A REVIEW ESSAY ON MESOSCALE SNOW BANDS:

HOW THEY FORM AND THEIR IMPORTANCE

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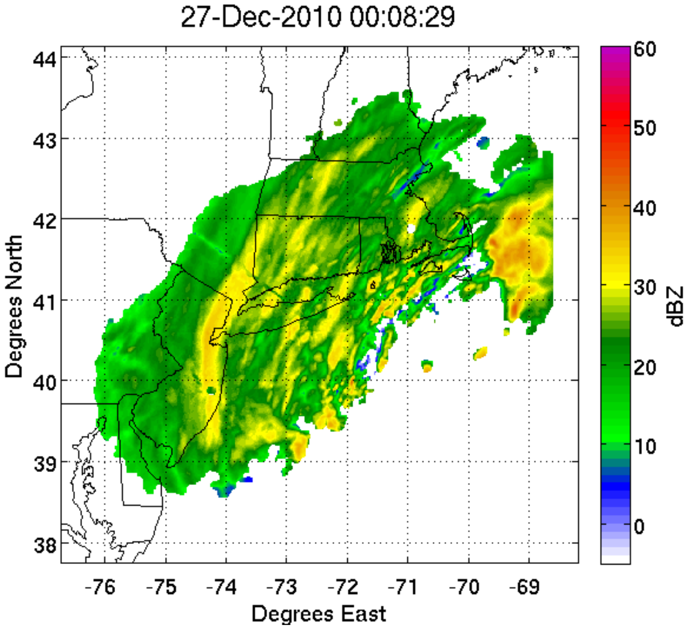
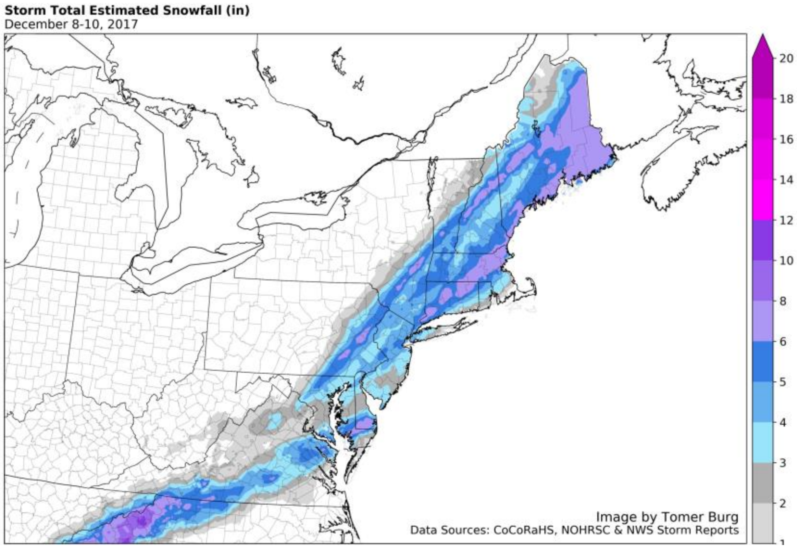


Credit: Stony Brook University School of Marine and Atmospheric Sciences



Credit: Tomer Burg

1. Introduction

Large, synoptic-scale snow events, which usually get plenty of attention because of their areal extent and wide-scale impacts on society, commonly have small, mesoscale components within the larger system. These features might not get a whole lot of recognition, but they are very important to understand when forecasting in the wintertime since snowfall rates and snow totals can be drastically impacted by their presence. This mesoscale phenomenon is referred to as mesoscale snow banding in winter storms, where heavy snow is concentrated over a relatively narrow and small area when compared to the entire system, with a common width of 10 – 100 km and a length of around 100 – 500 km (Novak et al. 2004, Ganetis et al. 2018). They are very important to study because these snow bands can produce snowfall rates of one to three inches or more per hour, severely reducing visibility to under a half of a mile and causing snow totals to be much higher in the areas that these mesoscale snow bands develop over (Scala et al. 2009). For instance, a laterally quasi-stationary mesoscale snow band in the northeastern United States was observed to have a gradient of six inches or more between the center of the snow band and about 50 km to the northwest of the band (Kenyon 2013). Similar tight gradients in snowfall amounts have been observed in other snowstorms due to mesoscale snow bands. Due to their small scale, forecasting for this aspect of winter storms is very challenging, since weather models and meteorologists often cannot accurately pinpoint exactly where or when a mesoscale snow band will develop in a winter storm, especially on longer time scales (Novak et al. 2009). There has been an abundance of research completed within the meteorological community that focuses on what environment is required for these mesoscale snow bands to form, but, as with many other mesoscale weather phenomena, there are very subtle factors that greatly influence the development and location of these snow bands that are not completely understood. This paper will summarize what we do know up to this point about this fascinating topic, including some of the environmental conditions that go into forming mesoscale snow bands and sustaining them. Eight scholarly, peer-reviewed journal articles are analyzed below on mesoscale snow banding that have many similarities, but also several differences that make each one of them unique and valuable to study. Most articles focused on mesoscale snow banding over the northeastern United States, since this is where these snow bands are most prevalent due to the interactions of the storm system with the Atlantic Ocean, but they can occur in other parts of the country as well. The synoptic scale factors that influence the development of mesoscale snow bands will be looked at first before diving into the specific mesoscale processes and forecasting implications.

