Building a Climatology of Snow Squall Conditions

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ABSTRACT

Snow squalls represent a significant hazard to drivers on the roadways due to the sudden onset of low-visibility snow. With the goal of addressing this threat, the National Weather Service began issuing warnings for snow squalls, but the visibility criteria used for those warnings differ from the criteria in the formal literature, which also contains varying criteria. So long as this disagreement exists, it is impossible to objectively diagnose snow squalls. This study begins the process of addressing the issue of conflicting definitions by stepping back from the issue of snow squalls, and looking at sudden snow-induced visibility drops more generally. Five-minute Automated Surface Observation System observations from commercial airports across the CONUS were examined for visibility drops associated with snow consistent with snow squalls. Observations were classified as sudden visibility drop events if no snow occurred in the hour before the snow started and if the minimum visibility threshold was met within the first hour of snow. At 0.4 km (0.25 mi), the NWS visibility requirement for snow squall warnings, requiring this suddenness definition to be met reduces the number of events per year by 66-90% . Sudden drops in visibility were most common in the Intermountain West, the Northeast, the Great Lakes, and the northern Great Plains. By increasing the visibility threshold from 0.4 km to 1.6 km (1.0 mi), the number of events generally increased by a factor of four to six times, though some regions saw an even greater increase. Lake-effect areas that receive the most amounts of heavy snowfalls generally are not the locations with the most sudden drops in visibility.

1. Introduction

The sudden onset of snowfall during the cold season can pose a major threat to those traveling on the roadways. Call et al. (2018) found that limited visibility or a rapid decrease in visibility played a role in many multi-vehicle chain-reaction crashes. Visibility is one of the most important factors in crashes related to winter weather because it determines how far ahead a driver can see and how long they have to stop based on their speed and reaction time (Tobin et al. 2022). Thus, any snow event that causes low visibility represents a risk to traffic, particularly when that low visibility happens quickly.

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	NWS Warning Criteria	Banacos et al. (2014)	Rosenow et al. (2018)	Colby et al. (2022
Visibility (km)	≤ 0.4	≤ 0.8	≤ 0.8	≤ 3.3
Snow	Falling an/or blowing snow	Moderate to heavy snow	Observation of snow	Sudden snowfall
Wind Speed	Gusty Winds	Increase in wind speed within one hour of the start	Winds at least 10 m s^{-1}	Winds at least 3.6 m s^{-1}
Other	Sub-freezing road temperatures; Dropping temperatures behind an arctic front	Wind direction between 190° to 360°	N/A	Duration of less than an hour

TABLE 1. The conditions associated with the NWS warning criteria or the definitions proposed by each study.

A snow squall is an example of a phenomenon that produces quick changes in visibility, due to its short burst of sometimes intense snowfall. In an attempt to mitigate the sudden onset effects of snow squalls, the NWS began issuing short-fuse snow squall warnings in 2018 (NWS 2018). Despite the existence of operational warnings, there is still no exact, agreed-upon definition of a snow squall in the literature (Colby et al. 2022). The lack of a concrete definition makes it difficult to determine what events constitute a snow squall, particularly in an objective, automated paradigm. Previous studies use different criteria and thresholds to determine what defines a snow squall (Table 1). Out of the four separate definitions of a snow squall in Table 1, three different visibility thresholds were used: 0.4 km (0.25 mi), 0.8 km (0.5 mi), and 3.3 km (2.0 mi). This disagreement alone prevents automated detection of these events, as well as differences in other parameters such as wind speed/wind direction/snow duration.

To issue a Snow Squall Warning, the NWS separates its criteria (Table 1) into two sets. First, a warning is issued if visibility is less than or equal to 0.4 km with sub-freezing road temperatures. Second, a warning can be issued if temperatures behind a front drop quickly enough to produce a flash freeze and if there is a significant reduction in visibility (NOAA 2020). The common element of visibility in both sets of rules suggest that the NWS seeks to warn motorists of quick, low-visibility snow. However, these rules cannot be quantitatively implemented , making it difficult to create snow squall climatologies. Banacos et al. (2014) and Colby et al. (2022) performed climatologies using their own definitions of snow squalls, but these were only over portions of the northeast US, tying their parameters to the meteorology of that region. The conflicting rules in the literature and the qualitative warning criteria used by the NWS do not easily scale up to creating a national climatology.

