Understanding Microphysical Processes Occurring in Lake-Effect Snowbands Using Quasi-Vertical Profiles of WSR-88D Parameters

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Understanding Microphysical Processes Occurring in Lake-Effect Snowbands Using Quasi-Vertical Profiles of WSR-88D Parameters

An honors thesis presented to the
Department of Atmospheric and Environmental Sciences,
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Abstract

Knowing the composition and microphysical processes that occur in lake-effect precipitation systems is important in making sure models capture these processes accurately, and could aid forecasters in predicting snow totals and snow water equivalents. Many studies have shown that processes such as riming and dendritic growth can be seen in dual-polarization radar data through parameters such as equivalent radar reflectivity factor, differential reflectivity ($Z_{DR}$), correlation coefficient, and differential phase. This research examines WSR-88D data from the KTYX (Montague, NY) radar located on the Tug Hill Plateau for several long-lake-axis-parallel lake-effect systems from the Ontario Winter Lake-effect Systems (OWLeS) field campaign which took place in the winter of 2013-2014, and more recent cases from the winter of 2017-2018. Quasi-vertical profiles (QVPs), in which the radar parameters are azimuthally averaged at a fixed elevation angle and time, were generated. The spatial and temporal variations of reflectivity and the dual-polarization parameters seen in the QVPs were compared with other datasets including surface observations, vertically-pointing micro-rain radars (MRRs), and aircraft data. QVP results show variations in dual-polarization parameters which, along with other datasets, can be used to characterize processes occurring within the bands such as riming and aggregation. Multiple cases show transitions from higher $Z_{DR}$ aloft to near 0 $Z_{DR}$ at the surface. The higher elevation angle QVPs agree well with the MRR data, which shows that QVPs can be applied in lake-effect events, as long as the band is directly over the radar.
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1. Introduction

Intense long-lake-axis-parallel (LLAP) bands of convective snowfall can form downwind of the North American Great Lakes when the lake surface temperatures are at least 13°C warmer than the air at 850hPa and when the low-level winds are parallel to the long axis of the lakes. This type of convection, although shallow (usually less than 3km deep), can be persistent and result in locally enhanced snowfall which can be destructive. These bands are narrow (less than 40km wide) and difficult to forecast, so learning more about the dynamics and physical processes that occur within the bands may help models better predict their location and intensity. Multiple studies have shown dual-polarization radar data can be used to look at microphysical processes such as dendritic growth, riming, and aggregation (e.g. Moisseev et al. 2009; Oue et al. 2016; Schrom and Kumjian 2016). These are all processes that can occur within LLAP lake-effect bands. The relatively new technique of producing quasi-vertical profiles (QVPs) of radar data to analyze the structure and composition of convection has been used to study synoptic storms, but not lake-effect systems (LeSs). This research uses the QVP technique to analyze smaller scale LLAP LeSs from the Ontario Winter Lake-effect Systems (OWLeS; Kristovich et al. 2017) field campaign and more recent cases to better understand the microphysical processes occurring in the bands.

2. Background

a) Radar Signatures of Microphysical Processes

Dual-polarization radars transmit pulses of radiation with horizontal and vertical polarizations, and the manner in which they return back to the radar can provide information on the shape, size, and composition of hydrometeors within a given scan. Four radar parameters are
analyzed in this paper: equivalent radar reflectivity factor, differential reflectivity, correlation coefficient, and differential phase. Equivalent radar reflectivity factor (hereafter: reflectivity) is a measure of the power returned to the radar, and is a function of hydrometeor size and the number of hydrometeors. Reflectivity is commonly used to estimate the intensity of the precipitation.

Differential reflectivity ($Z_{DR}$) is the difference between the reflectivity factors of horizontally and vertically polarized radiation ($Z_H - Z_V$). $Z_{DR}$ is a dual-polarization parameter since it requires the power returned in the horizontal and in the vertical. This comparison between the horizontal and vertical returns helps to characterize the shape of the hydrometeors. Particles that are stretched in the horizontal will scatter more radiation in the horizontal and will have a higher $Z_H$ value, thus producing a higher, positive $Z_{DR}$ value. Particles that are spherical will scatter radiation roughly equally in the horizontal and vertical directions, so $Z_H$ and $Z_V$ will be nearly the same, resulting in a $Z_{DR}$ of near 0.

The copolar correlation coefficient ($\rho_{hv}$ or CC) is a correlation between the horizontal and vertical pulses returned and can represent the composition of particles in a given scan. Higher CC values mean that any changes in the horizontal pulses returned are also present in the vertical pulses returned, so the particles are all uniform. Lower CC values mean the changes in horizontal and vertical returns are no longer the same, and this would suggest a mixture of particles with different shapes and sizes.