2. The Influence of Synoptic-scale Factors on Mesoscale Snow Banding

Even though the development of mesoscale snow bands is highly dependent on small scale processes and forcing mechanisms that will be discussed later, there are many synoptic-scale conditions and patterns that first need to support a favorable environment for these snow bands to form in. Research has shown a general synoptic scale evolution that produces favorable conditions for mesoscale snow band development over the northeastern United States through a composite of 88 past mesoscale snow band events (Novak et al. 2004). This evolution does not guarantee that mesoscale snow bands will develop, but it gives meteorologists a general guideline of what synoptic-scale setup has commonly favored mesoscale snow bands in the past. Figure 1 starts twelve hours before the mesoscale snow band developed and shows the surface cyclone located over the Carolinas with as strong 300 mb jet found at the base of a 500 mb trough, which is a common jet configuration for the development of strong northeast snowstorms (Novak et al. 2004). The composite also shows a small east-west oriented band of midlevel frontogenesis across southern New York, located on the northern fringe of the midlevel warm air advection and in a broad and weak deformation zone (Novak et al. 2004). Twelve hours later in Figure 2, when the mesoscale snow band is developing and first being observed, the surface cyclone deepens and moves northeast as the 500 mb trough becomes negatively tilted (Novak et al. 2004). The presence of warm air advection, the implied increase in cyclonic vorticity advection, and the double jet structure provide support for large-scale ascent over the northeastern United States (Novak et al. 2004). The closed low at 700 mb also deepens by this time, which establishes a well-defined midlevel deformation zone that acts on the thermal gradient and contributes to the strong midlevel frontogenesis in the northwest quadrant of the surface low (Novak et al. 2004). Additionally, the cold conveyor belt of the low-pressure system plays a major role in transporting relatively warm, moist air from the Atlantic Ocean inland, towards the northeastern United States, supplying the deep moisture that is necessary for mesoscale snow band development (Moore et al. 2005, Novak et al. 2008). All these factors contribute to one or multiple mesoscale snow band(s), containing heavy snow, developing across the northeastern United States. Even though there is not another journal article included in this review essay that walks through all the synoptic-scale steps like this one did, this article used a large sample size of 88 mesoscale snow band events when creating the composite four panel plots (Novak et al. 2004). Therefore, these results are valid and can be used when attempting to predict when the synoptic-scale environment is favorable for mesoscale snow band events in the northeastern United States.

It has also been shown that most mesoscale snow bands form in the northwest quadrant of mature surface cyclones, and Figure 3 demonstrates this by plotting the location of mesoscale snow bands, relative to the center of the surface cyclone, in 108 cases that were studied (Ganetis et al. 2018). The northwest quadrant is the preferred location due to many of the synoptic-scale reasons that were just discussed, but primarily because this is where the most ascent is located within the mid-latitude cyclone. There is usually one primary, or dominant, mesoscale snow band as a part of the low-pressure system, and this band is usually 200 km or longer in length (Ganetis et al. 2018). These primary bands are usually oriented from the southwest to the northeast within the northwest quadrant of the surface cyclone (Ganetis et al. 2018, Novak et al. 2004). A common pivoting motion of these intense snow bands has also been observed, and the way that they pivot, usually from a west-east orientation to a southwest-northeast position, is important to understand because the pivot point experiences heavy snow for the longest period of time (Novak et al. 2004). It is also important to note that there are usually several groups of smaller bands shorter than 200 km within the winter storm, sometimes close to the dominant single band, that can enhance snowfall accumulations, and these are often not talked about as much as the primary band (Ganetis et al. 2018). However, there was some disagreement among the literature about how to classify the mesoscale snow bands and categorize them into single band, multi-band, and no band groups, or even create additional classifications (Ganetis et al. 2018, Novak et al. 2004). These discrepancies arose because of different reflectivity thresholds that were used and variations in the ways that banded events were separated into categories. Therefore, it is hard to draw any concrete conclusions about whether single-banded events or multi-banded events are more prevalent in winter storms that impact the northeastern United States.

With an understanding of the evolution of a common synoptic-scale environment for supporting mesoscale snow bands in the northeastern United States and insight about where and how many of these snow bands form within the surface cyclone, we can examine the mesoscale processes that are involved with the generation of mesoscale snow bands.

3. Mesoscale Processes Important for Mesoscale Snow Banding

Many of the journal articles that were researched agree on three primary factors - frontogenesis, stability, and potential vorticity - that create a favorable environment for mesoscale snow bands to form in. Specifically, mesoscale snow bands will be most likely to form in an environment with strong frontogenetical forcing to provide lift, in an area of weaker conditional stability and where conditional symmetric instability is being released, and within a region of negative moist potential vorticity (Ganetis et al. 2018, Novak et al. 2004, Novak et al. 2009, Novak et al. 2010, Moore et al. 2005, Schultz and Knox 2007). All these independent variables are tied together and work collectively to produce mesoscale snow bands. For example, a relationship has also been found between frontogenesis and instability described by the Sawyer-Eliassen equation, with the frontogenetical response being enhanced in the presence of small moist symmetric instability (Novak et al. 2004, Novak et al. 2010). There is also a connection between potential vorticity in the mid-levels of the atmosphere and frontogenesis, both of which are important to diagnose when analyzing the formation of these mesoscale snow bands (Ganetis et al. 2018, Novak et al. 2004, Novak et al. 2009, Novak et al. 2010). Additionally, there is a distinct relationship between latent heat release and frontogenesis, and the positive feedback between these two features is important for understanding the formation and maintenance of the snow band (Novak et al. 2009, Novak et al. 2010). All these processes and forcing mechanisms work together and play a critical part in the evolution of mesoscale snow bands within winter storms.

