ESTIMATING SNOWFALL RATES USING POLARIMETRIC RADAR DATA

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ABSTRACT

Using radar data to estimate snowfall rates is of great interest in regions of rough terrain. Snowfall rates can provide information on potential flood hazards, water resource problems, and aide in agricultural planning. Several attempts have been made estimating snowfall rates using radar data, but a sufficient method is not available. Therefore, in this study a technique is developed using polarimetric radar data to estimate snowfall from data recorded during the Mesoscale Alpine Programme (MAP).

MAP is a field experiment that took place in Northern Italy whose goal was to understand heavy precipitation events including flash-floods. Data was collected remotely by S-Pol, which is the National Center for Atmospheric Research (NCAR) ground based S-Band dual linear switchable polarization radar with copolar and cross-polar components, plus NCAR's in-situ particle measuring system probes mounted on the Electra aircraft.

This study attempts to find a correlation between polarimetric variables and snowfall rates. In-situ aircraft data provides information on hydrometeor size, shape, and concentration. To estimate hydrometeor density and fall velocity, the aircraft data has to be compared to polarimetric information from S-Pol. For this purpose, it is important to create and validate a matching program that correlates points between aircraft flight tracks and radar scans. Such matching was realized for the first time among the scientific community at NCAR. This study will utilize this matching program to provide hydrometeor concentration, density, and fall velocity in a cloud, and thus determine snowfall rate.

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I. INTRODUCTION

In this study, a method is developed for estimating snowfall rates using polarimetric radar data. It is part of an international effort determining snowfall rates in rough terrain. This study combines two important atmospheric science fields: radar meteorology and cloud microphysics. It uses data from the Mesoscale Alpine Programme (MAP), a field experiment that took place in Northern Italy in 1999. This study looks at data derived from the following platforms: S-Pol, the National Center for Atmospheric Research (NCAR) transportable S-Band dual linear switchable polarimetric (S-Pol) radar with copolar and cross-polar measurements, and Knollenberg in-situ particle measuring system (2DP PMS) probes mounted onto the wings of NCAR's Electra aircraft. This study use S-Pol polarimetric capabilities to deduce hydrometeor density, fall velocity and thus deduce snowfall rate. Hydrometeor is another word for precipitation particles. The study's larger goal is to provide people with more information about potential flood hazards, water resource problems, and aid in agricultural planning.

Comparing in-situ measurements with S-Pol radar data was of prime interest. The radar is well suited for measuring snowfall rates over rough terrain because it is a stationary instrument that can provide information on the entire storm at the speed of light with a resolution of 100 km in all directions. However, a good relationship between radar return and snowfall rate has not been established. This relationship is difficult to determine due to the complexity of snow particles. Snowfall varies in shape, size, and water content. Some hydrometeors are highly dense, compact, and contain more water as compared to less dense fragile crystals with air inclusions.

The aircraft can provide the needed information about the complexity of the snow if the data collected by the aircraft and the radar can be matched in space and time. Therefore, it was important to create and validate a matching program to correlate points between aircraft flight tracks and radar scans. Such a program was realized for the first time by the scientific community at NCAR. It was developed by William Al Cooper (NCAR/Advanced Study Program Director (ASP)) and Sabine Goeke (ASP postdoctoral student).

The area under observation was the Swiss Alps, where rough terrain makes it difficult to measure snow on the ground. It was chosen because it is an area susceptible to treacherous snowstorms. After these storms, the snow melts and produces flash-floods that can wipe entire villages away. Understanding and calculating hydrometeor density \( \rho \) and terminal fall velocity \( V_t \) can provide valuable information about the amount of water that falls to the ground as snow during a storm.

A) Map Background

The MAP field experiment proposed to study cloud and precipitation processes over rough orographic terrain. An international effort by over 25 institutions from more than 12 countries in Europe and North America began MAP in the early 1990’s. American involvement was motivated by the possibility of solving prediction problems
of orographic meteorology, while utilizing European contributions of project infrastructure. The focal points of this study are data collected by the NCAR S-Pol polarimetric radar and the NCAR Electra scientific aircraft.

**B) Snow Crystal Classifications**

A determination of how much water is brought to the earth can be made by examining the habit (type) of snow crystals. Understanding the ways in which snow crystals are formed and classified provides knowledge about the various ways that crystals fall to the earth. For example, different types of snow crystals (i.e. needle, dendritic, bullet shaped, capped columns, etc.) have different densities, therefore their fall velocities are different.

The Magono and Lee (Magono and Lee, 1966) scheme was used to classify snow crystals. This scheme is the most widely used and accepted classification of natural snow crystals. Magono and Lee extended prior work done by Nakaya (Nakaya, 1954) on snow crystal classifications from 38 to 80 snow types. They also made sketched drawings of the natural snow crystals and created two diagrams-- one linear diagram displaying crystal classifications with transition in temperature, and the other which showed the temperature and super saturation conditions for the growth of each type of natural snow crystal.