Differential phase ($\Phi_{DP}$) is the difference in the horizontal and vertical phase shifts ($\Phi_H - \Phi_V$), much like $Z_{DR}$ for reflectivity. The main difference between the two is that $\Phi_{DP}$ is affected by the concentration of particles as well. A positive $\Phi_{DP}$ value would mean there is a greater horizontal phase shift which suggests the pulse is travelling through an area with larger particles,
or more particles that have a horizontal orientation, and the pulse is delayed or shifted. This phase shift accumulates as the pulse moves away from the radar.

Several papers (summarized in Schrom and Kumjian 2016) have shown that riming, dendritic growth, and aggregation have specific signatures in dual-polarization and profiling radar data. Riming is consistent with a decrease in $Z_{DR}$ towards the ground such that $Z_{DR}$ values near the surface are zero or slightly negative. There is also an increase in reflectivity towards the ground typically of values between 15 and 20 dBZ, and usually fall speeds $> 2\text{ms}^{-1}$, which can be estimated by the profiling radars. The aggregation signal is very similar to the riming signal, except that fall speeds are typically lower than rimed particles ($< 2\text{ms}^{-1}$). The temperature profile can be used to distinguish between aggregation and riming since aggregation typically occurs beneath the dendritic growth zone, which is the region characterized by temperatures around -15°C and high ice supersaturations where dendrites are favored to grow. Therefore, decreasing $Z_{DR}$ and increasing reflectivity towards the ground around the -15°C isotherm can be attributed to aggregation (Schrom and Kumjian 2016). These signals were also seen in the recent paper by Vogel and Fabry 2018, where they compared radar data from cases with and without rimed particles. They saw that for nonriming events, there was a localized maximum in $Z_{DR}$ between -19°C and -11°C, and a decrease in $Z_{DR}$, an increase in reflectivity, and an increase in CC towards the ground, although the magnitudes varied between cases. Their results for nonriming cases can be seen in Figure 1a. They attribute these signals to the dendritic growth zone and aggregation of dendrites beneath. For riming events, they saw a similar signature aloft compared to the nonriming events. However, near the -5°C isotherm, the fall speeds increase and the $Z_{DR}$ values become even lower than those observed during the nonriming events. These results are
shown in Figure 1b. These signals suggest riming is occurring in this region since the particles are becoming even more spherical and more dense (Vogel and Fabry, 2018).

b) QVP Technique

Analyzing radar parameters over time within LeSs may provide insight into the types of processes occurring within the bands. One way to show variations with time is by using QVPs. The QVP methodology is detailed extensively in Ryzhkov et al. 2015. QVPs are generated by azimuthally averaging the desired parameters at a fixed elevation angle and time. Once the QVPs for each time are computed, a height vs. time plot can be produced to look at the temporal and spatial variations of the parameters. QVPs are beneficial because they filter out noisy signatures in the dual polarization parameters which would otherwise still be present in PPI scans. A PPI scan displays the radar parameters on a 2-D surface for each sweep, and data further from the radar represents what is occurring aloft, not at the surface. QVPs have higher vertical resolution than PPI scans which also makes them a valuable tool. Additional masking can be applied to isolate the meteorological signals, and the specifics of the QVPs produced for this research will be explained in the data and methodology section.

Kumjian and Lombardo (2017) applied the QVP technique to look at the composition and evolution of coastal blizzards across Long Island, New York using WSR-88D dual-polarization parameters. The high vertical resolution of QVPs can be seen in Figure 2 which shows a time-height plot of WSR-88D reflectivity at a fixed location in range and azimuth, pieced together from PPI scans, in panel (a), reflectivity from the MRR in panel (b), and a QVP generated from the WSR-88D reflectivity in panel (c), all for the same time period. Using the QVP allows for more details to be seen which could easily be overlooked if someone was just looking at PPI scans from the radar. Kumjian and Lombardo produced QVPs for six coastal blizzards and
analyzed them to understand the structure of the storms. Their main results show enhancements in $Z_{DR}$ and $\Phi_{DP}$ around the -15°C level which they attribute to separate processes. Enhanced ascent around the -15°C level corresponds to areas of increased $\Phi_{DP}$ and increased reflectivity towards the ground which suggests that these enhancements occur in regions of supersaturation and result in higher snow-to-liquid ratios (SLRs) at the surface. They also note that regions of enhanced $Z_{DR}$ could be a result of both plates and dendrites and more information is needed to determine which crystal habit is present (Kumjian and Lombardo, 2017). Their results are consistent with signatures seen by others regarding aggregation and riming.