The way that the primary environmental factors that influence mesoscale snow bands evolve over time as the snow bands develop, intensify, and then dissipate, provides insight about how the mesoscale processes and forcing mechanisms work in tandem with one another throughout the band's life cycle (Figure 4, Novak et al. 2010). Prior to about six hours before the mesoscale snow band's formation, weak midlevel frontogenesis and strong conditional stability are found in the northwest quadrant of the developing surface cyclone, and the combination of these two parameters limits ascent in this region (Novak et al. 2010). Between approximately six hours before the snow band forms and when the band is first observed, the lower-tropospheric frontogenesis nearly doubles, and the conditional stability above the frontal zone is reduced (Novak et al. 2010). The increase in frontogenesis is primarily due to the development of a midlevel trough that forms largely because of latent heat being released by heavy precipitation in the area, but not yet organized into a discrete frontogenesis band (Novak et al. 2010). This latent heat release also creates a potential vorticity anomaly that helps to enhance frontogenesis within the region of heavy precipitation (Novak et al. 2010). The band forms within an elongated region of intense forcing for ascent co-located with the midlevel frontogenesis maximum, in an environment of small conditional stability (Novak et al. 2009, Novak et al. 2010). Additionally, the release of conditional symmetric instability helps to organize the bands (Ganetis et al. 2018). During band maturity, frontogenesis continues to increase due to the latent heating and the associated induced circulation of the band itself (Novak et al. 2010). However, the resulting strong ascent usually leads to a differential vertical potential temperature advection pattern that stabilizes the environment, which serves as a local brake on the positive feedback loop (Novak et al. 2009). Band dissipation commonly occurs as new diabatic potential vorticity anomalies, associated with latent heat release, form to the east of the primary snow band (Novak et al. 2009, Novak et al. 2010). Therefore, the midlevel flow in the band region is altered both in terms of wind direction and speed, creating a more symmetric midlevel flow, resulting in a reduction of the deformation, convergence, and associated frontogenesis, which weakens the snow band (Novak et al. 2009, Novak et al. 2010). To be specific, 77% of 36 cases studied exhibited a 700 mb potential vorticity maximum to the east of the band, suggesting that the flow near the band was affected by the upscale growth of this anomaly during band dissipation (Novak et al. 2010). The midlevel trough is also important to monitor for band dissipation, as a weakening of this trough will decrease the amount of frontogenesis present and could lead to premature band dissipation (Novak et al. 2008). The development, intensification, and dissipation of mesoscale snow bands relies on many different mesoscale processes and forcing mechanisms that dictate the band’s maximum strength and size, as well as its lifetime, which will be discussed next.

4. Time Evolution and Temporal Changes of Mesoscale Factors

Analysis of the lifetimes of mesoscale snow bands shows that they are generally short lived, with many of them only lasting for around two hours, since the conditions favorable for band formation occurs on limited time scales (Novak et al. 2004). However, research has also shown that there are some outliers, with a few bands persisting beyond 12 hours, the longest of which that was studied lasted 22.5 hours (Novak et al. 2004). Furthermore, some short-lived bands can form in one place, dissipate, but then be replaced by another band in the same location, causing a large accumulation of snow with the cycling nature of the intense bands (Novak et al. 2004). The sometimes subtle differences in all these mesoscale factors related to intense snow band development, maintenance, and dissipation are important to understand because those variations can provide insight into the location, intensity, and lifetime of the snow band.

Frontogenesis and conditional stability are arguably the two most important parameters that influence mesoscale snow bands, and their evolution in time plays a major role in determining how individual bands develop and strengthen. Figures 5 and 6 were created by analyzing 36 different banded events and 22 different "null" events, where no mesoscale snow band developed (Novak et al. 2010). These figures show how frontogenesis and conditional stability change over time throughout the band formation and dissipation process (Novak et al. 2010). Frontogenesis gradually increases before the band forms at t=0, and this increase in frontogenesis continues for about two or three more hours as the band matures before dropping off rather sharply as the band dissipates (Figure 5, Novak et al. 2010). Conditional stability decreases before the band forms and it remains low up until the time of band formation, before gradually increasing as the band dissipates (Figure 6, Novak et al. 2010). Frontogenesis and conditional stability act differently in the cases where mesoscale snow bands do not develop, as they remain rather constant throughout the time period that was studied (Novak et al. 2010). This difference between banded and non-banded events can also be seen in Figure 7 with a composite cross-section comparison of frontogenesis, potential vorticity, upward motion, and other variables in cases where mesoscale snow bands form versus where bands do not develop (Novak et al. 2004). In the cases where mesoscale snow bands did occur, the cross-section shows that the band position is embedded within a sloping frontal zone (Novak et al. 2004). There is also a layer of equivalent potential vorticity of less than 0.25 potential vorticity units higher up in the atmosphere, between 550 and 350 mb, that is coincident with the mean band position and indicative of a small amount of moist symmetric stability at this location (Novak et al. 2004). The frontogenetical response in the presence of this small moist symmetric stability takes the form of a concentrated updraft that is slightly tilted towards the colder air (Novak et al. 2004). This tilt can also be seen in the relative humidity values, indicating that slantwise ascent is present where the band is located (Novak et al. 2004). In contrast, with the composite cross-section where mesoscale snow bands did not develop, frontogenesis is weaker and conditional stability is larger, leading to broader and weaker ascent (Novak et al. 2004). This further demonstrates that frontogenesis and conditional stability are two of the most important parameters to consider when trying to predict whether mesoscale snow bands will develop in a certain environment.