**C) Raindrop-Size Distribution**

In order to understand how to calculate snowfall rate from radar it is instructive to examine the relationship between rainfall rate and radar return. Extensive studies of raindrop size distributions have been occurring for over 40 years. The Marshall and Palmer (Marshall and Palmer, 1948) distribution is widely used in meteorology and can be used to calculate rain rate (i.e., mm/s), liquid water content (i.e., g/m³), and radar reflectivity (i.e., mm²/m³). The Marshall and Palmer distribution is convenient because it gives an approximation of size distribution for raindrops as a function of rain rate. This is given by the following formula: $N_D = N_o e^{-ND}$, where $N_D$ is the number of raindrops per cubic meter per category, $D$ is the diameter, $N_o = 8000$ m⁻³ mm⁻¹ (the intercept parameter), and $\lambda = 4.1 R^{-0.21}$ mm⁻¹ (the slope).

By inverting this relationship and using it with a specified rain rate, further calculation of the number of raindrops per unit volume and raindrop size interval can be made for a particular storm. Once these are calculated they can be used to determine liquid water content. Marshall and Palmer found that there is a relationship between radar reflectivity ($z$) and rain rate ($R$), better known as the $z-R$ relationship. By measuring drop-size distributions, one can calculate the $z-R$ relationship. This relationship can be expressed by the power law: $z = aR^b$, where $z$ is the radar reflectivity factor, $R$ is the rain rate, and $a$ and $b$ are constants that are dependant on hydrometeor habit. Marshall and Palmer calculated the most commonly used $z-R$ relationship for stratiform rain: $z = 296R^{1.47}$. This has been the basis for most of the research that calculates rainfall.
amounts from radar data. Another calculation found that the $z-R$ relationship for aggregate snow is: $z = 2000R^{2.0}$ (Gunn and Marshall, 1958).

There are many uncertainties about these computations when they are used to compute snowfall rates. In order to calculate how much water falls to the earth, $D$, $V_t$, material phase, and the concentration of hydrometeors per size must be known. Raindrop diameter ($D$) varies as a constant function of size because raindrops are nearly spherical. Water has a constant density so $V_t$ for raindrops can be given as a function of $D$.

However, snow crystal diameter changes with habit and material phase (water-ice mix/ice type). Thus calculating snow crystal volume, $\rho$, $V_t$, and ultimately snowfall rate is difficult (refer to Figure 1). To get around this difficulty, the rate of snowfall is usually calculated by converting snow to liquid and expressing it in $\text{mm/h}$, as a rainfall rate for melted snow. This study attempts to calculate snowfall rates and address this uncertainty. In order to compare the radar and aircraft data, and thus deduce snowfall rate, we must calculate $z$ for each.

II. RADAR

A) Instrumentation

S-Pol emits polarized radiation in the form of a 10 cm wave. S-Pol provides information on the entire area of a storm at the speed of light. It also provides information above, within, and below the cloud layers. The polarized energy releases into the atmosphere and is reflected back according to the target that it hits. The target returns a wave that is dependant on hydrometeor size, i.e. bigger hydrometeors return greater energy. The energy returned is proportional to $z$ and is less energy than was originally emitted by the radar. Polarized radars record the following values.

a) Power Received ($P_r$)

Radars record $P_r$, the return power as a function of distance to the hydrometeors. $P_r$, depends on radar constants (i.e. gauge, antenna gain, wavelength, beam) dependant on the radar type (i.e. wavelength emitted by the radar).

b) Refractive Index ($|K|^{\frac{1}{2}}$)

Refraction is the process in which the direction of energy propagation is changed as a result of a change in the speed of propagation caused by changes in density within the medium or as the energy passes through the interface representing a density discontinuity between two media (Rinehart, 1997). The refractive index ($|K|^{\frac{1}{2}}$) is a
measure of the amount of refraction. From \( P_r \), \( z \) can be deduced if \( |K^2| \) of the hydrometeor is assumed. The back scattering energy of the radar is larger for hydrometeors comprised of water than for hydrometeors comprised of ice. This is due to the difference in \( |K^2| \). This index is approximately 4.5 times larger for water (\( |K_w^2| = 0.93 \)) than for solid ice (\( |K_{ice}^2| = 0.197 \)). Additionally, frozen hydrometeors are seldom solid. Most have air inclusions and can therefore be considered to be ice-air mixtures. For these hydrometeors \( |K^2| \) is lower than the index for solid ice. A good approximation for graupel is: \( |K_{graupe}^2| = \rho^2 0.197 \), where \( \rho \) is the density of the graupel particles. This approximation is used in the present study.