c) OWLeS

The OWLeS field campaign took place downwind of Lake Ontario in the Tug Hill Plateau region of New York during the winter of 2013-2014 (Kristovich et al. 2017). There were three main goals of the project which included analyzing surface and atmospheric influences on lake-effect convection, collecting data on LLAP snow bands, and understanding the importance of the Tug Hill during LeSs. A myriad of instruments were deployed for the project, some of which include four K-band profiling micro-rain radars (MRRs), two manual snow observation stations (North Redfield and Sandy Creek), three Doppler on Wheels (DOWs) mobile X-band radars, and the University of Wyoming King Air (UWKA) research aircraft, which included the W-band Wyoming Cloud Radar (WCR), the Wyoming Cloud Lidar (WCL), and in-situ measurements. The National Weather Service WSR-88D, KTYX (Montague, NY), which is the permanent S-band dual-polarization radar for the Tug Hill region, was also an important source of data during the field campaign. A map of the datasets can be seen in Figure 3. The OWLeS project was successful in that it collected high quality data for 24 intensive observing periods.
(IOPs), providing an extensive amount of information on LeSs in New York (Kristovich et al. 2017).

Several studies thus far have utilized many of the datasets mentioned above, but none have completed an in-depth analysis of IOPs using the dual-polarization capabilities of KTYX. Welsh et al. (2016) was the most comprehensive study of radar signals from OWLeS, specifically IOP2b. The authors compared radar signals from the W-band Wyoming Cloud Radar (WCR), the K-band MRRs, the X-band profiling radar on the Mobile Integrated Profiling System, the X-band DOW, and the S-band WSR-88D KTYX during IOP2b over each of the five legs the aircraft flew (from west to east). They saw that the KTYX reflectivity at low levels increased inland over aircraft legs 4 and 5 which is consistent with enhancement of snowfall. They also used the dual-wavelength ratio, a ratio of the equivalent radar reflectivity factors at two different frequencies, to look at the size distributions of hydrometeors. Under most frequencies, hydrometeors scatter in the Rayleigh regime, but under W-band frequency, larger particles scatter in the Mie regime. The reflectivity under the Mie regime does not depend on size as much as in the Rayleigh regime, so there is a significant decrease in reflectivity between the two frequencies for larger particles. When comparing KTYX and the WCR, the authors saw higher dual-wavelength ratios over legs 4 and 5 which suggests larger aggregates were present. Their findings comparing KTYX and the WCR are seen in Figure 4. They also briefly looked at the dual-polarization parameters from KTYX during IOP2b. The differential reflectivity was small and negative, between -0.6 and 0.0 dB, the correlation coefficient was very high, between 0.97 and 1.0, and there was very little variation in dual-polarization parameters for the entire event. They noted these signatures were consistent with aggregates (Welsh et al. 2016).
3. Data and methodology

Five IOPs from the OWLeS field campaign were chosen to be analyzed based on their band morphology and band location to KTYX. IOPs 2b, 3, 4, 5, and 7 were classified as LLAP bands and were close enough to KTYX that a high elevation QVP could be used to look at the evolution of radar parameters. NEXRAD Level II data for KTYX was downloaded from the National Oceanic and Atmospheric Administration’s National Centers for Environmental Information (NOAA NCEI) for each IOP time period. Using the Python-ARM Radar Toolkit (Py-ART), PPI scans at 0.5° of reflectivity, $Z_{DR}$, CC, and $\Phi_{DP}$ were generated to provide an overview of the event. Py-ART was also used to generate the QVPs. Other OWLeS datasets including MRR data and surface observations were compared with the QVPs.

After the QVPs for the OWLeS cases were generated, it was noticed that the $Z_{DR}$ values were almost always negative, which is very unlikely since there are no hydrometeors that are shaped in a way that would produce a vertical reflectivity factor that is larger than the horizontal reflectivity factor. A QVP of $Z_{DR}$ for IOP2b is shown in Figure 5. After further investigation and contact with the NWS Radar Operations Center, it was found that a negative $Z_{DR}$ bias had been recorded at KTYX for the entire OWLeS project. This bias is most likely associated with a calibration issue after the WSR-88Ds were upgraded to dual-polarization in the Fall of 2012. It is not known how long this bias was present, or what the specific bias was, although it varied between storms. This unfortunately brings increased uncertainty into the interpretation of the dual-polarization QVPs from OWLeS, so more recent cases were briefly analyzed after the bias had reportedly been fixed. Two LLAP cases from the winter of 2017-2018 were analyzed and the QVPs were compared with surface observations from New York State Mesonet (NYSM) sites.
a) QVP Methodology

QVPs can be produced using a range of different elevation angles, each one representing a different view of the storm. Ryzhkov et al. 2015 recommend using elevation angles greater than 10° to minimize the impact of beam broadening, as well as effects from horizontal inhomogeneity since lower elevation angles are sampling a greater horizontal area. The impacts of storm inhomogeneity would be especially large in LeSs since these bands are often only 10-20km wide. Lower elevation angle QVPs do have the benefit of having higher vertical resolution, though.