5. Microphysical Processes

Hydrometeor lofting is an interesting consequence of intense mesoscale snow bands, and this phenomenon is important to understand as it poses a big challenge to forecasters. Research has shown that hydrometeor lofting can lead to considerable horizontal displacement between the areas of strongest ascent and the areas that receive the most surface snowfall accumulations (Lackmann and Thompson 2019). This process occurs when snowflakes are falling through an updraft that exceeds their fall velocity, thus lofting the snowflakes higher into the atmosphere instead of allowing the snowflakes to fall to the surface (Lackmann and Thompson 2019). As the snowflakes are being lofted vertically in the atmosphere, the slanted nature of the updraft also advects them horizontally, away from the location at the surface where the heaviest snow would have been situated if hydrometeor lofting did not occur (Lackmann and Thompson 2019). Therefore, snow lofting and the horizontal advective transport of snowflakes needs to be accounted for in model microphysical parameterizations so that the heaviest surface snowfall can be accurately pinpointed (Lackmann and Thompson 2019). Figure 8 shows the researchers' hypothesis for what would happen when the updraft is strong enough for lofting compared to when the updraft is not substantial enough for lofting (Lackmann and Thompson 2019). Their hypothesis was oversimplified since additional regions of lofting are not accounted for such as cloud-top generating cells and elevated convection, but it did accurately depict a zone of reduced reflectivity and a lower snow mixing ratio beneath the location of the strongest ascent in the cases where lofting was present (Lackmann and Thompson 2019). However, contrary to their initial hypothesis, in both cases, the zones of snow lofting tended to be more upright and less sloped than what is depicted in Figure 8 (Lackmann and Thompson 2019). Overall, this research provides some great insight as to why snowfall is distributed much more uniformly within a mesoscale snow band that has a weaker updraft and no snow lofting present, in contrast to a snow band with a much stronger updraft that promotes snow lofting and will concentrate the snowfall accumulations over a much smaller area.

6. Forecasting Implications of Mesoscale Snow Banding

A variety of synoptic-scale and mesoscale processes and forcing mechanisms create a favorable environment for mesoscale snow bands to form within snowstorms, and how they evolve over time will dictate the strength and duration of the bands. However, forecasting the presence and duration of mesoscale snow bands within a synoptic-scale winter storm is rather challenging, not only because of factors like hydrometer lofting, but also because of the existence of many different mesoscale contributors, such as frontogenesis, stability, and potential vorticity, to come together and produce an environment that is favorable for mesoscale snow bands to form and sustain themselves. Therefore, it has been determined that the forecasting skill of mesoscale snow bands decreases substantially beyond twelve hours before the predicted event (Novak et al. 2009). There have been some successful short-range predictions of intense snow bands, but band occurrence, meaning predicting that a mesoscale snow band will form somewhere within the cyclone, is still more predictable than pinpointing the band timing or location (Novak et al. 2009). One model simulation that was created to predict mesoscale snow bands, under-forecasted the snowfall accumulation and displaced the axis of heaviest snow by about 50 km (Novak et al. 2008). The reasons for these errors were due to several subtle differences between the model and the observations, and because if one factor is slightly off, then many parameters will be incorrect because everything is connected throughout the evolution of mesoscale snow bands. For example, there was a slight deviation in the predicted location of the midlevel trough which impacted the placement of the strongest mesoscale forcing, and the model also predicted that this trough would weaken earlier which led to premature band dissipation due to early weakening of frontogenesis in the presence of stronger conditional stability (Novak et al. 2008). This demonstrates that mesoscale models can generate realistic snow bands, but due to the inherent uncertainties associated with forecasting the evolution of forcing, stability, and moisture, ensemble approaches will likely be required to improve forecasts of mesoscale snow bands in the future (Novak et al. 2008). An increase in the number of observations of temperature, vertical velocities, and microphysics would also help to increase the accuracy of models (Novak et al. 2008). These additional observations could also help future research on the structure and dynamical evolution of mesoscale snow band events to provide more insight about this meteorological phenomenon (Novak et al. 2008). There is so much more research that can be done in relation to mesoscale snow bands that will help meteorologists understand them better and, therefore, help to improve the accuracy of our forecasts for this mesoscale phenomenon.

