Response to Reviewer #2

Author reponses are black, bolded, and italicized
Text updated in the paper are green, bolded, and italicized

This study investigates an important topic regarding how to improve the quantification of surface snowfall rate from radar reflectivity. The authors applied a large amount of objectively analyzed data from NWS operation radars and airborne and ground-based radars from a field campaign, as well as ASOS data. I find that the analysis is unique and logic, and the conclusions are mostly reasonable. However, I would like to see more clarifications, such as the interpretation between the defined feature and the continuous radar reflectivity values. Some other comments are given below as well.

Specific comments:

1. Line 31: The presence of frontolysis in snowbands was analyzed in Han et al. (2007) through solving the Sawyer Eliassen equation. It is relevant to the "frontolysis" discussion here. Please refer to the study and its frontolysis anlysis.

We added the following sentence (line 37) :

"Han et al. (2007) examined the precipitation structure of 2 winter storms and found that couplets of frontogenesis and frontolysis were present in the vicinity of both the occluded front and the warm front"

2. Table 1: It is a good idea to consider the microphysical processes and the difference between the mass and radar reflectivity. But please put in justification. A thorough justification may have to consider radiative transfer calculation, which is not necessary if the authors do not already have those experience or knowledge. But some degree of justification is necessary.

(Repeated from Reviewer 1 response)

We are listing the change to mass per unit volume as either IWC in the case of frozen precipitation and LWC in the case of liquid precipitation. We have clarified the Table 1 caption as follows to be more clear about this:

"Table of microphysical processes and their associated change to mass per unit volume (IWC and LWC), and radar reflectivity. Radar reflectivity is a function of diameter and dielectric constant.The dielectric constant is larger for liquid water than for ice particles. "

We have also included an expanded version of the table here with 2 extra columns, change to particle diameter and change to dielectric constant to provide more context for the change to mass per unit volume. In the paper, we have included the "Change to particle diameter" column.

Process	Change to mass per unit volume (IWC and LWC)	Change to radar reflectivity	Change to particle diameter	Change to dielectric constant
Riming	Increase	Can increase [1,3]	Can increase [1,3]	Slight increase[2]
Vapor Deposition	Increase	Usually increase[1]	Increase	Slight change[2]
Collision-Coalescence	Increase	Increase	Increase	*No change*
Condensation	Increase	Increase	Increase	*No change*
Aggregation	*No change*	Increase	Increase	Slight decrease[2]
Melting	*No change*	Increase	Usually decrease[1]	Increase
Evaporation	Decrease	Decrease	Decrease	*No change*
Sublimation	Decrease	Usually decrease[1]	Decrease	Slight change[2]
Freezing	*No change*	Decrease	Usually increase[1]	Decrease
Ice Fragmentation	*No change*	Decrease	Decrease	Slight increase[2]
Raindrop breakup	*No change*	Decrease	Decrease	*No change*

[1] Depends on ice crystal habit or habits of preexisting precipitation particle
[2] Changes in dielectric constant related to changes ice density are much smaller than those associated with change of phase
[3] Depends on degree of riming. For example, light riming will not change reflectivity or diameter much if at all.

3. Line 55: "Unlike convective cells …" this sentence is not clear. I think you are probably saying that in convective cells, the snow/graupel particles aloft melt while

they fall to warmer temperature at low levels, which is the melting level. So, the enhanced reflectivity column from the frozen particles does not usually extends to the surface …… However, in snowstorms, it is different. Please make this sentence clear.

We have rephrased the paragraph to read (line 60):

"There are several complicating factors in the analysis of winter storms using weather radar observations. Increases in radar reflectivity in snow do not necessarily equate to increases in mass per unit volume (Table 1). Aggregation and partial melting increase the radar reflectivity but do not change the mass per unit volume. Additionally, there are important differences between the 3D structures of enhanced reflectivities in rain versus snow. In warm-season precipitation systems the 0◦C level is 3 km altitude or more above the surface and it is reasonable to deduce that stronger locally-enhanced radar reflectivity features a few km above the surface are associated with higher rain rates at the surface. The typical fall speeds of raindrops (~2-8 m s^{-1}, depending on raindrop size) often yield nearly vertical columns of enhanced reflectivity features in rain layers. In contrast, the slower fall speed of snow, (~ 1 m s^{-1}, equivalent to 33 minutes to fall 2 km) yields sufficient time for the the advection of the snow by horizontal winds, which are typically ≥10 m s^{-1}, to form curved ice streamers (Wexler, 1955; Wexler and Atlas, 1959). Falling snow particles can be blown sideways more than 50 km horizontally from the locations where they first achieve precipitation size near the top of the storm."

