Using dual-polarization weather radar observations to improve quantitative precipitation estimation in snowfall

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ABSTRACT

Variability in ice particle physical properties is one of the major error causes in radar quantitative precipitation estimation in snowfall. In this study, morphological analysis of polarimetric radar observations is used to identify dominating snow growth mechanisms. It is demonstrated that polarimetric measurements can be used to identify aggregation, riming, vapour deposition growth patterns as well as regions of intense secondary ice production. The polarimetric weather radar observations are compared against vertically pointing Doppler radar observations, which are used to identify different snow growth mechanisms. The proposed morphological analysis is then used to explain differences in snow packing, ratio of snow depth change to accumulated liquid water equivalent, for three snowfall events that took place in southern Finland.

1. INTRODUCTION

Weather radar quantitative precipitation estimation in snowfall is notoriously difficult. Radar observations depend on phase, size, shape, and density of precipitating particles. The physical properties of ice precipitation are governed by growth mechanisms, i.e. water vapour deposition, aggregation and riming processes. It was observed that in case of rimed snowfall about half of ice mass flux is due to accreted supercooled liquid water [1,2]. Or in other words, for the same number flux, precipitation rate for rimed ice particles is about twice the snowfall rate of unrimed particles. These observations show importance of identification of a dominating snow growth mechanism for radar quantitative precipitation estimation.

Typically, fuzzy logic polarimetric radar classification schemes [3-5] are used to distinguish between different types of hydrometeors. Unfortunately, experience shows that polarimetric radar signatures are not very different for many types of ice particles, i.e. aggregates and rimed ice particles. This is seriously affecting the ability of dual-polarization classification to improve quantitative radar observations of snowfall.

The goal of this work is to study whether dual-polarization radar observations can be used to identify dominating snow growth mechanisms. The main difference of this study from the traditional approaches [3-5], is that we are not trying to identify different types of ice particles for each radar pixel. Our approach is rather to analyze spatial behaviour of dual-polarization radar observations and link it to underlying physical processes.

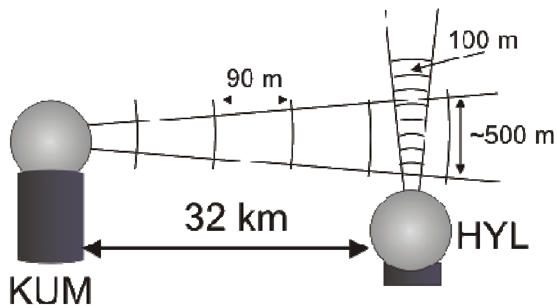

Figure 1. University of Helsinki measurement setup.

Similar to [6], vertically pointing Doppler radar was used to identify cases where riming was present. By carrying out a joint analysis of polarimetric and vertically pointing Doppler radar measurements, signatures that are corresponding to aggregation, riming, vapour deposition and secondary ice production were identified. The proposed morphological analysis is then was used to explain differences in snow packing, ratio of snow depth change to accumulated liquid water equivalent, for four snowfall events that took place in 2005 and 2009 i9n the greater Helsinki area.

2. MEASUREMENT SETUP

In Figure 1 the measurement setup used in this study is shown. University of Helsinki Kumpula radar (KUM) is a C-band polarimetric weather radar located at the top of the Department of Physics building. The radar is positioned 59 m above the mean sea level and 30 m above the ground level.

The transportable C-band weather radar (HYL) used in this study is stationed 32 km North (azimuth 11.8 degrees) of Kumpula radar. There is a clear line of sight between the radars.

Data collected in snowfall events that took place during years 2005-2009 was used in this work. For most of the measurements transportable radar was operating in Doppler spectral mode with antenna pointing to the zenith. Doppler spectra were collected every 10 s. At the same time, Kumpula radar was performing RHI scans over HYL radar. These scans were repeated every two minutes.

