1. Introduction

Thundersnow is a rare event that fascinates many meteorologists because it is a mysterious meteorological phenomenon. This literature review will describe six of the different ways that thundersnow can form. There are several case studies on thundersnow, so we will be looking at these and how they compare to one another. Understanding how thundersnow forms will help meteorologists predict these rare events better in the future and therefore improve forecasts. As mentioned earlier, thundersnow is an extremely rare event, approximately six events per year. Less than two percent of thunder reports from October to May are associated with frozen precipitation events, and less than one percent of all snow events reports thunder (Schultz, 1999). “A Climatology of Thundersnow Events over the Contiguous United States” specifies seven main types of thundersnow. The most common of the causes is the events that occur within a cyclone. The other causes include thundersnow associated with orographic lifting, coastal cyclone, fronts, lake effect events, and upslope (Market et al., 2002).

Each cause has specifications and will be covered in this literature review. As the cyclonic event is most likely to occur, it will be discussed in more length than the other causes.

2. Formation Types

The formation types above are classified by Market et al. in “A Climatology of Thundersnow Events over the Contiguous United States.” In this study, 229 events were examined, but only 191 of these events contained thundersnow. Thundersnow events are defined by thunder occurrences with continuous or showery-type snow. The observations were taken over a thirty year period (1961-1990) and were examined from 3-hourly reports from 204 stations in the contiguous United States. These events occurred between the months of October and April, with March being the month with the most occurrences. The overall monthly distribution can be seen in Chart 1. This study also looked at the times of the day at which the thundersnow events
occurred, but no conclusions could be made from the data. It was determined that approximately half the time the events were happening, light snow was occurring and the other half was split almost evenly by moderate and heavy snow (Market et al., 2002).

a. Orographic Lifting

The second cause of thundersnow occurred in the western United States due to orographic lifting, and these events were defined by several different characteristics. If the event was only occurring at the specified station with extremely different weather at surrounding stations, it was classified as orographic. If the event was also occurring at surrounding stations, the cause was more likely cyclonic than orographic. The station at which the thundersnow was occurring typically had temperatures 11 K cooler than surrounding stations, and overcast skies at the thundersnow location compared to clear skies at the surrounding areas (Market et al., 2002). Unfortunately we were unable to find a case study on this type of event.

b. Coastal Cyclone

All events with this cause were identified by a coastal station sounding that reported thundersnow when a cyclone was offshore. The cyclones were classified by large wind and pressure gradients instead of the two-closed-isobar rule used in the first type. There may have been more complex reasons for these events, but the available observations did not permit more details (Market et al, 2002).

One case study was available by Neil A. Stuart of the National Weather Service in Wakefield, VA. This study looked at a thundersnow event that occurred during the December 30th, 2000 snowstorm. This event was caused by a large snowstorm moving towards the northeast after developing off the Atlantic coast. Some areas received a two different periods of thundersnow, and some areas received over two feet of snow (Stuart, 2001).

Upper level conditions right before this event can be seen in Figure 1. The upper air plot shows an exit region of a 300 hPa jet streak in the Carolinas, where there was also an increasing upper-level divergence. Mesoscale waves offshore suggested considerable turbulence and an intensification of the upper jet. Since mesoscale disturbances increase upward motion, the chances of convection increased greatly. The very strong jet and center of the upper level subsidence that moved over New York can be seen in Fig-

![Figure 1](image-url)

**Figure 1.** 300-hPa plot with height contours (solid gray), wind barbs (Knots), and divergence (black contours) at 0000 UTC (Stuart, 2001).
The heavy snow began by 1600 UTC in New Jersey, New York and New England. Base reflectivities were as high as 45 dBz, and the mesoscale waves began moving into the system. The inbound southeasterly low level jet and the northeasterly out-bound maximum were around 50 knots each. These values indicate a very powerful cyclonic curvature of the low level flow. Soundings showed that the entire atmosphere was below freezing and saturated below 800-hPa. The vertical wind profile showed veering northeast winds of over 50 knots. These two factors show how strong the low level moisture and thermal advection were for this event. The sounding also showed 51 J kg\(^{-1}\) of CAPE between the 830 and 610-hPa levels. These conditions greatly supported elevated convection above New York. Satellite, radar and lightning data provided the needed information to help forecast the thundersnow before it was observed (Stuart, 2001).

c. Frontal

The fourth cause of thundersnow occurred poleward of a frontal zone. These fronts are usually sloping from west-southwest to east-northeast and are stationary, without a well-defined cyclonic circulation. These systems had weak pressure centers if at all that did not show a coherent wind field or two-closed-isobar (Market et al, 2002).