4. Line 63: last sentence of this paragraph. Can you please quantify the range of the factor as well?

It is not clear what you are asking. For Reviewer #1 we have rephrased the text and added a reference to the figure as follows (line 76):

"For reflectivities > 0 dBZ, which usually contain some precipitation-size falling ice particles, IWC generally increases as Z increases. But given the spread of the observed values, there is at least a factor of two uncertainty in the volumetric ice mass as a function of radar reflectivity (Fig. 1; Zaremba et al., 2023)."

5. Line 67: the key finding is not clear. I think it needs to be clarified that snow bands are instantaneous features in the radar reflectivity at a certain level above the ground. Even if it can be related to the surface snow rate, like you would argue for

rain, it is still just instantaneous snowfall rate. Or you may need to say frontogenesis-related primary band are more likely to be associated with hourly accumulated surface snowfall, but multi-bands may not.

We have rephrased the last sentence of the introduction to read (line 80):

"The key finding is that locally enhanced linear features (i.e. mesoscale snow bands) in operational scanning radar reflectivity within northeast US snow storms (which exclude orographic and lake effect snow storms) are usually not associated with heavy surface snow rates."

6. Line 130: Please provide information how the reflectivity is rescaled to snow rate. Also, please clarify that this snow rate is not liquid-equivalent as ASOS's is.

We added the following text to clarify (line 155):

"To rescale the reflectivity, we use the wet snow Z-S relationship from Rasmussen et al. (2003); $Ze = 57.3S^{1.67}$ ***where Ze is equivalent radar reflectivity with units of*** $mm^6\ m^{-3}$ ***and S is snow rate with units of*** $mm\ hr^{-1}$***. Note that the snow rate obtained from this relationship represents an instantaneous rate and is not liquid-equivalent unlike the data reported from the ASOS stations."***

7. Line 146 and 147: You define two metrics called 'area x time fraction'. Both are based on the definition of feature, the first one includes strong and faint features, and the second one adds in the background. The features and background are sort of masks from the radar reflectivity, which does not reflect the continuous value from the radar reflectivity. So, why not use radar reflectivity to define a metric to account for more continuous change of the radar reflectivity?

We have added the following to Section 2.1.3 (line 163):

"The relationship between reflectivity and liquid equivalent snow rate has large uncertainty as it depends on the ice particle shape, density, degree of riming, aggregation, and terminal velocities of the snow particles present. It would not be suitable to use the quantitative values from a single Z-S relationship (e.g. Fujiyoshi et al., 1990; Mitchell et al., 1990; Rasmussen et al., 2003; Matrosov et al., 2008; von Lerber et al., 2017; Wen et al., 2017). We developed our technique based on the method of Krajewski et al. (1992) who used an area-threshold method to estimate

mean areal rainfall using radar reflectivity observations. Krajewski et al. found that when there is high uncertainty in the Z-R relationship, the rainfall estimates from the area-threshold method perform significantly better than the estimates from the Z-R relationship. Our area × time fraction method estimates space-time integrals from quantities derived from radar reflectivity spatial patterns thereby avoiding issues that would result from using a highly uncertain transformation from reflectivity to snow rate. Yeh and Colle (2025) compared several different identification methods for identifying snow bands in winter storms and found that object-based methods performed better than methods using an absolute or variable reflectivity thresholds."

References:

von Lerber, Annakaisa, et al. "Microphysical properties of snow and their link to Z e–S relations during BAECC 2014." Journal of Applied Meteorology and Climatology 56.6 (2017): 1561-1582.