For this research, the 9.9°, 14.6°, and 19.5° elevation angles were used to generate the QVPs. For simplicity, the 9.9° and 19.5° elevation angles are referred to as 10° and 20°, respectively. Figure 6 shows the difference between using the 10° and 20° elevation angles. The spatial coverage of the radar 2km aloft at the 10° angle is 22.7km but only 11.0km using the 20° angle. If the band is directly over the radar, the highest elevation angle would be preferred to get an accurate vertical representation of the band. For this reason, IOPs with bands close to the radar were chosen and QVPs at the 9.9°, 14.6°, and 19.5° elevation angles were compared.

To eliminate contamination from ground clutter, especially potential impacts from the Maple Ridge Wind Farm, thresholds were applied to the parameters before the averaging occurred. The Maple Ridge Wind Farm is located to the northeast of KTYX, and consists of 195 wind turbines which show up in the radar scans (Steiger et al. 2018). Figure 7 shows the base level (0.5°) reflectivity and CC signature of the wind farm. To try and eliminate this signature, any range gates where the CC was less than 0.9 were masked out so that they were not included in the averaging. Kumjian and Lombardo (2017) showed that the CC was very high (> 0.95) for their blizzard events. Other meteorological processes have been shown to have lower CC values,
such as the bright band signature where melting is occurring aloft. The bright band often has CC values between 0.8 and 0.9. Large hail can also have a lower CC value, but values less than 0.7 are typically considered to be non-meteorological (Ryzhkov et al. 2015). There was no hail or bright banding in the LeS cases analyzed, so a CC threshold of 0.9 was decided on. To ensure only the main band was captured in the QVPs, a reflectivity threshold was also applied. Any range gates where the reflectivity was less than 5dBZ were also masked before averaging to reduce the impacts of weak echoes not associated with the LLAP band.

b) OWLeS datasets

Once the QVPs for OWLeS cases were generated the results were compared with other datasets including MRR, manual snow observations, and flight level data from the UWKA. These datasets can be found on the Earth Observing Laboratory (EOL) data archive site for the OWLeS field campaign (http://data.eol.ucar.edu/master_list/?project=OWLeS). There were four MRRs deployed, but the Upper Plateau (UP) MRR was used in this research since it was the closest to KTYX (approximately 5km to the southwest, see Fig. 3). The MRRs are vertically pointing K-band radars but they do not have dual-polarization capabilities. The range resolution is 200m and the time resolution after post processing (described in Minder et al. 2015) is 60s. The UP MRR reflectivity profile and the higher elevation angle reflectivity QVPs were compared, and the UP MRR vertical velocity and spectral width were also analyzed.

For surface observations, including snow depth, snow water equivalent, and hydrometeor type, the North Redfield manual observing station (seen in Fig. 3) was mainly used since it was closer to KTYX, however the Sandy Creek manual observing station was also used for a few IOPs (typically just for pictures). The snow depth was manually measured and the snowboard was wiped clean after each recording. Snow water equivalent was measured by taking snow
cores and melting the snow. These observations were recorded every six hours. The North Redfield site also had a hydrometeor videosonde (HYVIS; Murakami and Matsuo 1990) which captured images of the snow crystals.

Finally, the UWKA was deployed on four out of five IOPs analyzed in this research. The UWKA carried the WCR, WCL, and instruments to collect in situ measurements such as temperature, vertical motion, and liquid water content. Plots shown in this paper from the WCR and WCL were taken from the OWLeS field catalog webpage (http://catalog.eol.ucar.edu/owles).

c) NYSM surface observations

There are six NYSM sites on or around the Tug Hill Plateau, of which two will mainly be focused on due to their proximity to KTYX: Copenhagen (COPE, 20km NNE of KTYX), and Harrisburg (HARR, 5km N of KTYX). A map of all six sites can be seen in Figure 8. Unfortunately during the winter many northern sites shut down due to lack of power, since snow often covers the solar panels. This was the case for the January 2018 LLAP band studied for this research, so only data from COPE is analyzed for that band. NYSM sites collect data every three seconds, but the post-processed data is an average over every five minutes. The 10 meter towers at the NYSM sites are equipped with several sensors including an aspirated thermistor at 2m and a Lufft sonic anemometer at 10m. The sites also have a Pluvio\(^2\) 200, which is a heated, weighing rain gauge used to measure liquid precipitation. The rain gauges are surrounded by a dual Alter shield which helps prevent turbulence, and directs the wind-affected precipitation into the gauge. An SR50A-L snow-depth sensor is also installed at all the sites and measures snow depth using sound waves. A rough SLR can be computed from these datasets and related to signals seen in the QVPs.
4. OWLeS Results and Discussion

