Interactive comment on “Radar measurements of blowing snow off a mountain ridge” by Benjamin Walter et al.

Michele Guala (Referee)

mguala@umn.edu
Received and published: 18 January 2020

I do value the idea to use a precipitation radar to measure the spatial extent and intensity of wind blowing snow, and I understand the difficulty to adapt an instrument to perform new types of measurements. I have a few comments, suggestions on the results and I hope the authors may decide to clarify or implement, at least some of them.

Thanks a lot for your great ideas and suggestions. We were able to implement most of them!

Fig. 3a) during event 2, which is the most significant one, I note opposing trends between the measured velocity and the distance. I would expect the velocity of the snow to reduce as the wind gust propagates through the accumulation slope. I interpret it as an initially concentrated jet that entrains air along its streamwise axis, lose momentum as it spreads laterally causing the snow to settle on a wider area. So why is the snow velocity increasing with the distance (during some times of event 2, but also 3 and 4)? It would be interesting to correlate with the sonic to get a sense of the structure of the wind gust contributing to a blowing snow event. What is the sonic streamwise velocity time series for events 2 and 3?

Thanks for this good question! We added two more subplots of the sonic wind velocity and turbulence intensity to this figure and discussed it in the context of your question

L234: “Event No. 1 started with relatively high MRR radial velocities of about v_{MRR} = 10 - 11 m s^{-1}, while the velocities gradually decreased to about v_{MRR} = 7-8 m s^{-1} towards the end of this event. The USA wind velocities (Fig. 4c) are in good agreement also decreasing to about v_{Sonic} 8 m s^{-1} towards the end of event No. 1. The turbulence intensity I_{MRR} = 0.06 - 0.12 of this first event (Fig. 4b) shows low velocity fluctuations of the particle cloud, indicating a rather stable, low-level low-turbulence jet, which is supported by the sonic turbulence intensities (Fig. 4d). The velocity drop at the end of event No. 1 is likely the reason for the break in snow being blown off the ridge between event No. 1 and 2.
Blowing snow event No. 2 is different, starting with lower radial velocities of about v_{MRR} = 9 m s^{-1}, likely being initiated by again higher wind velocities starting around 04:16:00 (Fig. 4c), then suddenly dropping to about v_{MRR} = 6-7 m s^{-1} during the following 10 s because of another wind velocity v_{Sonic} decrease around 04:16:10 (Fig. 4c). Strong velocity changes are an indication for turbulent gusts which is supported by higher MRR turbulence intensities of up to I_{MRR} = 0.27 (Fig. 4b). The maximum turbulence intensity at the SDS measured with the Sonic in the direction of the MRR during event No. 2 was I_{Sonic} = 0.25 (Fig. 4d), thus in good agreement with the MRR result. However, the temporal agreement of the peak turbulence intensities is rather poor, as the peak in I_{Sonic} lags the peak in I_{MRR} although it should be vice versa. Nevertheless, an overall good agreement between the turbulence intensities measured with the Sonic and that of the first range gate of the MRR is found, with a mean difference of ΔI = mean(I_{MRR} - I_{Sonic}) = 0.011 and its standard deviation of $\sigma_{\Delta I}$ = 0.087 for the entire EP1 and EP2. The lower velocity particle cloud of event No. 2 is transported further within the field of view of the MRR compared to event No. 1, resulting in

a gradually increasing transport distance starting from 60 m, increasing to 80 m, 120 m and finally to 140 m after 20 s. Interestingly, v_{MRR} is increasing with distance for event No. 2, which is counter-intuitive, as one would rather expect a decrease of the wind velocity behind the ridge. However, the highly turbulent flow with changes in the wind direction and potentially large eddies of up to 100 m is likely causing this effect of higher velocities at longer distances. Events No. 3 and 4 both show rather high radial velocities similarly to event No. 1 and supported by the Sonic wind velocities (Fig. 4c), but also slightly higher turbulence intensities, indicating a more turbulent flow unlike for event No. 1. The transport distances are about 80 - 100 m for event No. 3 and 4."