Mitchell, David L., Renyi Zhang, and Richard L. Pitter. "Mass-dimensional relationships for ice particles and the influence of riming on snowfall rates." Journal of Applied Meteorology and Climatology 29.2 (1990): 153-163.

Rasmussen, Roy, et al. "Snow nowcasting using a real-time correlation of radar reflectivity with snow gauge accumulation." Journal of Applied Meteorology 42.1 (2003): 20-36.

Matrosov, Sergey Y., Matthew D. Shupe, and Irina V. Djalalova. "Snowfall retrievals using millimeter-wavelength cloud radars." Journal of Applied Meteorology and Climatology 47.3 (2008): 769-777.

Wen, Yixin, et al. "Evaluation of MRMS snowfall products over the western United States." Journal of Hydrometeorology 18.6 (2017): 1707-1713.

Krajewski, Witold F., et al. "The accuracy of the area-threshold method: A model-based simulation study." Journal of Applied Meteorology and Climatology 31.12 (1992): 1396-1406.

Yeh, Phillip, and Brian A. Colle. "A Comparison of Approaches to Objectively Identify Precipitation Structures Within the Comma Head of Mid-Latitude Cyclones." Journal of Atmospheric and Oceanic Technology (2025).

8. Line 150: I think you mean “Fig. 5d”.

Done.

9. Line 182: Do you mean “Fig. 6a”?

We meant “Fig. 7”. Thanks for catching this.

10. Line 250: “equating snow bands with heavy snow will … over prediction …”. I understand the goal and the method of this study. However, in Numerical Weather Prediction (NWP) practice, I don’t think the snowfall prediction is based on radar reflectivity bands, neither the observed nor the simulated radar reflectivity. I think this statement needs to be modified. Please also give reference of how National Weather Service use NWP models for snowfall prediction.

We have added the following paragraph to the introduction (line 25):

“US National Weather Service (NWS) forecasters use a variety of methods to predict snowfall accumulations. From numerical models, they use ice water context (IWC) as well as the presence of banded features from simulated reflectivity to estimate quantitative precipitation Radford et al. (2023). For nowcasting, NWS forecasts use observed radar reflectivity to determine locations of heavy snow (David Novak, personal communication).”

Reference:

Radford, J. T., Lackmann, G. M., Goodwin, J., Correia Jr, J., & Harnos, K. (2023). An iterative approach toward development of ensemble visualization techniques for high-impact winter weather hazards: Part I: Product development. Bulletin of the American Meteorological Society, 104(9), E1630-E1648.

11. Line 250 to 253: The problem of using feature mask, instead of the value of reflectivity, to quantify the persistence of the intensity of the snowband over a specific ground site is that the feature mask actually includes a large range of reflectivity values and reflectivity-derived snow rate. Like what you have shown in Figs. 5a and 5b, how do you quantify the changes in the magnitudes within the strong feature?

We are not quantifying the magnitudes between features. We are using our area x time fraction metric to avoid the very large uncertainties in converting Z to snow rate. We have explained this further in the following addition to the text (repeated from #7):

"The relationship between reflectivity and liquid equivalent snow rate has large uncertainty as it depends on the ice particle shape, density, degree of riming, aggregation, and terminal velocities of the snow particles present. It would not be suitable to use the quantitative values from a single Z-S relationship (e.g. Fujiyoshi et al., 1990; Mitchell et al., 1990; Rasmussen et al., 2003; Matrosov et al., 2008; von Lerber et al., 2017; Wen et al., 2017). We developed our technique based on the method of Krajewski et al. (1992) who used an area-threshold method to estimate mean areal rainfall using radar reflectivity observations. Krajewski et al. found that when there is high uncertainty in the Z-R relationship, the rainfall estimates from the area-threshold method perform significantly better than the estimates from the Z-R relationship. Our area × time fraction method estimates space-time integrals from quantities derived from radar reflectivity spatial patterns thereby avoiding issues that would result from using a highly uncertain transformation from reflectivity to snow rate. Yeh and Colle (2025) compared several different identification methods for identifying snow bands in winter storms and found that object-based methods performed better than methods using an absolute or variable reflectivity thresholds."