A quick overview of the 0.5° PPIs for reflectivity and the dual-polarization parameters for the OWLeS cases showed the oscillation of the LLAP band across the radar. The main core of the bands remained within 50km of the radar at all times. The PPIs of $Z_{DR}$ were noisy, but appeared to be negative for all the events. The PPIs of CC were also noisy, and there was a large amount of ground clutter near the radar, including the Maple Ridge Wind Farm. Example PPIs for IOP3 on 13 December 2013 at 04:30Z and IOP5 on 18 December 2013 at 20:43Z can be seen in Figure 9. Although the position of the band changed amongst cases, it appeared there was little difference in dual-polarization values between the cases. After generating QVPs, most of the cases again seemed to show little spatial and temporal variation in dual-polarization parameters. Because of this, only two cases will be focused on here, IOP3 which showed almost no variations, and IOP5 which showed variation, particularly in the $Z_{DR}$.

a) QVP results

The QVPs for all the OWLeS cases studied show that the LLAP bands were shallow at 2-3km deep. Most cases showed little spatial and temporal variation in the dual-polarization parameters, except for IOP5 which had a strong spatial and temporal gradient in $Z_{DR}$. QVPs at the 9.9°, 14.6°, and 19.5° elevation angles are shown for IOP3 and IOP5 in Figures 10 and 11, respectively. For both IOPs, there is a slight difference in the QVPs between elevation angles, which is most visible in the reflectivity. A more vertical structure of the LLAP band is depicted with higher elevation angles. The reflectivity values did vary both within each IOP and between each IOP, with the maximum of just over 30dBZ occurring during IOP3. The CC values range from 0.94-1.0 for both cases. The QVPs of $Z_{DR}$ for both cases show the negative $Z_{DR}$ bias associated with the radar. IOP5 does have positive values of $Z_{DR}$ which are towards the top of the band around 2km for the most part. The QVPs of $\Phi_{DP}$ show very small accumulations of $\Phi_H$ as
seen from the more positive $\Phi_{DP}$ towards the top of the bands. Kumjian and Lombardo (2017) also saw small vertical changes in $\Phi_{DP}$ values for their blizzard events.

b) Other datasets

The UP MRR reflectivity is compared with the 19.9° QVP of reflectivity for IOP3 in Figure 12a. The higher elevation angle QVPs of reflectivity for all the cases were more comparable to the MRR data. The 19.9° reflectivity QVP was most similar to the MRR, which shows that QVPs can be used with other vertically profiling radars to analyze LLAPs. The structure of the LLAP is similar between the two plots, and the reflectivity values have a similar distribution, although not the same magnitude since the MRR is K-band and depicts what is directly overhead, while the QVP, even at high elevation angles, is an average over the entire scan. Because the MRR operates at a higher frequency, any particles greater than 3.2mm will be measured in the Mie regime and will have lower reflectivity values as a result (Welsh et al. 2016). Therefore, the lower reflectivity values in the MRR data compared with the KTYX QVP could be a result of larger particles, most likely aggregates. The depths of the echoes shown in the MRR and QVPs can also be compared. For IOP3, the first period (20:00Z-02:00Z) has echo tops around 2.5km for the QVP and just under 2km for the MRR. During the second period (03:00Z-09:00Z), the echo tops for both the MRR and QVP are around 2km.

The MRR also has the capability to measure hydrometeor vertical velocity and spectral width, which is a measure of the distribution of velocities within each volume. Higher spectral widths mean there is a large range of velocities within that volume, suggesting particles are moving at different rates, possibly caused by strong updrafts or turbulence, or because there are a variety of different hydrometeors with differing fall speeds such as pristine dendrites and graupel. The MRR data for IOP3 is seen in Figure 12b. In the plots of vertical velocity, negative velocity is upwards. During most of the IOP, the vertical velocity was positive (downwards).
However, there is increased spectral width towards the end of the IOP which corresponds to
when the reflectivity was maximized in the QVP. There also appears to be a small updraft at the
end of IOP3 when the reflectivity is low.

The MRR was also deployed during IOP5 and data is shown in Figures 13a and 13b. Once again, the structure of the band is similar between the QVP and MRR, and distinctive cells
can be seen. The echo tops in both plots are around 2km. The relative maxima of reflectivity for
the MRR and QVP occur at the same time as well. The MRR data also shows a region of
negative vertical velocity (upwards) around 20:30Z which corresponds to a maximum in
reflectivity and higher spectral widths. This is different than IOP3, where the updraft occurred in
a region of weak reflectivity and lower spectral widths. Also, the fall speeds seem to be overall
lower than during IOP3.

