

Furthermore, visibility has been shown to be misleading when used to estimate snowfall intensities (Rasmussen et al. 1999). The measurement of liquid water equivalent (i.e., the amount of water frozen in a given amount of snow) is becoming the preferred method for determining snowfall intensity because it provides a direct measurement of the amount of water in the snow. Methods exist for relating visibility to the liquid water equivalent of snowfall, but there is significant scatter in the data, which can lead to erroneous estimates of the actual snowfall rate.

INTEGRATING WSIS WITH TRANSPORTATION AGENCIES' NEEDS AND PLATFORMS

While the identification of issues and needs related to the development and improvement of WSIs is the goal of this white paper, the importance of working hand in hand with agencies that will implement the WSIs (often state DOTs) cannot be understated. Working closely with implementing agencies is important for identifying the critical weather events that require a road maintenance response and the specific roadway conditions that influence maintenance operations. State DOTs are responsible for determining when road closures and other regulations, such as chain laws, should be in effect and can provide guidance regarding the ways these conditions relate to the formulation of potential WSIs. Beyond these considerations, working with implementing agencies to incorporate their level of service guidelines and the conditions, treatments, actions, and timeframes recommended in the guidelines will help better inform WSIs. Details such as materials, equipment, person hours, and associated costs can be used when applying WSIs to operations.

Working with an implementing agency to ensure the success of a WSI in the organization involves bringing relevant people to the table (Sturges et al. in review):

- Inside the agency – Project champion, director or high-level manager, meteorologists or RWIS staff, maintenance managers and operators, information technology (IT) staff, and others as needed

- Outside the agency – Meteorologists, weather data vendors, instrumentation maintenance vendors (e.g., RWIS maintenance contractors), consultants or university researchers, NWS representatives, and others as needed

By obtaining input and feedback from all relevant parties within an organization, the potential is greater for effective WSI development and implementation. The likelihood is also greater that users will find the WSI pertinent to their ongoing maintenance activities. Wider WSI use within an organization ensures that the knowledge of the WSI is retained within the agency, even with staff changes. By bringing in relevant parties from outside of an organization, the organization can leverage a diverse knowledge base to determine the data requirements for the WSI, develop the tool, and manage its evolution in response to changing conditions and sensors.

Additionally, it is not sufficient to simply deliver a WSI tool to an agency. Working hand in hand with an agency during the transition from the creation of the WSI to its end use can help ensure the long-term success of the tool. This transition phase can help developers determine how the agency is using the WSI tool, the challenges the tool presents, and potential modifications that will help the WSI better address the agency's existing and future workflows.

CONCLUSIONS

Considering all of the identified issues summarized below, identifying the issues that could impart the greatest improvement for WSIs is the logical next step.

- Data of insufficient quality and/or quantity
- Wide variety of data sources used
- Wide variety of parameters used
- Influence of the developer's background on the resulting WSI
- Complexity of WSIs
- Limited adoption of WSIs
- Establishing the ground truth of the WSI's output
- Validation of sensor data
- Spatial and temporal limitations in the application of a WSI
- Impacts/Influence of topography and geography on the accuracy of a WSI
- Need for a sufficient density of sensors
- Existing sensor locations in problematic areas
- Determining the appropriate resolution of a WSI
- Determining the appropriate number of years of historical data on which to base the WSI
- Use of a WSI as a retrospective or forecasting tool
- Capturing elusive weather phenomena:
    - Blowing snow
    - Black ice, freezing rain, icing events, freezing drizzle, etc.
    - Snow squalls
- Detecting high-impact, sub-advisory conditions
- Modeling challenges:

  - Snow density changes
  - Changes in temperature and precipitation type during a storm
  - Duration and intensity of storm precipitation
  - WSI accuracy in shoulder months (September, October, November, March, April, May)
- Effects on the timing of a storm (e.g., day versus night)
- Effects of the location of a storm (e.g., urban versus rural)
- Ability of sensors to detect and accurately report freezing drizzle, the presence of ice, etc.
- Accurately scaling up a WSI
- Determining the appropriate level of resolution of a WSI

Additional needs regarding WSIs are as follows:

- How can WSIs best be applied?
- How can progress be made toward a WSI that can elucidate longer trends such as weather versus climate?

Major issues with WSIs include how to best incorporate blowing and drifting snow, freezing precipitation events, and low-frequency but severe events. However, before issues like these can be addressed by WSI developers and users, the owners of and maintenance staff for sensor equipment must be informed of the importance of acquiring data of sufficient quality and quantity for use in WSIs.

An important next step is to identify and convene a working group of WSI users and developers consisting of individuals from across the meteorology and transportation communities to further discuss and implement solutions for the challenges identified in this white paper.

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