A Climatology of Thundersnow Events over the Contiguous United States

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ABSTRACT

A ‘‘climatology’’ (climatological description of spatial, temporal, and synoptic characteristics) of snow events with thunder is presented for the contiguous United States. Based upon 30 yr of 3-hourly reports from 204 stations in the 48 contiguous United States, 229 reports are extracted from the 3-hourly observations (consistently bearing the present-weather group in each surface observation) that featured thunder with snow *only.* When these reports are plotted spatially, the central United States, the intermountain west, and the Great Lakes region emerge as the preferred regions for thundersnow occurrence. A thundersnow event is then defined. Isolated thundersnow reports clearly constitute a thundersnow event. Also, multiple thundersnow reports that are not separated spatially by over 1100 km or temporally by 6 h are considered part of one event. The location reporting the first occurrence of thunder with snow in such a collection of stations then carries the representative time and location for the event. The 229 individual reports make up 191 thundersnow events. Temporal analysis of thundersnow events reveals a nationwide seasonal preference for occurrence in March but no clear diurnal preference. Most thundersnow events are typically reported at only one station and only rarely in consecutive 3-hourly observations. These results thus reinforce the notion of thundersnow as a fairly localized phenomenon of limited duration. In terms of intensity, the thundersnow events investigated in this study feature light snow about one-half of the time, with the remaining events split nearly evenly between moderate (25%) and heavy (23%) snowfall. Further analysis classifies each event according to the meso- to synoptic-scale environment in which it forms. Most events (52%) form in association with a transient midlatitude cyclone; other event types include an orographic class, events that occur with a coastal cyclone, events associated with an arctic front, lake-effect events, and those resulting from upslope flow.

1. Introduction

Convective snow events, commonly known as thundersnow, can be dangerous to both life and property. Often occurring as a component of synoptic-scale snowstorms, thundersnow events can produce mesoscale regions of locally enhanced snowfall, which can exacerbate already dangerous conditions for the public and hamper the efforts of emergency response personnel who serve them. Given the potential danger inherent in these storms, a further examination of their synoptic and dynamic characteristics is in order. As a first step in this process, a ‘‘climatology’’ (climatological description of spatial, temporal, and synoptic characteristics) of these events has been compiled.

2. Background

A review of the formal literature reveals that thundersnow events have not been studied in great detail, possibly because of their relatively infrequent nature. Three longer-term studies stand out in the literature, but none have addressed specifically the climatology of thundersnow events. Curran and Pearson (1971) examined a total of 76 cases of convective snow and, for a subset, generated proximity soundings of the upper levels of the atmosphere. They revealed the mean thundersnow environment as one capable of supporting elevated convection, with a stable boundary layer and a nearly saturated neutral thermal profile above the surface inversion. Although it provided a valuable look at the typical thermodynamic profile of convective snow events, the study did not purport to be a climatology, nor was it constructed as such. Nonetheless, they found a significant number of thundersnow events from parts of four winter seasons, largely over the central United States.

Colman (1990a,b) more recently examined the environment that attends the typical thunderstorm on the cold side of a surface frontal zone. This approach encompasses thunderstorms in both the warm and cold seasons, resulting in a composite climatology of all cold-sector thunderstorms. One important outcome of Col-

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man's (1990a) study was the identification of the central United States as a preferred location for elevated thunderstorms. Indeed, many thundersnow events do result from elevated convection; yet Colman's (1990a) effort was too broad to address thundersnow specifically.

Holle et al. (1998) examined an 8-yr period over the contiguous United States for the occurrence of winter thunderstorms. Although not concerned solely with the occurrence of thunder with snow, they identified a total of 245 h of thunder with various precipitation types at temperatures of less than or equal to 0°C from a 211-station sample during their 8-yr data period. They found a preference for such events over the central United States as well as northern Utah and the northern Great Lakes region. Our approach differs somewhat from that of Holle et al. (1998), but their findings are useful for comparison purposes.

Other recent studies include those of Schultz (1999) and Hunter et al. (2001), both of which address the climatological nature of snow occurring with lightning and thunder on regional scales. Schultz (1999) analyzed 49 lake-effect snowstorms associated with the Great Salt Lake and 26 lake-effect snowstorms from western New York to compare and contrast lake-effect snow events in disparate regions of the United States. Hunter et al. (2001) examine seven snowstorms from the southeastern United States that featured lightning and thunder. In both studies, lightning occurring with snowfall was frequently associated with near-freezing surface temperatures, a finding supported by Stuart (2001) in his analysis of a recent extreme East Coast thundersnow event.