The UWKA flew a three hour flight for IOP3, during which the WCR, WCL and in situ
instruments were active. The data from the leg flown closest to KTYX along -76°W (Leg5) at
1.5km is shown in Figure 14, and this leg was chosen to be analyzed so that the results were
comparable to the QVPs. The temperature was consistently around -16°C and liquid water
content (LWC) varied throughout the leg. The WCR shows a region of enhanced reflectivity
between 00:15Z and 00:18Z which is where the LWC is maximized. During this time, the WCL
has a steep gradient in power which means the visible light emitted by the Lidar cannot penetrate
the particles beneath the aircraft. This means there is liquid water in this region since water
absorbs more light than ice. The combination of these results suggest there is an area of
increased super-cooled water at this level (~1.5km). Unfortunately there was no flight for IOP5.

Manual surface observations of SLRs and hydrometeor type were used from the North
Redfield site to try and relate riming or aggregation signals in the QVPs to crystal habits. A table
of the SLRs and hydrometeor type from IOP3 and IOP5 can be seen in Figure 15. Observers reported pristine dendrites and aggregates during the first period, 00:00Z-06:00Z, of IOP3, which resulted in a high SLR of 25.0:1. The second period of IOP3 from 06:00Z-12:00Z had rimed crystals and an SLR of 15.0:1. For IOP5, the period from 14:00Z-18:00Z was characterized by dendrites and aggregates, with an SLR of 20.5:1. During the second period, from 18:00Z-00:00Z, graupel was recorded at the site, and an SLR of 10.9:1 for that time period was measured.

The HYVIS snowflake imager was also located at North Redfield and was active for some parts of IOP3 and IOP5. Images of the hydrometeors for IOP3 and IOP5 are shown in Figure 16. The first image during IOP3 captured at 05:17Z is of a small, pristine aggregate, and the second image taken at 08:08Z shows a heavily rimed particle. The first image from IOP5 captured at 15:01Z is also of an aggregate, although much larger than and not as pristine as the ones captured during IOP3. The second image from IOP5 was taken at 22:10Z and shows a graupel particle. These HYVIS images match the hydrometeor type recorded by observers during the corresponding time period.

c) Discussion

IOP3 and IOP5 were both LLAP band cases, but IOP5 showed significantly more variations in dual-polarization parameters than IOP3. Unfortunately due to the negative $Z_{DR}$ bias and potential radar calibration issue, the QVP results are impossible to fully interpret, although general comparisons between the cases can be made. For IOP3, the $Z_{DR}$ was remarkably uniform over space and time. This suggests that the particles were roughly the same shape throughout the scan. Records of hydrometeor type at North Redfield show aggregates for 00:00Z-06:00Z, with an SLR of 25.0:1, and rimed particles after 06:00Z, with a decreased SLR of 15.0:1. The crystal images from the HYVIS at these times support the hydrometeor type reported. There appears to be no shift in dual-polarization parameters around 06:00Z, although the reflectivity does increase
slightly at the surface. The MRR reflectivity also shows an increase in reflectivity at the surface around 07:00Z. This is where there is a maximum in spectral width, as well as a small updraft aloft. These signatures could suggest an increase in the production of super-cooled water, and a mixture of hydrometeors with different fall speeds due to different degrees of riming.

The sharp gradient in the power returned to the WCL, and the increase in LWC from 00:15Z-00:18Z suggests that there is a region of increased super-cooled water present around the 1.5km level. This region of super-cooled water could be important for the formation of aggregates, since a thin layer of the super-cooled water can make the crystals ‘sticky’ which helps them aggregate together. Temperatures in this region are around -16°C, which is in the favorable zone for dendritic growth. Unfortunately, even though Leg5 was the closest to KTYX, it was still flown approximately 25km to the west of KTYX, so none of the QVPs have data that represents what is occurring that far out. It is possible that the horizontal variations within the band are small such that the QVPs could be used to approximate what is occurring farther away, but it is impossible to tell for sure if the band is uniform. The surface observations, and flight data support the theory of a dendritic growth zone aloft, which would lead to aggregation beneath, and an increase in reflectivity near the surface from 00:00Z-06:00Z. The MRR data also suggests possible riming occurring after 06:00Z which was recorded at North Redfield. It is unclear why dual-polarization signatures of these processes did not appear in the QVPs, although, again, the uncertainty with the dual-polarization data is high due to the bias.