In “Winter Lightning and Heavy Frozen Precipitation in the Southeast United States” by Hunter et al, seven different events from the southeast region of the United States are looked at because they contain considerable cloud-to-ground lightning with frozen precipitation. Figure 3 shows the areas impacted by these events.

The cases were divided into arctic fronts and migratory cyclones, and some developed from an arctic front into a migratory cyclone. The cases had several similarities to one another: the upper-troposphere’s wind speed maxima were found east of 100°W and formed near 30°N; six of the cases featured a split flow pattern with a distinct north and south sector; some sort of troughing formed in the middle troposphere; lower troposphere jets and baroclinity creating warm air advection over a cold air mass. The arctic front cases had an east-west boundary and produced more precipitation than the migratory cyclones. To measure instability in these events, Hunter et al. looked at the temperature difference between the 700 and 500-hPa lev-
As the average temperature difference was 288.05 K, it was determined that there was significant conditional instability. The study found the arctic front cases showed a better pattern between the lightning and precipitation. Most of the arctic front cases had more than forty percent of the lightning strikes within 100 km of either side of the freezing line. For a majority of the cases, the flashes were near the heaviest precipitation. The arctic front cases were characterized by a prolonged period of synoptic-scale lifting of warm moist air over arctic air. It was determined that detection of lightning within 100 km of the boundary can be used to help forecast heavy precipitation (2001).

In “Lightning during Two Central U.S. Winter Precipitation Events” by Ronald Holle and Andrew Watson, two arctic fronts over the central United States were studied. The events occurred on January 4th and January 16-17th, 1994. The first event had only 27 cloud-to-ground flashes while the second had over 2000 flashes. During the January 10th event, the maximum reflectivities reached 35 dBZ, but 30 dBZ was much more common. The lightning and reflectivities reached a maximum and dissipated during the same time. During the time the lightning was occurring, the maximum 850-500 lapse rate was recorded at 295.15 K. In the January 16-17th event, high echo tops corresponded to more frequent lightning flashes. In lower levels of the atmosphere, warm air advection was evident due to veering. The low level moisture flowed north over a cold air mass to produce the precipitation.

Both events had slightly more positive flashes than negative flashes when looking at only the flashes that occurred during the frozen precipitation. The reflectivity cores for both events were in the moderate intensity when the lightning began. The lightning in the second event occurred in a region of conditional symmetric instability, but not in the first event. No thunderstorms were reported for the first event and only two were recorded for the second event (1996).

d. Lake Effect

This cause of thundersnow is defined by any event that is the result from lake effects. These cases were found near Salt Lake City, UT; Buffalo, NY; and Muskegon, MI. They all had major surface flow over the lake surface and six of the eight were not near a surface cyclone. The two events that were in the vicinity of a cyclone were far enough away from the cyclone that the surrounding stations had differing weather reports (Market et al, 2002).

One study was found on this type of event by David Schultz; forty-nine different cases for the Great Salt Lake region and twenty-six events in western New York were studied for comparison between lake effect events with and without lightning. Schultz found that the most important parameters for forecasting thundersnow for these events are lower-tropospheric temperatures and lifted index. Dewpoint depression and CAPE were found not to be significant in these cases. He found warmer and moister conditions in the lower troposphere are necessary to prevent lightning in this type of event. Strong updrafts in the mixed-phase region of the cloud provide water vapor and supersaturate the air. Rimming ice particles are then produced and interact with one another to create electric charges. The most probable hypothesis states that since the lightning events have a warmer lower troposphere, the 10°C isotherm is high enough off the ground that vertical motions can be great enough to separate the electrical charge and produce lighting (Schultz, 1999).

e. Upslope

The last uncommon cause includes
any case of thundersnow that is connected with up slope flow. All the events of this type were located west of the Mississippi River. For all cases, an anticyclone was near Minnesota with either a cyclone over the Rocky Mountains or an inverted trough over Texas. Every case had an easterly flow with low ceilings and visibilities with precipitation over the western plains and Front Range (Market et al, 2002). The case study found varies a little from the definition by Market et al due to other conditions also having a role in the event.