7. References

Eight Main Journal Articles

Ganetis, S. A., Colle, B. A., Yuter, S. E., & Hoban, N. P. (2018). Environmental Conditions Associated with Observed Snowband Structures within Northeast U.S. Winter Storms. Monthly Weather Review, 146(11), 3675–3690. doi: 10.1175/mwr-d-18-0054.1

Lackmann, G. M., & Thompson, G. (2019). Hydrometeor Lofting and Mesoscale Snowbands. Monthly Weather Review, 147(11), 3879–3899. doi: 10.1175/mwr-d-19-0036.1

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Schultz, D. M., & Knox, J. A. (2007). Banded Convection Caused by Frontogenesis in a Conditionally, Symmetrically, and Inertially Unstable Environment. Monthly Weather Review, 135(6), 2095–2110. doi: 10.1175/mwr3400.1

Miscellaneous Sources and Articles

Scala, J. R., Beachler, D., DeVoir, G., & Grumm R. (2009). A Remarkable Mesoscale Snow Band Event Over Southern PA: A Snow Lover's Dream and a Forecaster's Nightmare. AMS 23rd Conference on Weather Analysis and Forecasting/19th Conference on Numerical Weather Prediction. https://ams.confex.com/ams/23WAF19NWP/techprogram/paper_154284.htm

Kenyon, J. S. (2013). The Motion of Mesoscale Snowbands in Northeast U.S. Winter Storms. University at Albany, State University of New York. http://www.atmos.albany.edu/student/jkenyon/Kenyon_thesis.pdf

8. Figures

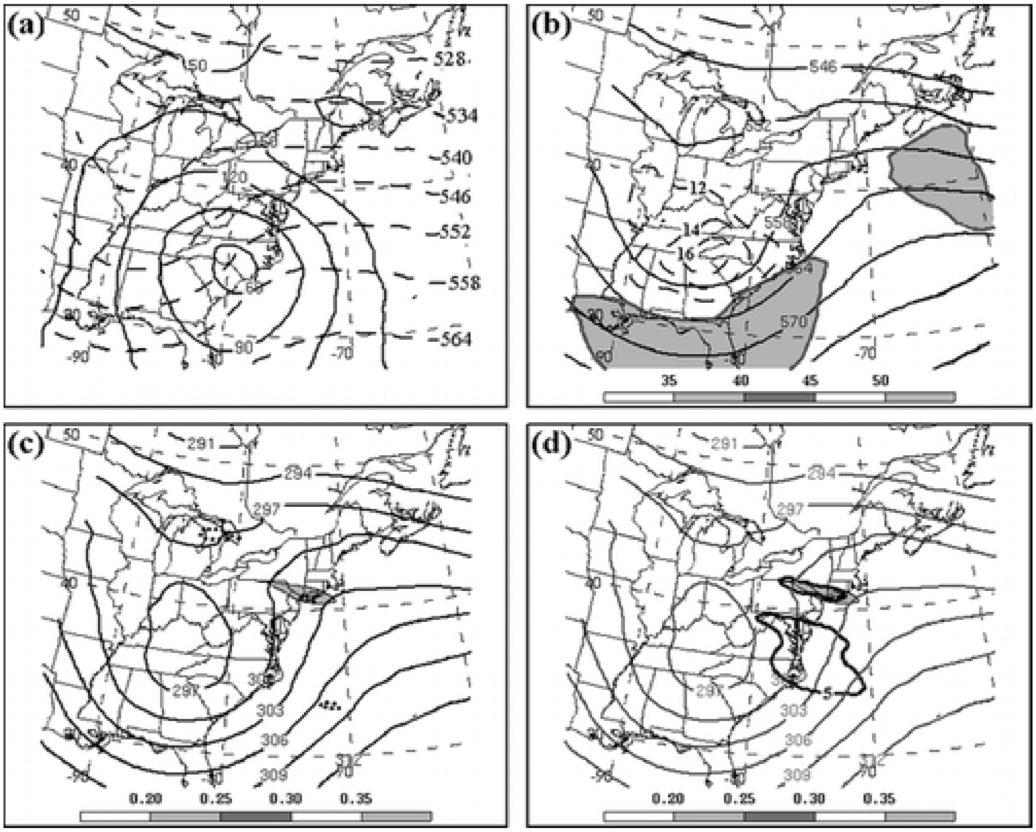

Figure 1: Composite four-panel plots of mesoscale snow band events in the northeast U.S. twelve hours before the band developed

a – 1000 mb heights (solid contours), 1000-500 mb thickness (dashed lines)

b – 500 mb heights (solid contours), absolute vorticity (dashed contours), 300 mb wind speed (shaded regions)

c – 700 mb heights (solid contours), 750-650 mb layer-averaged resultant deformation (dotted contours), 750-650 mb layer averaged frontogenesis (shaded regions)

d – 700 mb heights (solid contours), 750-650 mb layer averaged frontogenesis (shaded regions), 750-650 layer-averaged temperature advection (solid black contours)

(Novak et al. 2004)