12. Also, is snow rate in Figure 5a non-liquid-equivalent? It needs to be clarified.

We added the following to the text to clarify (line 157):

"Note that the snow rate obtained from this relationship represents an instantaneous rate and is not liquid-equivalent unlike the data reported from the ASOS stations."

13. Section 3.1: It is good to have your figures and analysis supplemented by the video. I would like to view that scenarios in the lower left (89.1%) and upper right (1.5%) quadrants are consistent in supporting that long-lasting elongated high-reflectivity regions observed by operational ground radars correspond to higher surface snowfall rate measured by ASOS. The the low-area x time faction just occurs much more often than high-area x time fraction.

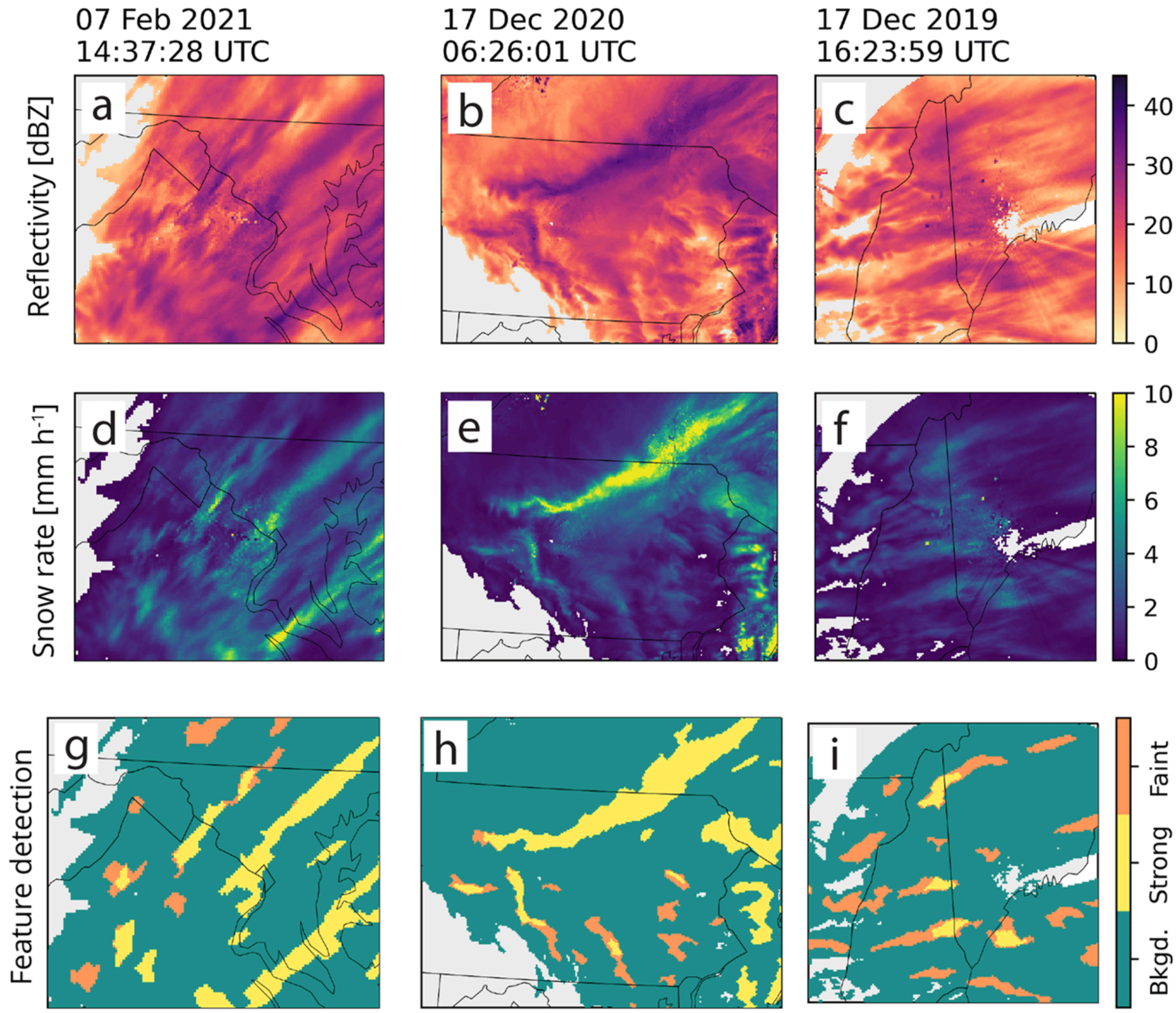
Examples from each of the 4 quadrants are provided in the Video Supplement and described in the detailed figure captions. The videos have been retitled to clarify.