IOP5 has more variation in the dual-polarization parameters than IOP3. Observations at North Redfield show that the period from 15:00-18:00Z was dominated by dendrites and aggregates, and there was a SLR of 20.5:1. After 18:00Z there was a change in hydrometeor type to pellets and graupel, which persisted for the remainder of the IOP. During the period of
graupel, the SLR dropped to 10.9:1. This makes sense since graupel particles are much more dense than aggregates. The images from the HYVIS correspond to the reports of hydrometeor type. Interestingly, the QVPs seem to show some variation during this time period which can be correlated to the hydrometeor change. Before 18:00Z, the precipitation is not very organized, and the reflectivity is weak. The $Z_{\text{DR}}$ is positive wherever the reflectivity is less than 20dBZ. This supports the presence of dendrites and oblate aggregates. After 18:00Z, the precipitation organized into a narrow band south of the radar. Between 20:00Z and 21:00Z, the reflectivity is at a maximum near 30dBZ, and there is a distinct vertical gradient in $Z_{\text{DR}}$, with positive values aloft switching to negative values between 1km and 1.5km. It appears that the CC is slightly lower in the region where the vertical $Z_{\text{DR}}$ gradient is the strongest, which would suggest this transition of particles from oblate to spherical. There is also a positive shift in $\Phi_{\text{DP}}$ during this time and in this region of the $Z_{\text{DR}}$ gradient which could suggest the beam encountering particles with a more horizontal orientation, such as dendrites. The MRR data depicts an updraft and increased spectral width during this time period which could mean there is an increase in supercooled water production during this time. This would increase the riming potential and lead to more graupel production, which is what was reported by the manual observing stations.

5. NYSM Results and Discussion

a) QVP results

Two LLAP bands from the 2017-2018 winter were analyzed since the KTYX $Z_{\text{DR}}$ bias had been fixed. Both bands, like those from OWLeS, were less than 3km deep. The QVPs of these bands showed more variation in the dual-polarization parameters than those from OWLeS cases, most likely because the radar was fixed. The first case analyzed occurred 10-11 December
2017 and the QVP at 9.9° is seen in Figure 17. The 9.9° elevation angle was chosen since the radar did not always scan at the higher elevation angles, so the QVPs using the 14.6° and 19.5° elevation angles have a lot of missing data. There appears to be three distinct features in the reflectivity which have their own characteristics in the dual-polarization parameters. The first feature lasts from 20:30Z-21:30Z and is characterized by high reflectivity values, high CC at the surface, and a phase shift aloft. The Z_{DR} profile has a slight enhancement around 1.5km which is just above the maximum reflectivity, and the Z_{DR} values beneath are less than 0.5dB. The positive Z_{DR} then descends to the surface around 22:00Z, when the reflectivity, CC, and Φ_{DP} are lower at the surface. The second feature lasts from 23:30Z-03:00Z and is characterized by weaker reflectivity values at the surface, lower CC near the surface, and a stronger vertical gradient in Z_{DR} with values ranging from near 1.5dB at 2.5km to slightly negative at the surface. The last period is from 04:30Z to 08:30Z and during this time there is an increase in reflectivity to around 30dBZ, an increase in Z_{DR} to >2dB, an even stronger vertical Z_{DR} gradient, and a positive phase shift aloft.

The second case analyzed occurred 02-03 January 2018 and the QVP at 9.9° is seen in Figure 18. The reflectivity for this case was the strongest out of any cases analyzed, >30dBZ. The region of maximum reflectivity was correlated with maximum CC, between 21:00Z and 22:00Z. During this time the Z_{DR} is around 0dB with a slight increase above the maximum reflectivity to around 0.5dB. After 23:00Z, a region of enhanced Z_{DR} develops between the surface and 1km which correlates to a decrease in CC and reflectivity. There is no variation in Φ_{DP} for this case.
b) NYSM surface observations

Surface observations from COPE and HARR were used for the 2017 case since these were closest NYSM sites to KTYX. The liquid equivalent precipitation and snow-depth for the band at COPE and HARR are seen in Figure 19a. Unfortunately the snow-depth data is intermittent, but the positive trend can still be seen in the data. A rough SLR for both sites was calculated for three periods that corresponded to the three features in the QVPs, and a table of the SLRs can be seen in Figure 20. The first period was from 20:00-23:30Z, and the SLRs at COPE and HARR were 17.7:1 and 17.0:1, respectively. SLRs for the second period were calculated from 00:30Z-04:30Z, and they were 11.3:1 at COPE and 15.0:1 at HARR. For the last period, the snow sensor was down for most of the time at both sites. An SLR for 04:30Z-06:00Z at COPE was calculated to be 10.5:1, and an SLR for 05:00Z-07:20Z at HARR was calculated to be 14.0:1.