3. Method

Hourly surface observations from 223 weather stations in all 50 states were obtained for the 30-yr period of 1961–90 using data derived from the National Climatic Data Center's Solar and Meteorological Surface Observing Network dataset. Of the original 223-station sample, 204 stations in the contiguous 48 states were identified for further examination. Only 3-hourly synoptic observations (0000, 0300, 0600 UTC, etc.) were used in the construction of the climatology, because the present-weather group was carried reliably only in those observations over the duration of the dataset. From these data, only reports of thunder with continuous or showery-type snow were counted.

An event is thus defined as any occurrence of thunder with snow. Multiple consecutive reports at a station also constitute a single event. For example, one event in the database spanned two times (2100 and 0000 UTC, inclusive) but was counted as one event. The time associated with the event in this case is 2100 UTC, because this was the time of the first observation of thundersnow. We call this the time of onset. If more than 6 h pass between one thundersnow report and another at the same station, then two separate events were counted. For simultaneous thundersnow reports at different stations, each was counted as a separate event if they occurred more than 1100 km apart. Justification for these specific values is found later in this section.

The colder half of the year is preferred for snowfall, but experience has shown that these snow events can occur as early as October and as late as April, especially in the northern United States. Thus, the seven months of October through April, inclusive, are considered in the study. In total, 229 reports making up 191 events are identified for the climatology over the contiguous 48 states, giving an average of 7.6 reports (6.3 events) per year occurring nationwide.

Last, we acknowledge several assumptions upon which this climatology is founded. First and foremost, we assume that these data and their distribution make them sufficient to compose a synoptic climatology of thundersnow events. That this is an event-driven climatology (like tornadoes or hurricanes) suggests that having data from *all* of the available stations would still result in events being missed because of gaps found in the finer-scale network. Indeed, even the use of all available surface observations would still exclude many events, especially those with few lightning flashes. Only an approach such as that of Moore and Idone (1999), who employed data from the National Lightning Detection Network (NLDN), is free of such constraint. Using 6 yr of NLDN data, they tallied 7701 cloud-to-ground flashes at temperatures of less than 32°F. Although their approach still fails to account for cloud-to-cloud and intracloud flashes, the spatial resolution of the cloud-to-ground strokes is exceptional. It is clear that the data used in our study are best suited to a broader, synoptic climatology.

Indeed, the distribution of stations in this study is sufficient to establish a valid synoptic weather analysis at any given moment. However, distinguishing events from one another that were spatially or temporally close together became a priority. Working from the assumption that most reports of thundersnow represent some mesoscale forcing, a distance criterion of 1100 km and a time criterion of 6 h between events are employed. The former criterion further assumes that the process that engenders thundersnow will likely be of the meso-β spatial scale (20–200 km). A value of 1100 km lies in the middle of the meso-α spatial scale (Orlanski 1975); the 6-h criterion is 2 times the typical timescale for midlatitude slantwise convection cited by Emanuel (1986) as f^{-1} (where f is the Coriolis parameter). These criteria presume to put adequate distance between the flows that may exhibit simultaneous thundersnow events. Only one of these criteria need be met, and two separate observations will then be considered to be separate events. It is fortunate that most of the events (82%) featured only one isolated report of thundersnow.

4. Analysis

The spatial distribution is given in Fig. 1 as thundersnow events by station. There is a distinct maximum