This study seeks to address this problem by searching for the impacts of snow squalls, rather than the meteorological event, snow squalls. Surface observations are examined for snow-induced visibility drops consistent with those experienced with those associated with snow squalls. While non-squall events will be included in the resultant dataset, the sudden onset of snow and low visibility would reasonably be expected to impact drivers similarly, regardless of the meteorological phenomena that cause the visibility loss. This work explores the geographic distribution of conditions consistent with snow squalls by using surface observations to find sudden drops in visibility. Section 2 provides the data and methods used in this study. Section 3 presents the results of the analysis, and section 4 provides the discussion and conclusions.

2. Data and Methods

This study uses data from the Automated Surface Observation System (ASOS, NOAA (1998)). We obtained 5-minute observation data from 398 ASOS stations at commercial airports around the CONUS. These observations ranged from the year 2000 until May 2022, with the exact start date for each station varying based on the start date of that station's archive. The date, time, temperature, visibility, wind speed, and present weather were collected from each observation. The present weather observation was only recorded if the station observed light, moderate, or heavy snow. A 5°C air temperature maximum was enforced for every snow observation to filter out errant snow observations.

Once the period-of-record data from each station was assembled, the dataset was analyzed to search for the onset of snow events with rapid visibility reductions. These

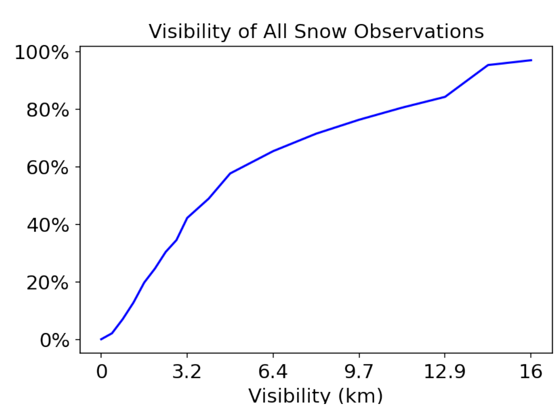

FIG. 1. Cumulative histogram of the visibilities of all snow observations between the year 2000 to May 2022 across all ASOS stations.

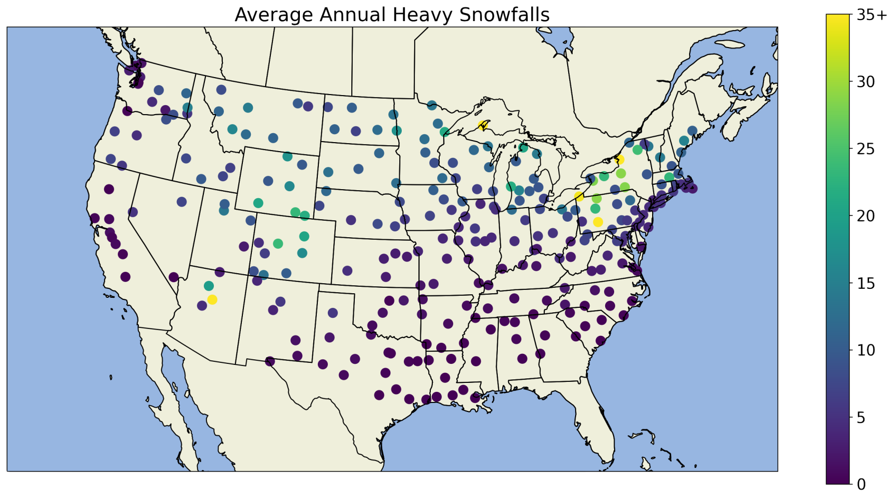

FIG. 2. The average annual heavy snowfalls for each ASOS station. The visibility dropped to 0.4 km or less at some point while it was snowing. Lighter colors indicate more heavy snowfalls and darker colors indicate fewer. Yellow dots may indicate numbers between 35 and 81 heavy snowfalls per year.

events were defined as a snow observation following multiple observations without snow and reaching the defined minimum visibility within the hour of the start of snow. For this study, one hour of no snow observations beforehand was required to declare a rapid visibility reduction event.