3. MEASUREMENT ANALYSIS

The authors in [7] have observed that there is often a little amount of liquid water present in atmosphere even when temperatures are below freezing. Hogan et al. [8] have demonstrated that high differential reflectivity values in the middle of an ice cloud, correspond to an area where supercooled liquid water was pre-

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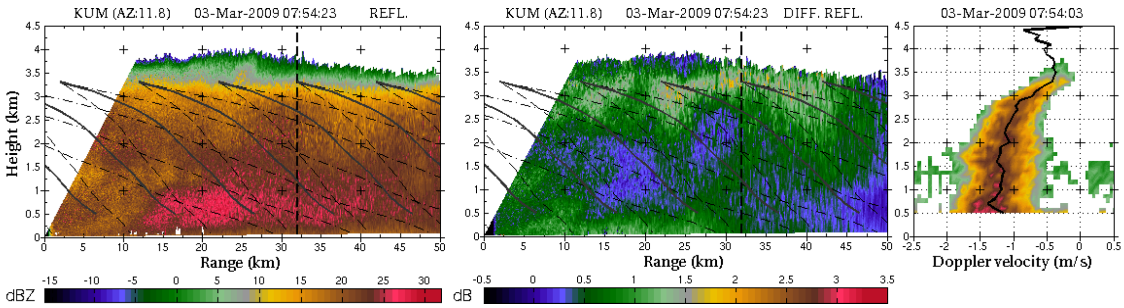

Figure 2. Radar observations of a "classical" aggregation case [7]. The measurements were taken during a snowfall event on March 3rd, 2009. Left two panels show reflectivity and differential reflectivity RHI observations as measured by KUM. The right panel shows Doppler spectrograph recorded by HYL.

The black dashed line on RHI plots shows location of HYL radar. Gray lines show trajectories of ice particles that fall with velocities that correspond to the right edge of the Doppler spectrum (dash-doted line), mean velocity (solid line) and left edge of the spectrum (dashed line).

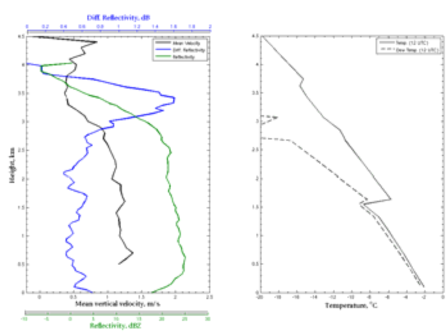

Figure 3. Left panel shows vertical profiles of mean velocity, reflectivity and differential reflectivity. This a vertical slice of the measurements shown in Figure 2 taken above HYL radar site. The right panel shows 12 UTC Jokioinen sounding.

sent, as was shown by aircraft measurements. They also have shown that there is an anti-correlation between reflectivity and differential reflectivity, i.e. higher Z_{dr} values correspond to lower reflectivity values. It is not explained; however, what is the reason for this anti-correlation and whether it is related to presence of supercooled water.

If supercooled water droplets are present inside of an ice cloud or precipitation, there are a number of processes that can manifest themselves as high Z_{dr} radar observations. Those processes are:

- Water vapor deposition growth of ice crystals
- Splinter formation during riming of ice crystals
- Enhanced ice nucleation in regions of spuriously high super saturations in the presence of large quantities of supercooled drops.

Regardless of a process that takes place inside of a cloud, higher differential reflectivity values are caused by formation and/or growth of pristine ice crystal. This, however, does not explain observed anti-correlation between reflectivity and differential reflectivity.

3.1 Aggregation

In Figure 2 measurements taken on March 3rd, 2009 are shown. It can be seen that high Z_{dr} layer is located between 3 and 3.5 km. This is also the layer where the mean Doppler velocity, as measured by vertically pointing HYL radar, changes from 0.5 to 1 m/s. By comparing central and left panels in Figure 2, one can also see that higher Z_{dr} regions correspond to lower reflectivity values. If we zoom in and look just at one vertical profile taken above HYL radar site, as shown in Figure 3, we will see that both Z_{dr} and reflectivity start to increase at about the same altitude. Then we can observe that the differential reflectivity starts to decrease as the mean Doppler velocity starts to increase.

Two snow growth processes take place in this layer. Due to presence of small amount of supercooled water, dendritic ice particles start to grow. Growth of these particles explains increase in Z_{dr} and initial increase in reflectivity. At the same time, these particles start to aggregate, that explains further increase in reflectivity and rapid change in the observed fall velocity. This aggregation pattern is very similar to the one observed by Lo and Passarelli [7].

The apparent anti-correlation between Z_{dr} and Z_e are most probably caused by particle sorting. Aggregates have higher fall velocities than pristine crystals. Given the velocity differential, it takes around 200 s for pristine crystal and aggregates to separate by 100 m. In Figure 2 trajectories of faster and slower falling particles are shown. We should note that due to the particle sorting the high Z_{dr} layer is self maintaining and acts as a good indicator of aggregation.