For the 2018 case, only data from COPE was used since the solar panels at HARR were buried under snow. The liquid equivalent precipitation and snow depth for this case can be seen in Figure 19b. SLRs were calculated for two periods where there were differences noted in the QVPs. The first was 19:30Z-00:00Z where the SLR was 13.3:1, and the second period was 00:00Z-02:00Z in which the SLR was 21.7:1.

c) Discussion

Although there is less of a variety of datasets for these recent cases, hypotheses about the signatures in the QVPs can still be made. For the 2017 case, there were three distinct periods where the radar parameters differed. The first period has a Z_{DR} profile which starts off low aloft, reaches a maximum of 0.5-1dB around 1.5km, and then decreases again towards the ground. One interpretation of this Z_{DR} profile could be a weak dendritic growth zone and aggregation, where
crystals start off small aloft, and as they fall towards the surface they reach this region of favorable growth around 1.5km where aggregation occurs, and the hydrometeors become more spherical. During this time the SLR at both COPE and HARR was greater than 17.0:1, suggesting particles are most likely dendritic and not rimed. Without images of the crystals, determining the crystal habit is difficult, but events with higher SLRs (>13.0:1) are associated with dendrites or plates (Colle et al. 2014). The second period is characterized by higher $Z_{\text{DR}}$ values, which suggests that the dominant crystal habit is dendrites or plates. The higher $Z_{\text{DR}}$ is present near the surface, and the reflectivity values are not as high as the first period. This might mean there is not as much aggregation occurring. The SLRs for this time period were lower for both sites compared with the previous period which may mean there was a change in crystal habit, or the liquid water content of the crystals increased, possibly due to light riming. For the third period, it is hard to say what is occurring without adequate snow depth measurements. The third period exhibits the strongest vertical $Z_{\text{DR}}$ gradient which occurs above the maximum reflectivity between 1.5km and 2km. This appears to be a strong dendritic growth zone and a transition to lower $Z_{\text{DR}}$ below may suggest either aggregation or riming. The SLRs are slightly lower than the previous period which could suggest slightly more riming, or a difference in crystal habits again. Without upper level data or vertical motion measurements, it is difficult to distinguish aggregation and riming.

For the 2018 case, the band was much more shallow than any other cases observed, both recent and from OWLeS. The first period from 19:30Z-00:00Z was characterized by the relatively low and uniform $Z_{\text{DR}}$ profile. The reflectivity during this period was maximized over 30dBZ and the SLR at COPE was over 13.0:1. Again, it is hard to distinguish between riming and aggregation signatures without additional datasets. Since there does not appear to be a
pronounced dendritic growth zone, it may be more likely that riming and possibly graupel was produced during this time, which would maximize the reflectivity and contribute to the lower SLR. The next period from 00:00Z-02:00Z exhibited a strong enhancement in $Z_{DR}$ 0.5km-1km above the surface, which can most likely be attributed to a dendritic growth zone. The CC during this period decreases as well, which is consistent with particles of different sizes and shapes growing and aggregating. The SLR at COPE during this time period was 21.7:1 which further supports the hypothesis of dendritic growth and possibly aggregation, although the reflectivity is not very high.

6. Conclusions

Using QVPs to look at microphysical processes occurring in LLAP bands seems to be a useful technique if the band is directly over the radar, the radar is calibrated correctly, and a variety of datasets are available to make inferences from the reflectivity and dual-polarization signals in the QVPs. Higher elevation angles of QVP reflectivity were shown to be similar to the MRR reflectivity for LLAP bands. The combination of the QVPs, MRR data, and surface observations from the OWLeS cases could be used to make hypotheses about the processes occurring within the bands, although the uncertainty within the dual-polarization parameters of the QVPs is high due to the calibration issue. An analysis of cases from the 2017-2018 winter showed features within the LLAP bands that were visible in the dual-polarization QVPs. The NYSM surface observations provided rough SLR values, but more data would be needed to interpret exactly what the processes occurring within the band were. With the use of additional datasets, more research could be done into these QVP signatures for LLAP bands, and this technique could be applied to other regions where LLAP bands are prevalent.
7. Acknowledgements

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References


Figure 1: Plots taken from Fig 2 and Fig 3 from Vogel and Fabry 2018. Comparison of reflectivity, Z_{DR}, CC, and fall speed for a) nonriming and b) riming events.
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<table>
<thead>
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<th>IOP</th>
<th>Time</th>
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<th>SLR</th>
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<td>91 kg/m³</td>
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<table>
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<th>HARR SLR</th>
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Figure 20: Table of SLRs calculated from NYSM data at COPE and HARR