Old Title	New Title
17 December 2020 area x time fraction example	Heavy snow rate and high feature area x time fraction: 16 December 2020 20:00 UTC to 17 December 2020 20:00 UTC for KALB ASOS station in New York. Corresponds to Figure 9 in Tomkins et al (2025).
27 January 2021 area x time fraction example	Low/moderate snow rate and high feature areas x time fraction: 26 January 2021 12:00 UTC and 27 January 2021 00:00 UTC for ASOS station at KVPD in Rhode Island. Corresponds to Figure 10 in Tomkins et al. (2025)
02 February 2021 area x time fraction example	Low/moderate snow rate and low feature area x time fraction: 02 February 2021 00:00 UTC to 03 February 2021 00:00 UTC for ASOS station at KLEB in New Hampshire. Corresponds to Figure 11 in Tomkins et al. (2025)
26 Jan 2021 area x time fraction example	Heavy snow rate and low feature area x time fraction: 27 January 2021 00:00 UTC to 27 January 2021 18:00 UTC for KORH ASOS station in Massachusetts. Corresponds to Figure 12 in Tomkins et al. (2025)

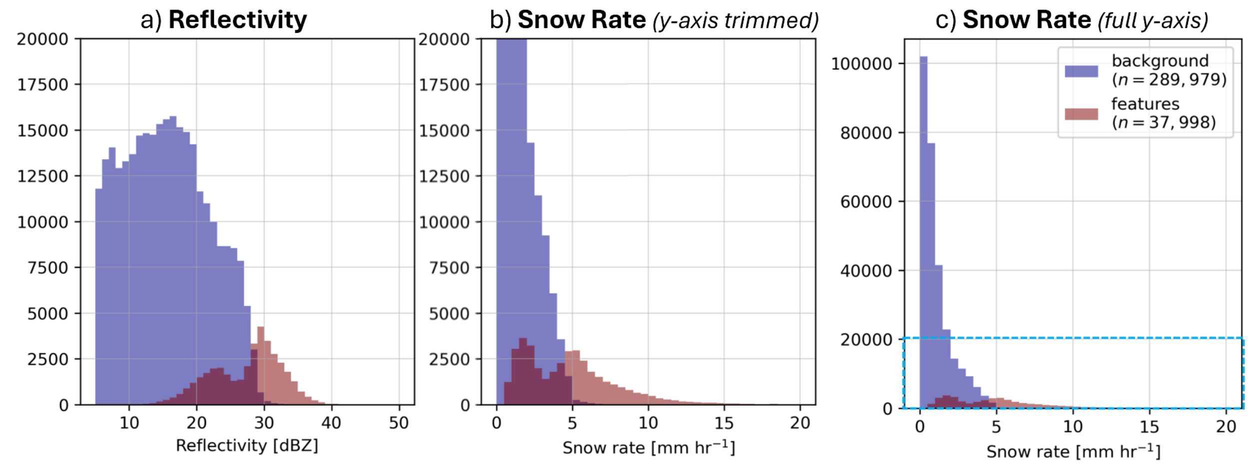
14. Differences between Fig. 9 (upper right, 1.5% quadrant) and Fig 10 (lower right 4.6% quadrant), is it possible to provide the comparison of the histograms of the reflectivity values that were included in your feature area x time fraction analysis? As the feature mask may have masked out the changes of reflectivity within the feature. Of course, Fig. 9 has slightly larger feature area x time fraction than Fig. 10, 0.62 vs. 0.58, which may have contribution to higher surface snowfall rate too.