3.2 Riming

Following [6], we have used vertically pointing Doppler radar to identify instances where riming was present. If one of the following two criteria was satisfied, we have concluded that riming is taking place. Firstly, we have assumed that riming is present if mean fall velocity of ice particles exceeded 1.7 m/s. Secondly, if we could detect a bimodal spectrum. Often, presence of a second mode also corresponded to a rapid increase in a mean fall velocity.

By comparing Doppler and dual-polarization radar observations, we have found that riming cases were observed where higher Zdr, lower reflectivity plumes were extending to the ground. A good example of such a case is shown on RHI plots in Figure 4, in the range interval of roughly 20 to 35 km. Here also particle sorting plays an important role. Riming efficiency is size

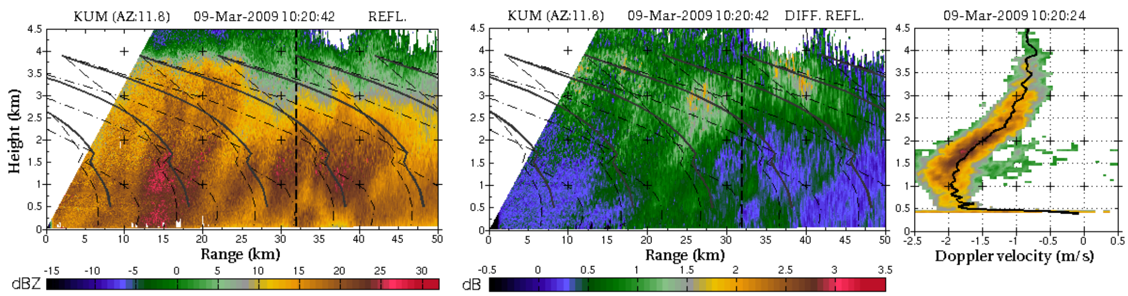

Figure 2. Observations of a riming case. The measurements were taken on March 9th, 2009.

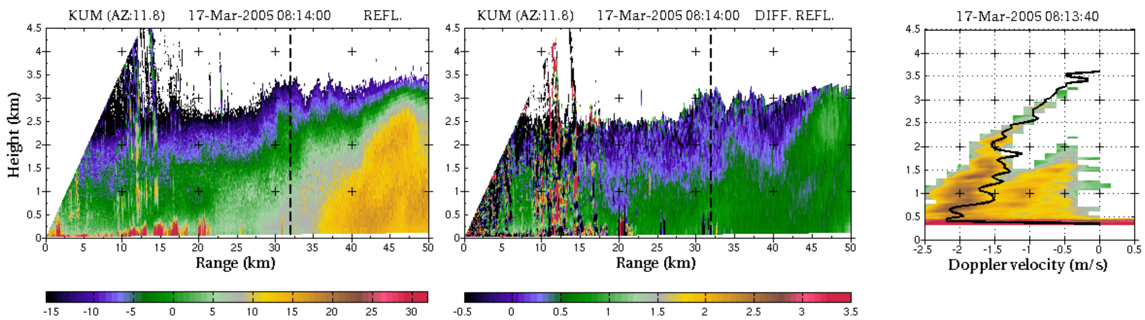

Figure 5. Observations of secondary ice generation on March 17th, 2005.

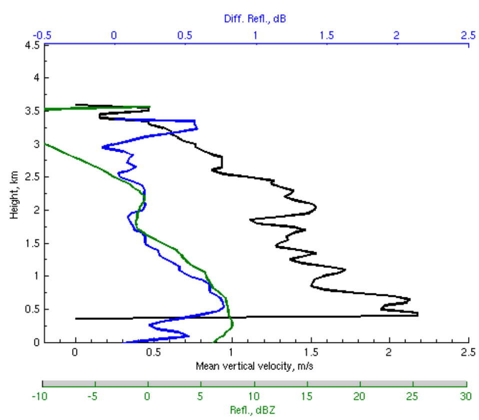

Figure 6. Same as Figure 3 only for March 17, 2005 measurements.

dependent, larger ice particles are more efficient than smaller ones. Rimed particle fall faster and fall out of the volume.