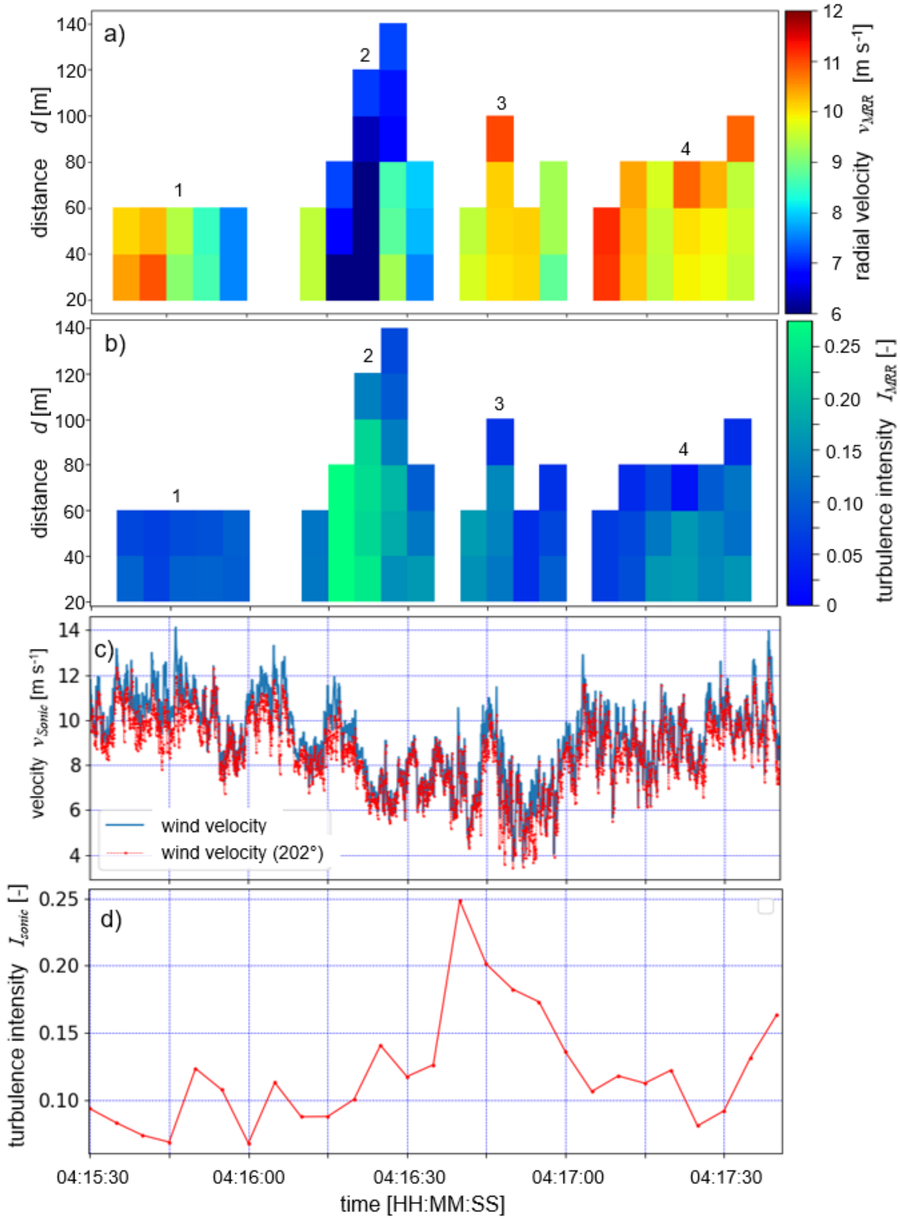

Figure 4: a) MRR radial velocity in the azimuth direction 22° for a two-minute period containing four different blowing snow events on 2019-03-04. b) Corresponding turbulence intensity I, USA c) wind velocity and d) turbulence intensity.

Fig 4b: why the vMRR velocity occurs randomly and not necessarily at higher wind velocity. I understand sonic recording are continuous and I would expect suspended snow event to occur more systematically under strong winds.

We agree. Generally, a trend for MRR velocities occurring at higher wind speeds is given, e.g. around 05:00 and after 08:30 (now Fig. 5) the wind velocities were small and only few MRR events were detected. The outliers, e.g. low MRR velocities around 2.5 m/s after 08:30 are most likely instrument artefacts. We added one more sentence on this in

L285: "Very low MRR velocities around v_{MRR} = 2.5 m s^{-1} are either an instrument artefact because of very low blowing snow particle concentrations, or wind directions temporarily deviating significantly from the MRR field of view direction."

Fig 5: the y axis should be normalized by the sonic velocity to provide a % difference. Alternatively, a scatter plot of vs versus vMRR could be provided for different ranges of directions. The figure as it is not particularly informative.

Good idea, this has been done and the text been changed accordingly!

L290 "To assess a potential dependency of the velocity difference on the wind direction, Fig. 6 shows the relative difference between the MRR and the Sonic velocity as a function of the wind direction α for all three evaluation periods. A positive trend is found with a bias of $v_{MRR} > v_{Sonic}$ for wind directions α > 180°. Nevertheless, an overall good agreement between the MRR radial and SONIC velocity is found, with a mean difference of mean((v_{MRR} - v_{Sonic}) / v_{Sonic}) = 10% and a standard deviation of ± 20%. The intersection of the linear fit with the v_{MRR} - v_{Sonic} = 0 line for α = 170° (Fig. 6) suggests a stable wind direction in the vicinity of the MRR and the SDS for winds coming from that direction. This result is most likely strongly related to the local topography (Fig. 2b) influencing the nearby wind field and direction, where the mountain station is located west and another SW-NE oriented mountain ridge east of the MRR and the SDS, resulting in a rather undisturbed flow for southerly winds. "