The next step was attempting to develop a visibility threshold for the analysis, given the disagreement between sources for snow squalls. Figure 1 displays a cumulative histogram of the visibility from all snow observations in the entire dataset. There is no clear break point to use in the snow visibility data, and the thresholds in Table 1 have substantially different frequencies in Figure 1. Only two percent of snow observations occur at or below the 0.4 km threshold used by the NWS. Additionally, looking at the threshold used by Banacos et al. (2014) and Rosenow et al. (2018), around seven percent of snow observations fell at or below 0.8 km. Finally, 43.5% of observations occurred at or below the 3.3 km threshold set by Colby et al. (2022).

Two visibility thresholds were used for this work. The first, 0.4 km, is the threshold the NWS uses for snow squall warnings, owing to the importance of the operational NWS definition. For the second threshold, we started with the threat these events represent to vehicular transport. The goal for this threshold is to choose a value under which it becomes impossible for some vehicles to stop for an obstruction in the road. A semi-truck requires 0.16 km (525 ft) to stop in dry, clear conditions (Utah Department of Transportation cited 2022). This stopping distance increases by a factor of three to twelve in snow and ice, depending on the severity of conditions; thus, the stopping range is 0.48-1.92 km (0.3-1.2 mi) (Saskatchewan Government Insurance cited 2022). A visibility threshold of 1.6 km (1.0 mi) covers most of this range, as truck drivers cannot stop when they notice an obstruction in the road below this value.

3. Results

To put the sudden visibility drop events in context, we first examined where heavy snow occurs, without requiring a sudden onset. For the purposes of this analysis, heavy snowfalls are defined as a period of snow where the visibility reached 0.4 km or less within three hours after the snow began. Figure 2 shows the geographic distribution of annual heavy snowfalls. The maximum average number of heavy snowfalls per year occurred in the Great Lakes region at Hancock, MI, with approximately 81 heavy snowfalls per year. Many stations east of Lakes Erie and Ontario record yearly averages ranging from the low-20s to upper-30s of heavy snowfalls. Most stations (except Hancock, MI) along the other Great Lakes had fewer heavy snow periods than near Lakes Erie and Ontario, but they still average around 20 heavy snowfalls per year. Stations in interior New England record anywhere from 10 to 35 heavy snowfalls per year, except for stations along the Atlantic coast. The Intermountain West tends to fall between 10 and 25 heavy snowfalls, with the outlier

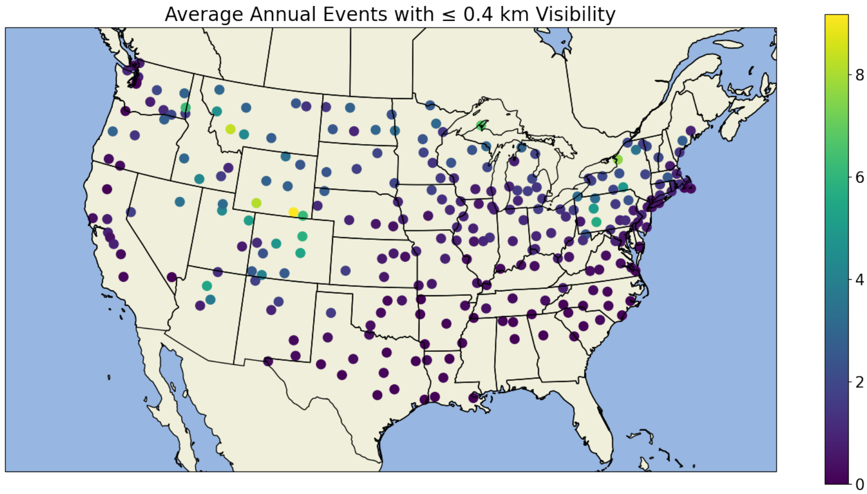

FIG. 3. The average annual events that reach 0.4 km visibility or less for each ASOS station. Lighter colors indicate more events and darker colors indicate fewer. The maximum occurs in Laramie, WY, at 9.17 events per year.