During riming, smaller ice crystals are also created; either by collision breakup of larger particles or due to Hallet-Massop splintering mechanism. Those smaller crystals will rapidly grow in moisture rich environment and result in elevated Z_{dr} values.

Often aggregation and riming signatures are present at the same time as can be see in Figure 4, where in the layer between 2.5-3.5 km aggregation is probably taking place and below 2.5 km riming is dominating.

3.3 Secondary ice production

Secondary ice production is clearly observed during severe riming cases. Zawadzki et al [6] have shown that in those cases a clearly identifiable secondary mode can be observed in Doppler spectral measurements. Such an event took place on March 17th, 2005. It was observed that during this event there was no longer the anti-correlation between Z_{dr} and Z_e. Furthermore, there is almost a perfect correlation between reflectivity and differential reflectivity as can be seen in Figure 6. This confirms that detected bimodality of Doppler spectra are due to secondary ice.

4. APPLICATION OF POLARIMETRIC RADAR TO SNOWFALL MONITORING

Based on proposed above analysis, three snowfall events that took place in the greater Helsinki region were classified into whether they were dominated by aggregation or riming processes. It is not to say that during those events only one type of snow growth mechanism was present. This classification was done to identify events were riming was an observable phenomenon.

For this analysis we have selected snow events that took place on March 3rd, March 9th 2009, and March 17th 2005. For these days we have compared 24 h precipitation accumulations, as liquid water equivalent, and snow depth change within 24 h. These surface measurements were collected at 5-7 locations in the greater Helsinki area. The accumulations and snow depth changes are calculated for a time period from 6 UTC to 6 UTC. As a result, the snowstorm on March 17th 2005 was split into two parts. The snow storm has started around 0UTC on March 17th and has continued till late evening on the same day. This was a very fortunate split, since our analysis has indicated that before 6 UTC no (or very little) riming took place. After 6 UTC on the other hand, presence of heavy riming is indicated by the analysis.

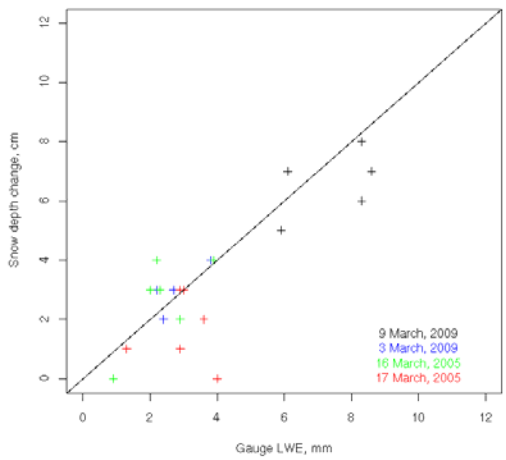

Figure 7. Accumulated 24 h precipitation (as liquid water equivalent, mm) and change in snow depth (in cm), 06-06 UTC at 5-7 weather stations within greater Helsinki area. Straight line represents the 1:10 density line.

From the other two cases, March 3rd 2009 is expected to have little or no riming and March 9th 2009 shows detectable riming signatures.

It is usually assumed that 1 mm of liquid water equivalent yields 1 cm of snow on the ground. This is based on assumption of snow density being equal to 0.1 g/cm^3.

In Figure 7 surface measurements during the selected snow events are shown. Straight line represents the 1:10 density line. Measurements above the line correspond to smaller density snowflakes, and measurements below the line correspond to denser, rimed particles.

These observations are in good agreement with our analysis. Snow storms on March 17th 2005 and March 9th 2009 produced denser particles. Snow storms on March 16th 2005 (first part of the March 17th snow storm) and March 3rd 2009 have produced less dense particles.

5. CONCLUSIONS

It was demonstrated that morphological analysis of polarimetric measurements can be used to identify aggregation, riming, vapour deposition growth patterns as well as regions of intense secondary ice production. Based on comparison of polarimetric weather radar and vertically pointing Doppler radar observations patterns that correspond to different snow growth mechanisms were identified.

It was shown that a combination of reflectivity and differential reflectivity provides valuable information about underlying physical processes. The proposed morphological analysis is then used to explain differences in snow packing, ratio of snow depth change to accumulated liquid water equivalent, for three snowfall events that took place in southern Finland. It was shown that surface observations are in good agreement with the proposed analysis.

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