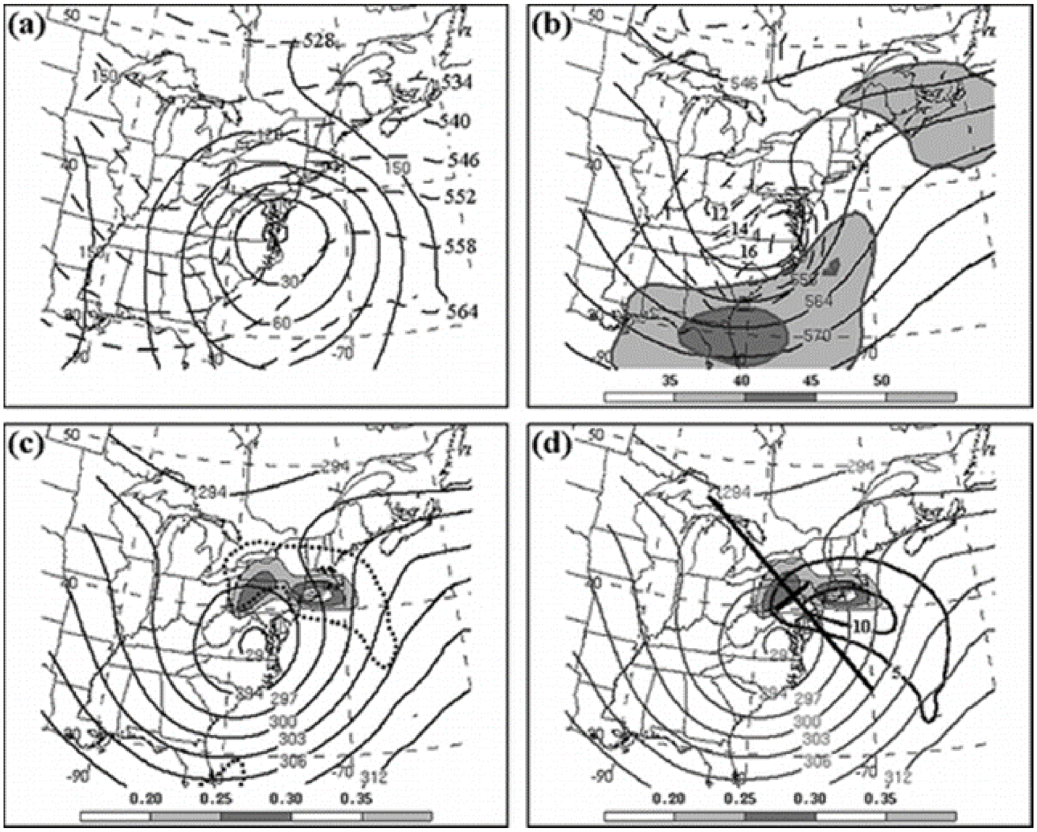

Figure 2: Composite four-panel plots of mesoscale snow band events in the northeast U.S. when the band is developing and first being observed. Same parameters plotted as in Figure 5. (Novak et al. 2004)

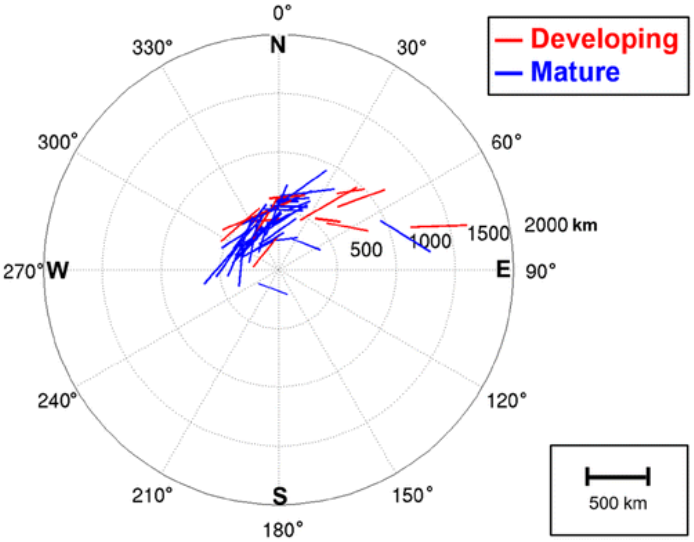

Figure 3: Large mesoscale snow band locations and orientations relative to the cyclone center (origin of plot), with the radius in km and angle in degrees. Bands associated with mature cyclones are in blue, and developing cyclones are in red.
(Ganetis et al. 2018)