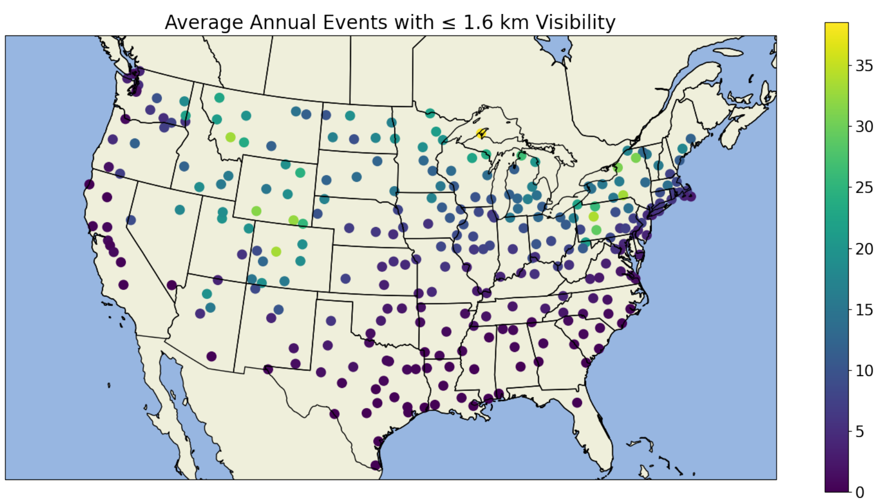

FIG. 4. The average annual events that reach 1.6 km visibility or less for each ASOS station. Lighter colors indicate more events and darker colors indicate fewer. The maximum occurs in Hancock, MI, at 38.5 events per year.

being in Flagstaff, AZ, averaging 40 heavy snowfalls annually. The northern Great Plains tend to receive between 6 and 20 heavy snowfalls per year.

Next, we examined how the geographic distribution changes when the 0.4 km minimum visibility is added to conform to the requirements of a quick onset event. Figure 3 shows the average annual events that reached visibility of 0.4 km or less. With the added time criteria, there is a significant decrease in the quantity of events. The maximum occurs in Laramie, WY, with 9.17 events per year. This is almost nine times fewer than the maximum number of heavy snowfall events shown in Figure 2. Also, the concentration of events with respect to the geographical distribution shifts between Figure 2 and Figure 3. Except for Watertown, NY, right on the coast of Lake Ontario, more events occur in the interior northeast than on the eastern coastlines of the Great Lakes. For example, Erie, PA, averages around 3.22 events per year. However, Reynosldville and Johnstown, PA, both further inland than Erie, average 5.0 and 5.61 events per year, respectively. High averages also occur in interior New York. Johnson City, NY, averages 4.87 events per year, and Saranac Lake, NY, averages 3.5 events per year. Additionally, many stations across the northern Great Plains have the same or more annual events than the coastal Great Lakes areas. Stations across eastern Montana and the Dakotas mostly record between one and four events per year, whereas most stations along the Great Lakes record three or fewer yearly events.

Figure 4 shows the average annual events that reached visibility of 1.6 km or less. The maximum number of events has returned to Hancock, MI, at 38.5 events per year instead of being in the Intermountain West. Laramie, WY, which was the maximum for events under 0.4 km of visibility, now records around 32.44 events per year under 1.6 km of visibility. Except for Hancock, MI, the stations along the Great Lakes coast receive anywhere from eleven to thirty events per year. This is a six to ten times increase in the number of events, as shown in Figure 3. The inland portion of the northeast shares a similar range in the number of events under 1.6 km visibility; however, that is only around four to six times the number of events as in Figure 3 in the same region. Similarly, the northern Plains averages between ten and twenty 1.6 km-or-less events per year, around five to six times the amount of 0.4-km-or-less events. The Intermountain West averages between ten and thirty-five events per year, between three to six times the amount as in Figure 3. In terms of the concentration of events, most occur in the Intermountain West and the northeast. Events less than 1.6 km in visibility still occur and peak around the Great Lakes, but they are not as frequent as in the other two regions.