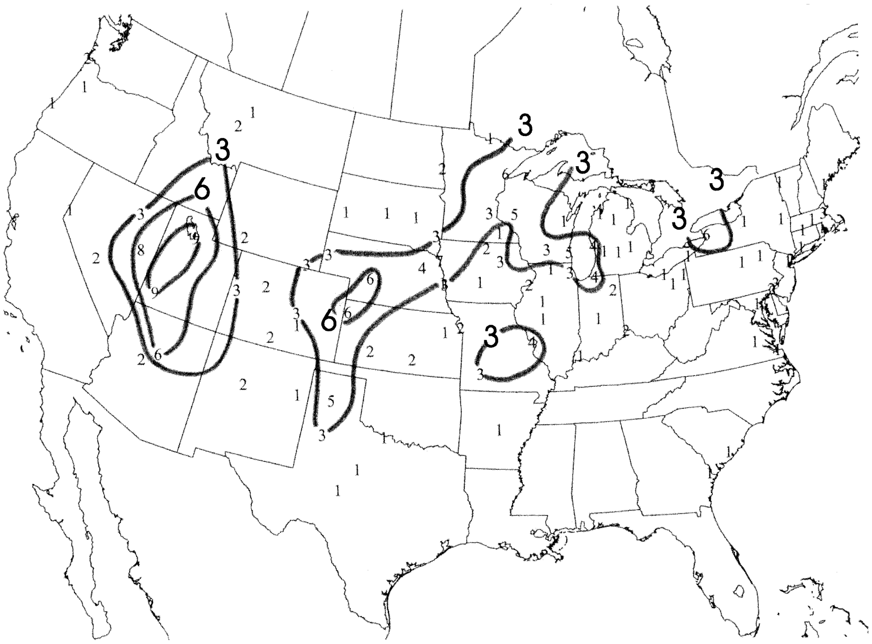

FIG. 1. Counts by station of 3-hourly observations of thunder occurring with snow for the period of 1961–90. Values are subjectively analyzed with contours of three, six, and nine counts per 30 years.

over Utah and Nevada, and other lesser maxima appear over the central plains states and (still smaller) scattered over the Great Lakes. Frequency decreases with decreasing latitude, and all of the Gulf states (with the exception of Texas) observed no convective snow within the constraints of our dataset. In addition to dynamic forcing for ascent, other, perhaps finer-scale, processes are surely at work in some of these regions. The western maximum is likely due in part to orographic forcing (and lake-enhanced effects near the Great Salt Lake); farther east, reports from Great Lakes stations signal a lake influence if not actual lake-effect events—Schultz (1999) contrasted such events in a recent paper. Some East Coast events may have benefited from the mesoscale forcing provided by coastal fronts associated with mature coastal cyclones (Bosart 1975).

The diurnal analysis of the initiation time of all events (Fig. 2) reveals no clear trend, which reinforces the view of thundersnow events as being dynamically forced and largely independent of daytime heating. In terms of a preferred season of occurrence (Fig. 3), March is seasonally favored nationwide for thundersnow reports. This fact may be due largely to seasonal transition as the climatological position of the polar jet migrates poleward (spring) and equatorward (autumn). The result is

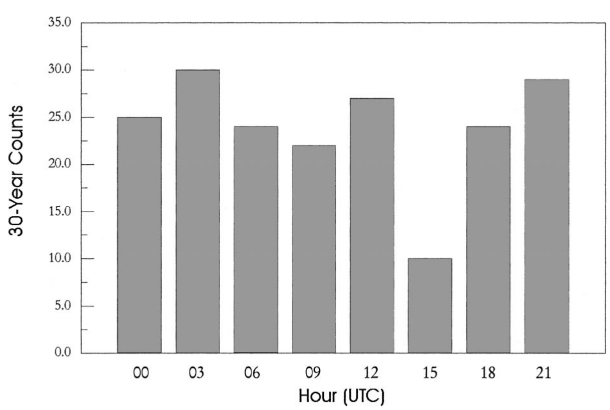

FIG. 2. The 3-hourly diurnal distribution of thunder events occurring with snow for 1961–90. The bars represent the number of thundersnow observations reported at each of the hours (UTC). Events with multiple observations of thundersnow are counted only once; the time of the first thundersnow observation (event initiation) is the time counted for such events.

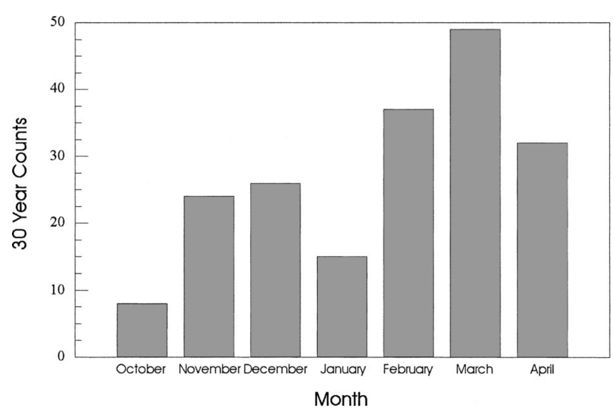

FIG. 3. The monthly distribution of thunder events occurring with snow for 1961–90.