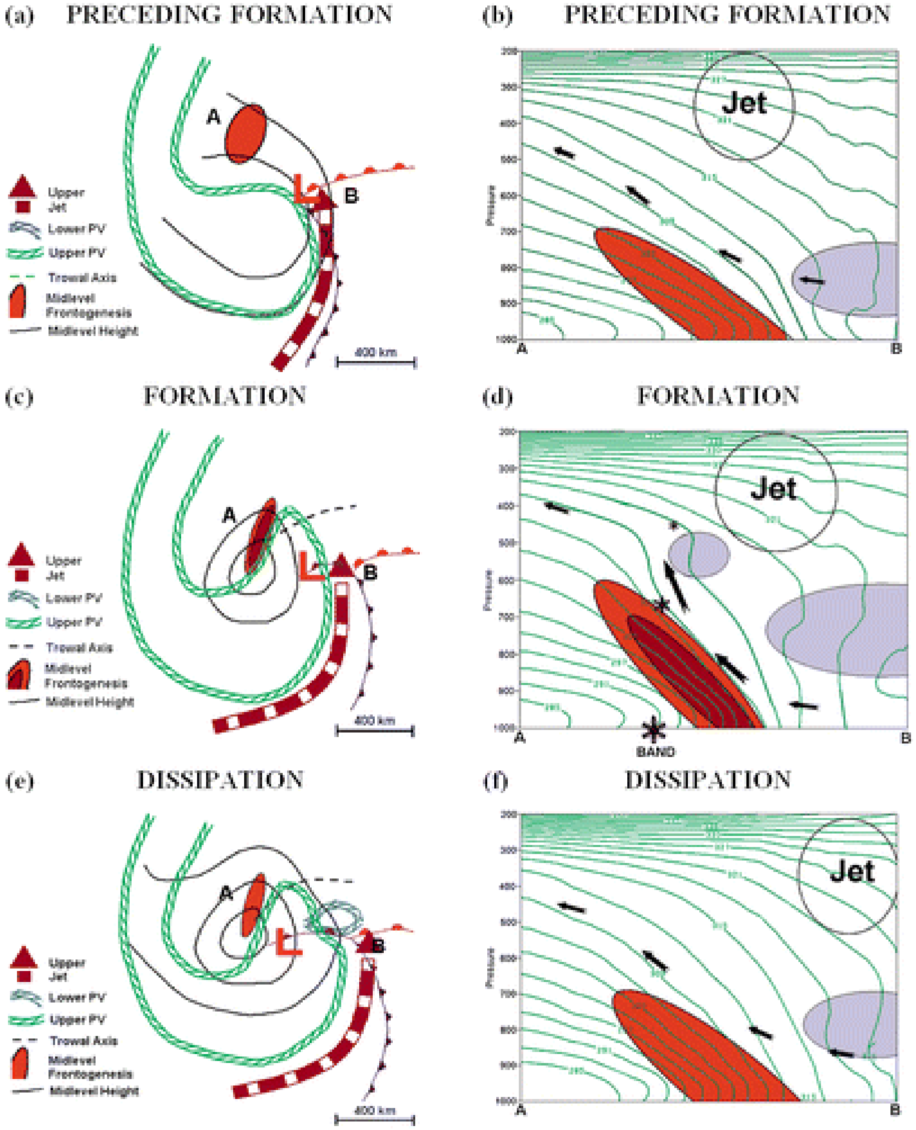

Figure 4: Schematic depiction of the banded potential vorticity hook cyclone evolution over time. Key features shown in plan-view depiction include the upper jet (dashed thick arrow), the lower potential vorticity anomaly (blue hatched outline), the upper potential vorticity anomaly (green hatched outline), the midlevel trowal axis (gray dashed), the midlevel geopotential height (thin black), the midlevel frontogenesis (red shading), and the surface fronts and pressure centers. Cross section end points ("A" and "B") are marked. Key features shown in cross-sectional depiction include frontogenesis (red shading), isentropes (green solid), upper jet (labeled), conditional instability (gray shading), and representative airstream through the ascent maximum in the plane of the cross section (arrows).
(Novak et al. 2010)

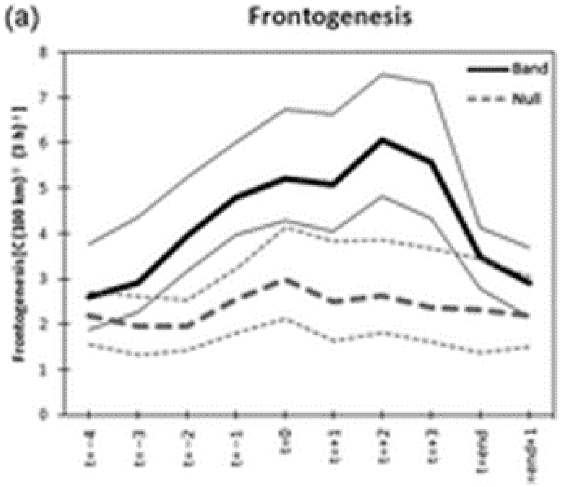

Figure 5: How frontogenesis changes throughout the band formation and dissipation process. Cases that were studied where mesoscale snow bands occurred are summarized by the solid, dark black line and cases that were studied where bands did not form are summarized by the thicker, gray, dashed line labeled "null." The x-axis is in units of time with t=0 being when the band forms, and the y-axis is mean frontogenesis in units of K (100 km)$^{-1}$(3 h)$^{-1}$. 90% confidence intervals are overlaid, represented by the thinner and lighter solid lines (for the banded cases) and dashed lines (for the null cases).
(Novak et al. 2010)

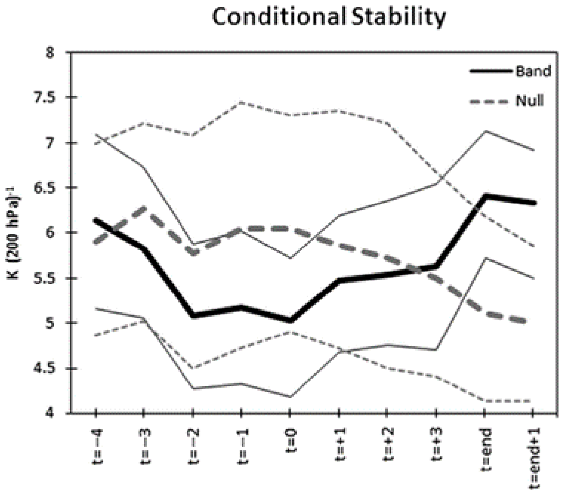

Figure 6: How conditional stability changes throughout the band formation and dissipation process. Cases that were studied where mesoscale snow bands occurred are summarized by the solid, dark black line and cases that were studied where bands did not form are summarized by the thicker, gray, dashed line labeled "null." The x-axis is in units of time with t=0 being when the band forms, and the y-axis is the conditional stability in units of K (200 hPa)$^{-1}$. 90% confidence intervals are overlaid, represented by the thinner and lighter solid lines (for the banded cases) and dashed lines (for the null cases).
(Novak et al. 2010)