This case study was about an event that happened over the Sierra Nevada on November 9 and 10th, 2000. While thunderstorms are common in this region in the summer months, this event included snow showers and even thundersnow, an uncommon occurrence in this area. The moist convection appeared to be surface-based and produced snowfall amounts of up to nine inches in some areas with elevations between 3000 and 4000 ft above mean sea level. This is a very unusual event for November in this area.

The conditions leading up to this event include: a short wave off the central coast of California, a strong, cold upper-level trough and a moderately strong vorticity maximum over the Sacramento Valley. This vorticity maximum resulted in substantial differential positive vorticity advection over the area shown in Figure 4. Normally this kind of set up would not have the moisture available for high precipitation amounts, but there was excess low-level moisture present in the area. Due to this extra moisture, thunderstorms began on the eastern side of the Sacramento Valley and became more intense as they moved to higher terrain.

The ETA model was used in forecasting wind profiles for this area. The model forecast southwest to westerly winds of 9 to 12 knots, but the winds backed to the southwest and sped up to 12 to 17 knots. These stronger southwest winds increased the up slope flow across the western slopes of the Sierra Nevada. The elevated terrain helped destabilize the air mass and helped intensify the storms to produce thundersnow. The model then depicted a steep lapse rate of almost 8 K km^{-1} and a deep layer of low-level moisture. The satellite imagery made it easy to see that the short wave trough contributed to the lift and destabilization, and the elevated terrain provided the needed surface moisture convergence. These factors helped set off and uphold the thunderstorms. The soundings showed temperature and moisture in the atmosphere would support maximum growth of snow crystals. Strong updrafts in this region helped supply enough water vapor for supersaturation and the same interaction of rimed particles explained early likely occurred to create lightning in these storms. These storms had a small number of lightning strikes, but of those flashes, a large percentage was positive.

f. Cyclonic
Using observations from several different storms, Martin observed very interesting patterns in cyclonic thundersnow events. The most noticeable pattern is that the areas with the highest ratio of cloud-to-ground lightning also tend to receive the largest amounts of snow. This can be seen

![Figure 4. Vorticity maximum shown over the Sierra Nevada region at 500-hPa (Tardy, 2002).](image-url)
when looking at a map of the two plotted next to each other. Figure 5 demonstrates this for a storm that tracked across the central United States, with heavy snowfall being reported in Missouri for thirteen consecutive hours. This particular case very clearly shows the correlation between cloud-to-ground lightning and snowfall. Also, one can note from Figure 5 that there were some areas of heavier snow into southern Wisconsin, which can be attributed to some personal observations of cloud-to-cloud and in-cloud lightning (1998).

This case also shows the relationship of the low pressure system structure as a way of determining the strength of thundersnow. According to Martin’s first paper about the frontal structure, the storm exhibits many characteristics of maritime cyclones that can explode rather quickly. The similarity might also be what caused the January case over the Midwest to become so instable. The unique feature between the maritime cyclones and the winter cyclone is the bent-back occlusion, or occlusion traveling in the opposite direction due to other forces. The low pressure system also had a deep warm front and a cold front, though the low itself was relatively light (1998).

Another interesting feature noted by Martin was that the occluded front first started to form in the mid-troposphere and not immediately at the surface. Near 1200 UTC on January 19th, an occluded front can be noted above the surface, but it is not shown on the surface until 2000 UTC (1998).

Both of Martin’s papers focus on looking at the trowal region of the storm. A trowal is an area of warm air intruding into cooler air aloft. Because the trowal creates a sort of canyon on the 309K θₑ surface, warm air from the south quickly tries to fill it. The air is then warmer than its surroundings, so it becomes positively buoyant. This rising motion creates a lot of precipitation, which in this case fell in the form of snow. The trowal overlaps the region where the heaviest snowfall occurred, as well as almost all of the lightning strikes shown in Figure 6 (1998).

A similar case occurred in February and was reviewed by Market et al. One of the first things noticed when reviewing the RUC analysis was a band of significant winter values of CAPE in central Iowa around 2100 UTC (Figure 7). As the storm tracked to the east, the models gradually
decreased the amount of CAPE in the atmosphere to a smaller area of 10 J kg\(^{-1}\) on 0000 UTC Friday, February 11\(^{th}\). While the CAPE values had greatly decreased, it was believed that the actual generator of the thunder within the snow event was the increase in Petterssen frontogenesis along the border between Iowa and Illinois (2009). Petterssen frontogenesis is a process that looks at the relationship between the horizontal potential temperature gradient and properties of the horizontal velocity field. (Keyser et al 1988) As this continued to propagate, high vertical velocity values were found in the same areas as the CAPE, which coincided with the highest precipitation values (Market et al., 2009).