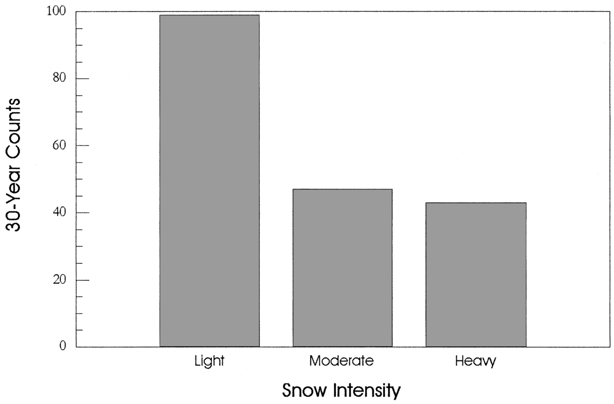

FIG. 4. The intensity of snow concurrent with the observation of thunder for events occurring with snow for 1961–90.

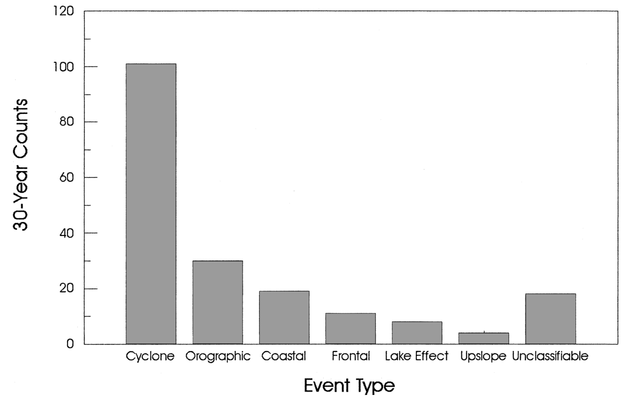

FIG. 5. Counts of thundersnow events by event type.

a relatively high frequency of transient extratropical cyclone activity over the central United States in spring and autumn. Indeed, it is noted that a weaker late-autumn maximum is suggested, although it may be influenced by regional peaks in activity over Utah and Nevada as well as the Great Lakes regions.

Of the 191 events identified, 170 featured only one report of thundersnow. This fact suggests a limited areal extent to such convective events, as one would expect. In addition, 171 of the 191 events exhibited thundersnow at only one 3-hourly observation. Indeed, the temporal resolution of the data over the life of the dataset affords observations only every 3 h, so that an individual thundersnow event may well last up to 5 h at one station. For example, thundersnow reports may begin at the 0100 UTC observation and last until 0500 UTC, yet the event will only be ''seen'' in the 0300 UTC observation. However, the majority of events in the dataset with *hourly* present weather in the observations (generally after 1980) failed to report thundersnow for more than one observation time.

With regard to the intensity of thundersnow events, we focus on the qualitative rate of snowfall in each event. In this instance, the intensity is that stated explicitly in each surface observation. Actual snow rates or snow totals were not considered, because such data were not readily available. The results are shown graphically in Fig. 4 and reveal a bias toward light snowfall, with 52% of the events featuring light snow. However, events with heavy snow account for nearly one-quarter of all events, resulting in a mean expectation of at least one occurrence of heavy convective snowfall in the United States per winter season.

5. Event types and characteristics

Within the dataset are found seven broad thundersnow event types: 1) associated with a cyclone, 2) general orographic, 3) associated with a cyclone—coastal, 4) frontal, 5) lake effect, 6) upslope, and 7) unclassifiable. The classification is based upon surface analyses (not shown) only, and the occurrence totals for each are plotted in Fig. 5. Some of these categories (i.e., types 3 and 7) may not be entirely different in their characteristics from type 1, the largest of the categories (101 occurrences). However, the constraints of the dataset's spatial coverage force the analyst to segregate clearly defined cyclone centers (type 1) from those that are obviously related to a cyclone (type 3) but that exist on the fringes of the data. To be classified as a type-1 event, the associated cyclone had to possess at least two closed isobars (4-hPa contour interval) at the time of onset for the thundersnow event; center pressure was not a consideration. This approach reduces the need to produce multiple surface analyses, although events in this category were commonly associated with a very powerful cyclone. Also, many thundersnow events in this class did occur in the vicinity of a cold or (especially) a warm front. However, these fronts were associated with a transient extratropical cyclone and did not exhibit a stationary or arctic frontal structure (type 6, to be discussed). As an example of the latter case, an arctic frontal structure can be an earlier phase of the cyclone stage as discussed by Hunter et al. (2001).