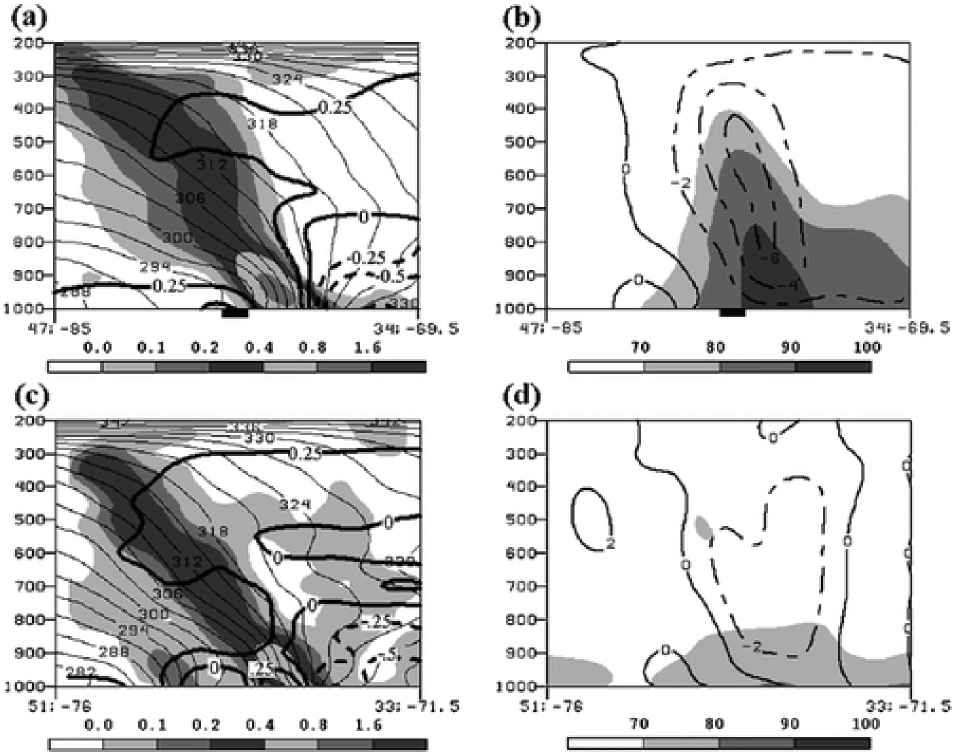

Figure 7: Composite cross-section of mesoscale snow band events (figures a & b – mean band position plotted as the black box along the x-axis in these figures), and composite cross section non-banded events (figures c & d). Figures a & c: frontogenesis is shaded parameter, saturation equivalent potential temperature is the thin lines every 3 K, and saturation equivalent potential vorticity is the thick lines every 0.25 PVU. Figures b & d: relative humidity is shaded parameter, beginning at 70%. Vertical motion is the plotted lines – dashed lines indicate upward motion. (Novak et al. 2004)

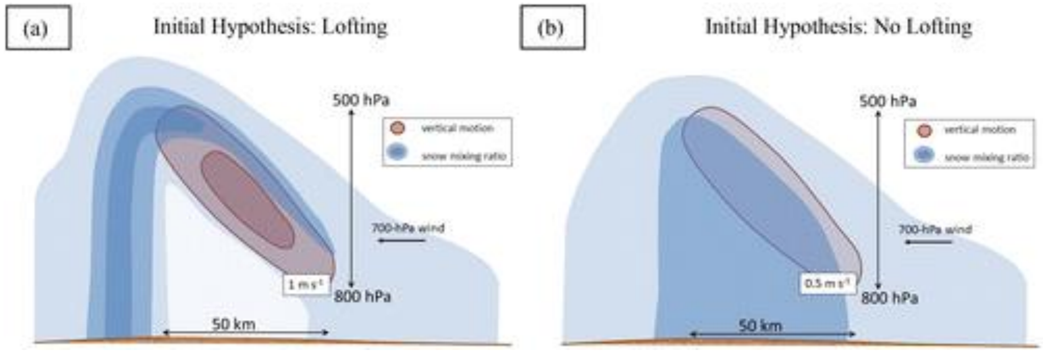

Figure 8: (a) Preliminary hypothesized snow mixing ratio and vertical motion fields near mesoscale snowbands: Idealized schematic cross section of vertical velocity (dark red contour and shading, labeled, shade and contour interval 1 m s−1) and snow mixing ratio (blue shading). (b) As in (a), but in a situation where the upward vertical velocity does not exceed the terminal fall velocity of snow, resulting in a relatively uniform snowfall distribution. Labeled arrows denote approximate hypothetical vertical and horizontal length scales.
(Lackmann and Thompson 2019)