There were many strange phenomena that occurred with this storm system as well. Typically in a winter thunderstorm event, the cloud-to-ground lightning flashes are about half negative and half positive. This storm created an environment suitable for mostly negative flashes as reported by the National Lightning Detection Network (NLDN). Also, in most cases of severe weather the convection is not directly at the surface, it is higher up in the atmosphere. This storm had a great atmosphere of convection within the boundary layer, which is unusual. These unusual parameters in combination with frontogenesis in the lower levels and strong pressure gradients created the perfect atmosphere for some increased winds at the surface. These winds ended up being above the “severe” criterion (Market et al., 2009).

Mills and Walsh examined a case from the 1980s that moved across the Upper Mississippi Valley and showed how hard thundersnow can be to forecast. One of the main things shown in this case study was that winter meso-lows can develop rapidly under conditions that occur just as the backside of a trough is moving through an area (Figure 8). This low originated with very little moisture in an extremely cold environment. This particular storm also demonstrates that in order to get thunder and lightning there must be some form of forcing aloft. The most unique feature of the storm according to the paper is the extremely large horizontal temperature gradients in the middle of the troposphere (1988).

This storm may seem odd when based off of other typical winter-time lows,
but it demonstrates a lot of the characteristics of “polar lows.” One of the most noticeable similarities is that the low develops on the backside of the trough as opposed to the front side, which is more typical. Polar lows also tend to take a southeastern path, which is similar to what this storm did. The most noticeable similarity is strong positive vorticity advection (PVA), giving the storm the lift required. The biggest difference between this storm and the polar lows is how it forms. This storm developed over a continental region, as opposed to maritime as it would if it were a polar low (Mills and Walsh, 1988).

The final paper on cyclonically based reports of thundersnow takes a slightly different approach to understanding the development of thundersnow within a mesoscale cyclone. Moore et al. takes an in-depth look at the storms from the 4th and 5th of December 1999. These storms developed and traveled through Kansas and into parts of Texas, Oklahoma, and Missouri. This paper developed a basic model of a “typical” low pressure system associated with thundersnow shown in Figure 9. The thought behind this paper was to develop a forecasting tool to see what conditions were similar and different from this case to other cases (2005).

This particular case also introduces a concept of conveyor belts for the air streams within the atmosphere. The conveyor belt is thought of as a group of air parcels that originate in the same area and travel in a general pattern. These conveyor belts are usually associated with extratropical cyclogenesis. Looking at Figure 5, there are two distinct belts listed: the warm conveyor belt (WCB) and the dry conveyor belt (DCB). There is sometimes a third cold conveyor belt: (CCB) associated with these cyclones. The WCB typically causes the higher clouds that wrap around the low, and it is also a main factor in bringing moisture into the troughal region. The DCB contains high amounts of potential vorticity. The DCB usually spreads out along the back side of the cold front, which can help contribute to frontogenesis in that region. It is typically seen by looking at water vapor images and locating the dry slots flowing into the cyclone. The CCB is the easterly flow ahead of the warm front. It also aids in organizing the precipitation around the low pressure system (Moore et al., 2005).

One of the biggest things that Moore et al. noticed was that this cyclone was actually a fairly weak one. Most other papers associate deep, occluding cyclones with reports of thundersnow, but this particular storm was a relatively weak low pressure system but still produced large amounts of snow as well as thunder and lightning. Looking at the model in Figure 5 you can see that the snow formed north of a large area of negative equivalent potential vorticity (EPV), yet south of the frontogenesis, which is similar to what was found in the Martin paper. A final observation to note from the paper is that convection and thunder usually occur to the northwest of the center of the low pressure (2005).

Figure 9. A model of a typical low pattern as well as some of the flow required to produce a convective snowstorm (Moore et al., 2005).
Conclusion
As shown in this review, thundersnow can occur under several different environments. The most common type of thundersnow occurs within a cyclone. Other types of events include: orographic lifting, coastal cyclone, frontal, lake effect, and upslope. This review shows that there could be more research done on thundersnow events, and hopefully the research on thundersnow will provide better forecasting of these types of events in the future.

References


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