4. Discussion and Conclusions

This study analyzed events with snow-induced visibility drops to investigate the geographic distribution of visibility conditions typical of snow squalls. By design, the dataset included non-snow squall events with similar visibility drops. The intention was to develop a climatology of conditions that cause impacts similar to those attributed to snow squalls, regardless of cause. If a method is developed to automatically detect snow squalls, this analysis can be performed again by restricting the dataset to snow squalls to ascertain if there is a substantial difference in the results.

There is no obvious break point in visibility with a threshold for snow observations. Thus, the way to resolve the visibility disagreements would be to consider the impacts of visibility on drivers. Utilizing the 0.4 km threshold set by the NWS warning criteria would make snow squalls or events similar to snow squalls extremely rare and may prevent issuing warnings in dangerous scenarios for drivers. The lower estimated value of semi-truck stopping distance is 0.48 km (0.3 mi). However, NWS warning criteria visibility is less than this stopping distance, so trucks may not have enough time to slow down, thus creating dangerous travel conditions outside warning criteria. The visibility threshold of 0.8 km set by Banacos et al. (2014) and Rosenow et al. (2018) falls within the approximated truck stopping distance. The 3.3 km threshold set by Colby et al. (2022) does not fall within this range; however, they mentioned that lowering this value would eliminate cases of "multi-vehicle crashes that had occurred in 'whiteout conditions.'" To set this visibility threshold more precisely, further analysis of the relative risk of driving at the various visibilities might help determine where we can draw the threshold line for dangerous visibility.

Determining a threshold that encompasses the risks associated with operating on roadways during a snow squall without including non-snow squall events poses a challenge. This is because changing the visibility thresholds significantly impacts the number of events per year. Most regions saw a four to six times increase in events when comparing the thresholds of 0.4 km and 1.6 km. The Great Lakes had an increase of up to ten times the amount of events in some areas. From this, the Great Lakes region is more likely to receive heavy snowfalls than events with sudden drops in visibility. This region seems to have many events that reach low visibility, but that number shrinks significantly with the added criteria for suddenness. However, visibility drops become substantially more common if the visibility threshold is relaxed. At least in the case of the Great Lakes, it is not possible to directly associate frequent heavy snowfall with sudden drops in visibility. Future analysis could look at the reason for these regional differences of drops in visibility.

By virtue of those disparate effects on frequency between stations, the geographical concentration of snow-induced visibility reduction events shifts based on the visibility threshold used. The maximum peaks in different places when comparing the two thresholds used for sudden drops in visibility. The lower visibility threshold (0.4 km) maximum peaks in Wyoming, whereas the higher threshold (1.6 km) peaks in Michigan. Looking back at the stopping distances of fully-loaded semi-trucks, truck drivers cannot see a stopping distance in front of them twenty percent of the time it is snowing (Figure 1). Note that this is if truck drivers were traveling at highway speeds under ice and snowy conditions, though it seems likely that they would slow down if the roads are snow-covered. However, with clear road conditions and the sudden onset of snow, drivers might travel at higher speeds and would not have time to slow down after that initial drop in visibility.

Future work could include additional analysis of road conditions and crash data to determine which visibility thresholds would best suit warning criteria. By quantifying the impacts of different visibility thresholds on crashes and fatalities, emergency managers could use this data to anticipate catastrophic events better. This study did not consider other forms of precipitation, such as rain, freezing rain, or sleet, occurring in the hour before the snow starts. Further analysis could determine whether the presence of other types of precipitation in the preceding hour affects the impacts of a sudden visibility drop due to snow or if the most dangerous conditions are snow squalls and similar events, where no precipitation precedes the onset of snow.

We can also examine whether the duration of snow matters in defining snow squall conditions. Snow squalls are generally defined as short-duration events, so requiring cessation of the snow shortly after reaching the minimum visibility could help determine the cut-off for classifying something as being similar to a snow squall or as part of some other winter weather event. This study used the one-hour threshold for finding minimum visibility because it encompassed the typical length of NWS warnings; however, determining whether or not this duration matters should be further explored. Snow events that last longer might have a more standard NWS headline (e.g. winter storm warning, winter weather advisory) associated with them, and the driving public may be more aware of the hazard than for a shorter, unhighlighted event.

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