The feature detection algorithm is not a "mask" but an object identification. Below we show data from three examples that we present in Tomkins et al. (2024) to create histograms of the reflectivity and snow rate values within features vs. background.

The 3 examples: from Tomkins et al. (2024) refer to their Fig. 3a-f and Fig. 8g-i



Caption: Close-up examples of (a)–(c) reflectivity [dBZ] re-scaled to (d)–(f) snow rate [mm h−1] and (g)-(i) feature detection output. Panels (a), (d), and(g) show data from 7 February 2021 14:37:28 UTC with an area of 263 km×222 km; panels (b), (e), and (h) show data from 17 December 2020 16:26:01 UTC with an area of 472 km×361 km; and panels (c), (f), and (i) show data from 17 December 2019 16:23:59 UTC with an area of 326 km×306 km. Grid spacing is 2 km×2 km for all examples.



Histograms of the reflectivity and snow rates within features as compared to echo background:

a) Distribution of reflectivity within identified features as compared to reflectivity in the background echo, The blue histograms are for background pixels (teal regions in feature detection field) and red histograms are for feature fields (yellow and orange regions in feature detection field). b) and c) show the distributions of snow rates within identified features and background echo. Note that b) has a trimmed y-axis and c) has the full y-axis. The blue box in c) indicates the extent of the graph in b).

These distributions illustrate that there is overlap between the reflectivity values in the background echo and in the feature echo. A threshold-based method would miss many weaker locally enhanced features as well as underestimate the size of stronger features. The two modes in the feature distributions are related to the weak versus strong features.

15. As you pointed out in the last scenario (Fig. 12), the radar beam height may be above the locally enhanced features. It is very likely that the height of the radar beam, i.e., the distance between the radar site and the ground station also plays a role.

We tested the sensitivity of the results to the beam height (discussed briefly in Section 3.1.1 and fully in Section 5.1.4 in Tomkins (2024)) and found that thresholding the results by the beam height did not change the findings. The relevant figure illustrating this sensitivity test is below:

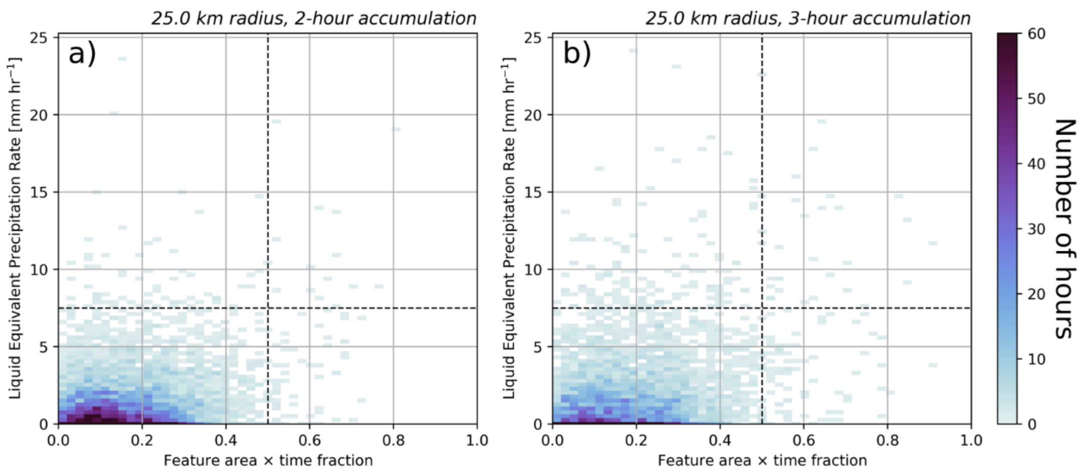


Figure 5.14: Sensitivity of results to number of hours of accumulation. 2D distribution of feature area × time fraction versus liquid equivalent precipitation rate [mm hr^{-1}] for snow observations accumulated over (a) 2 hours and (b) 3 hours. Area × time fraction calculated with a 25 km radius and and observations are paired with a 0-hour lag. Zero feature area × time fraction observations are removed. 0.5 area × time fraction is annotated with a vertical black dashed line and 7.5 mm hr^{-1} is annotated with a horizontal black dashed line.