Type-2 events, termed general orographic, constitute the secondmost prevalent category (30 occurrences). All of the events in this category were found over western states. To be classified as an orographic event, two criteria were employed, requiring an examination of the observations from surrounding stations. If extensive precipitation was not occurring at neighboring stations or if surrounding stations were drastically different in their characteristics from the one reporting thundersnow, then the report was classified as type 2. An isolated event with very different weather at neighboring stations implies a thundersnow event more likely forced by orography, whereas multiple neighboring events, although perhaps still influenced by orography, suggest forcing for ascent on a larger scale (more typical of type-1 events). A common occurrence was to find a station reporting thundersnow, an overcast sky, and a temperature of up to 20°F colder than neighboring stations at which the skies were clear. In converse, the classification of type-3 events (19 occurrences) is simple. Those reports of thundersnow from coastal stations (Pacific Northwest or Atlantic coast) near which there was clearly a cyclonic circulation offshore fall into this category. These cyclones do not permit the application of the two-closed-isobar rule used for type-1 events. Instead, large wind and pressure gradients along the coasts were used primarily to identify type-3 events. Although the processes that forced type-3 events may well have been more complex, such determinations are simply not possible with the available data.

The fourth type of event is classified as frontal (11 occurrences). In these cases, thundersnow occurs poleward of a frontal zone (generally oriented from west-southwest to east-northeast) that is typically stationary and without a well-defined cyclonic circulation. Pressure centers were present in some cases, but they were weak, failed to exhibit a coherent wind field, and did not meet the two-closed-isobar rule needed to introduce them into the type-1 category. These events are similar in form to the arctic-front type of system discussed by Hunter et al. (2001). It was also found that these events typically occur with less frequency than type-1 events, which also concurs with the findings of Hunter et al. (2001).

Type 5 encompasses those events resulting from lake effects. Of the eight occurrences clearly identified as lake-effect events, four occurred at Salt Lake City, Utah; three at Buffalo, New York; and one at Muskegon, Michigan. These events all had a significant surface flow that had been recently over an open lake surface. Also, six of the eight events transpired in the absence of a significant surface cyclone. The two that featured a surface cyclone in the vicinity (both in Salt Lake City) were in northwesterly flow, southwest of the surface cyclone centered over southern Canada. Moreover, these two events featured little in the way of inclement weather at neighboring stations. These characteristics and the distance of each event from a cyclone center disqualified them as type-1 events. Also, the four eastern events were largely observed in the autumn season, whereas the Salt Lake City events occurred more in the midwinter months. There were many cases in the autumn with a flow off a lake that were not classified as type-5 events. For example, Duluth, Minnesota, experiences a large number of thundersnow events north of a transient midlatitude cyclone and with an easterly to northeasterly flow off of Lake Superior. From the available data, it is not possible to discriminate purely cyclone-related from purely lake-effect or even, perhaps, lake-enhanced thundersnow events. As such, all of the thundersnow events that fit this pattern at Duluth were classified as type-1 events.

Thundersnow associated with upslope flow constitutes type 6. All of these events occurred west of the Mississippi River, and only four could be clearly termed upslope events. In each type-6 case, an anticyclone was present over the north-central United States (e.g., Minnesota) with either a weak cyclonic circulation over the Rocky Mountains or a weak inverted trough originating over Texas. The result in each case was easterly surface flow with a strip of low ceilings and visibilities along with precipitation in the western plains states and along the Front Range of the Rocky Mountains. Events that did not fit into any of these six clearly defined categories were deemed unclassifiable and were placed into type 7.

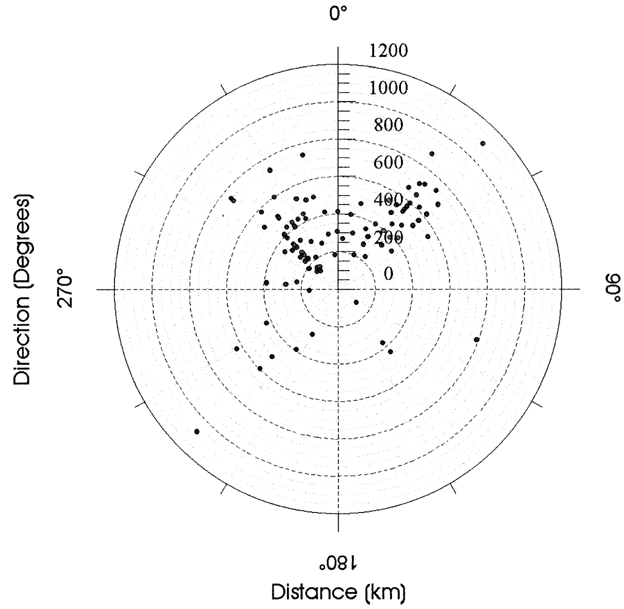

FIG. 6. Scatterplot of thundersnow event initiation with respect to a transient cyclone center (type-1 events). This figure comprises 99 type-1 events identified during 1961–90. Solid radials represent distance from the low center (km). Axes represent standard meteorological azimuth, with north at 0°, east at 90°, south at 180°, and west at 270°.