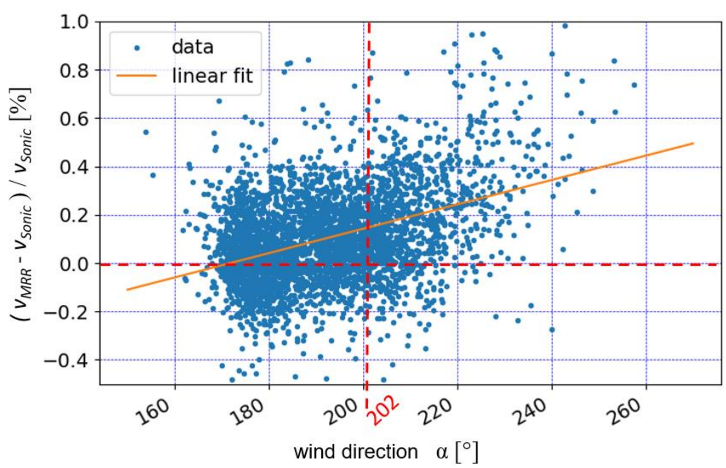

Figure 6: Relative difference between MRR and Sonic wind velocity in the direction 202° as a function of wind direction for all three evaluation periods.

Fig 6: the exponential distribution should be assessed with log scale vertical axis. The formula are not required in my opinion as they are dimensionally questionable.

We totally agree, so we changed this. Thanks!

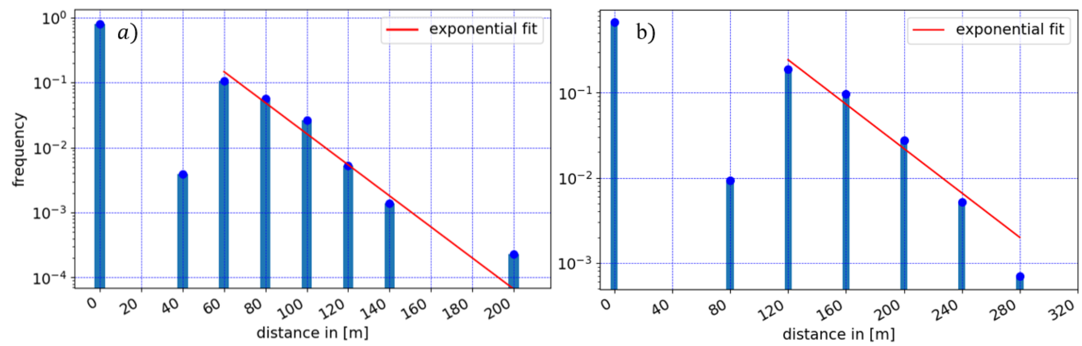

Figure 8: Histogram of the transport distance of all blowing snow events for a) EP1 (Fig. 5a), and b) EP2 (Fig. 7a), including exponential fits for distances larger than the minimal transport distance.

Perhaps the shear velocity (from the Reynolds stress) could be introduced to normalize the distance (like a term u*ˆ2/g) ? Just a thought... May be different events could be combined under a generalized law.

We think for a first attempt of characterizing blowing snow off mountain ridges with a radar it is OK to keep the real distances, this makes it easier for the reader e.g. when comparing it to the snow height distribution in Fig. 2a. Furthermore, we have only 2 distributions (events). Finding a generalized law would require more blowing snow events for different conditions, e.g. wind, snow surface, etc. Therefore, we decided to keep it as it is leaving this for future studies.

In general, the interpretation of MRR turbulent intensity is difficult to provide and to some extent speculative. Mostly because a wind gust is a transient phenomenon and therefore any reduction in "mean" velocity with distance could be perceived as a high turbulence intensity.

We agree, therefore we added more information in

L114: "The definition of I_{MRR} includes the assumption that within each range gate of length δr and for each time interval T_i the MRR velocity is normally distributed around the mean velocity v_{MRR}. This assumption is supported by the good agreement between the MRR turbulence intensity I_{MRR} and the turbulence intensity I_{Sonic} determined from a 3D Ultra-Sonic anemometer (Sonic) as will be shown in Section 3.2."

Fig 7 is convincing. I am again curious about the structure of the wind gust, they might be quite coherent in both space and time to have such a lasting signature on the distance of the snow cloud. Still debated if these gusts are more like atmospheric surface layer coherent structures (see e.g. Heisel et al JFM 2018), or large sweep events that expand in the slope like a jet structure or a mixing layer.

We changed Fig. 7 (now Fig. 9) to separate the two evaluation periods (See comment of other reviewer above). We agree that it would be great to further investigate the flow structures with a better setup. However, the goal of this study was to introduce a new method for characterizing blowing snow on larger spatial scales, which certainly leaves room for more detailed future studies building upon the here presented results.

What I suggest to the author in the next campaign, for a future paper perhaps, is to place the MRR in a flat region, such as a frozen lake and make sure that the sonic is located downstream of the MRR so that comparison in velocity could be more local, in space and time, and over a more homogeneous topography, thus limiting as much as possible unsteady effects.

Thanks for this valuable suggestion, something similar has already been done as mentioned:

L447: "The MRR instrument was also recently tested by the CRYOS group at EPFL Lausanne, Switzerland, for measuring vertical blowing snow velocity profiles and its temporal variability in eastern Antarctica at the site S17 near the Japanese research station Syowa (unpublished work in progress), where blowing snow layers can reach a vertical extend of up to 200 m (Palm et al. 2017)."