Because type-1 events compose the bulk (52%) of the dataset, we focus on them for the remainder of this discussion. For those thundersnow events associated with a cyclone, reports usually come from the colder, northern half (Fig. 6) of the cyclone, the center of which is at the center of Fig. 6. These thundersnow events concurrently exhibit a peak of activity between 200 and 400 km from the cyclone center, with more than one-half of the events between 200 and 600 km. The mean (arithmetic) distance of the thundersnow report from the cyclone center for nearly all (99) type-1 events was 440 km (2 of the 101 events were known to be type 1, but the locations of the associated cyclones were not precisely known when the thundersnow event began).

The distribution of these events evinces the presence of elevated convection. That the center of Fig. 6 constitutes the location of the surface cyclone at the time of each thundersnow event is useful, because it also signals the northernmost extent of the warm air (open-wave cyclone) if not a location well north of the apex of a warm sector (occluded cyclone). There are a number of events that occur well south of the low. However, a

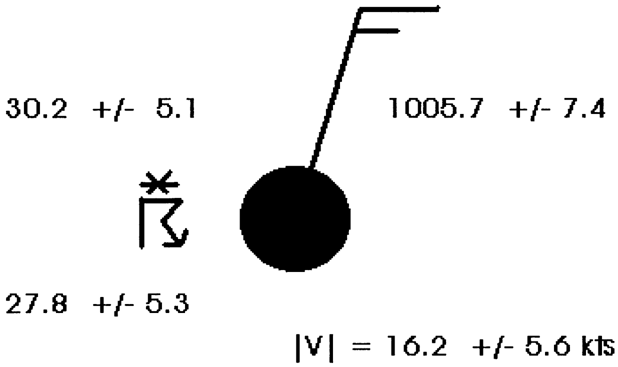

FIG. 7. Station model of composite variables for type-1 events (n = 99). Temperature (°F), dewpoint temperature (°F), and sea level pressure (hPa) are plotted in their usual locations, along with standard deviations of each variable. Mean wind speed (kt) with standard deviations (kt) are also shown numerically beneath the station circle.

subjective examination of the surface analyses reveals that the preponderance of the thundersnow reports came from regions of cold air north of a warm front (typically east of younger cyclones) or northwest of a cyclone center (often an older, occluded cyclone).

The composite surface observation (Fig. 7) for the initiation location of type-1 events (n = 99) concurs with the prior results, which place the typical thundersnow report approximately 400 km north of a surface cyclone. North-northeast winds with a mean speed of 16 kt and sea level pressures of 1005.7 hPa typify type-1 events; all pressures within one standard deviation reside below the standard sea level pressure (1013 hPa). Both the mean temperature and dewpoint temperature reside below 32°F (0°C), with an average surface air temperature of 30.2°F and a surface dewpoint temperature of 27.8°F.

6. Summary

A 30-yr climatology of thundersnow events in the contiguous United States has been assembled. In concurrence with the findings of Holle et al. (1998), we identified the preferred locations of occurrence as eastern Nevada and Utah, the central plains, and the Great Lake states. In addition, we have established March as a nationwide seasonal preference for thundersnow events. No diurnal preference was clear from the data analyzed. Individual thundersnow events are typically of limited areal extent, are short lived, and typically have light to moderate snowfall rates.

Beyond the climatological aspects of the thundersnow events examined, several other additional facts arise that should be of use to the forecasting community. First, thundersnow events often occur in association with a transient midlatitude cyclone, northwest or northeast of a cyclone's center at a mean distance of approximately 440 km. Second, the surface report featuring thundersnow is typified by overcast skies and a moderate northerly breeze of approximately 16 kt, surface temperatures that average around 30°F, and dewpoint temperatures that are only 2°–3°F cooler. Together, these results suggest a stable surface layer that is not only subfreezing but also very moist, thus inhibiting much additional cooling from melting or evaporation.

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