When the radar is measuring snowfall, \( |K^2| \) in the radar equation \( P_r = \pi^2 P_t g^2 \theta \phi \ h /|K|^2 \sum D t h^6 /\left(1024 \ln (2) \lambda^2 \ r^5\right) \) is set to the index of water. Generally the radar formula can be written as: \( P_r = C z \), where \( C \) is an instrument specific constant. In the case of solid ice hydrometeors, the reflectivity will be displaced by 5-7 [dB(Z)] (decibles).

c) Linear Values for \( z \) and \( z_{eff} \)

\( z \) and \( z_{eff} \) refer to the linear radar reflectivity factor, which is a meteorological parameter determined by hydrometeor size and number in a sample volume. They are not used interchangeably. \( z \) is related to the amount of energy that is returned to the radar by spherical shaped raindrops. The \( \text{eff} \) in \( z_{eff} \) has been added to take into account measurements of all other hydrometeors that were non-spherical shaped.

d) Logarithmic Values for \( Z \) and \( Z_{eff} \)

The large range of values of \( z \) is less convenient to deal with than logarithmic values, \( Z \) and \( Z_{eff} \). This is done by transforming into logarithmic radar reflectivity values through the equation: \( Z = 10 \log_{10} \left(z / 1 \ mm^6/m^3\right) \). This shows the logarithmic radar reflectivity factor \( Z \) compared to the non-logarithmic form \( z \). In the logarithmic form, \( Z \) is measured in decibels dB(Z). The linear form \( z \) is measured in \( mm^6/m^3 \). dB(Z) values are easier to use. For example: \(-30 \ dBZ\) for fog and \(+76.5 \ dBZ\) for hail compared to linear values of \(0.001 \ mm^6/m^3\) for fog and \(30,000,000 \ mm^6/m^3\) for hail.

B) Hydrometeor Classification Scheme from Polarimetric Radar Parameters

The following polarimetric parameters cannot provide useful information on hydrometeor type independent of each other. By combining them, hydrometeor type can be determined because each parameter provides a distinct way of analyzing hydrometeors within the sample volume.

a) \( Z_h \) and \( Z_v \)

S-Pol emits polarized waves: one in the horizontal and the other on the vertical plane. The returned radiation (\( Z_h, Z_v \)) is proportional to the hydrometeor's cross section over a sample volume in that plane. It is important to note that ice produces lower \( Z_h \) and \( Z_v \) values than does liquid water. This is due to lower dielectric effects of ice. A dielectric
is a substance in which a steady electric field can be set up with a negligible flow of current. The combination of $Z_h$, $Z_v$, and other polarimetric radar data are useful in discriminating among hydrometeor types.

b) $Z_{dr}$

$Z_{dr}$ stands for differential reflectivity. It is taken from the ratio of $Z_h$ to $Z_v$. $Z_{dr}$ is related to the axis ratio and size of the hydrometeors. According to Seliga and Bringi 1976, the axis ratio is defined as $a/b$, where $a$ is the horizontal axis and $b$ is the vertical axis. $Z_{dr}$ is a measure of the reflectivity weighted mean axis ratio of hydrometeors in a volume. For example, back scatterers that are small in comparison with S-Pol's 10 cm wavelength and oriented with their axis of symmetry on the vertical plane produce positive $Z_{dr}$. Back scatterers that are large in comparison with S-Pol's wavelength produce negative $Z_{dr}$. The hydrometeor canting affects $Z_{dr}$. This is due to changes in length of the hydrometeor axis along the direction of the orthogonal polarized waves as emitted by the radar.

c) $K_{dp}$ ($\phi_{dp}$)

$\phi_{dp}$, measured in degrees, stands for the differential phase and shows how much one wave ($Z_h$) lags behind the other ($Z_v$). The measure of degrees normalizes the interpretation of phase shifts. Polarized waves look like mathematical SIN functions. These waves are given in amplitude as a function of degree. $\phi_{dp}$ is at 0 when $Z_h$ and $Z_v$ travel with the same velocity. This occurs when $\phi_{dp} = \Delta \phi_{hh} - \Delta \phi_{vv} = 0$, i.e. the change in differential phase for the horizontal wave emitted and received subtracted from the change in differential phase for the vertical wave emitted and received equals to 0. Horizontally and vertically polarized waves have phase shifts (per unit length) and one wave propagates slower than the other through a medium when the hydrometeor's are oriented on the same plane as the polarization plane of the wave. Comparing this difference provides qualitative information about the hydrometeor types. $K_{dp}$ stands for specific differential phase. $K_{dp}$ is a derivative of $\phi_{dp}$ measured in units of degree per km and $\phi_{dp}$ is plotted as a function of distance from the radar. $K_{dp}$ provides the change in $\phi_{hh}$ and $\phi_{vv}$ with distance ($r$) through the following formula: $K_{dp} = \phi_{dp}(r_2) - \phi_{dp}(r_1) / (r_2 - r_1)$.

d) $\rho_{hv}(0)$

$\rho_{hv}(0)$ stands for the correlation coefficient. The degree of correlation between the returned horizontally and vertically polarized waves gives us information about the mixture of hydrometeor shapes present in the cloud. Good correlations present when the polarized horizontally and vertically back scatter waves are in phase. This is referred to as zero lag ($\rho_{hv}(0)$). When the hydrometeor's reorient and/or a change in concentration occurs, the waves become decorrelated causing non-proportionality in the horizontal and vertical waves. Significant decorrelation occurs more so when hydrometeors are wet or shaped irregularly. Observation and modeling show that $\rho_{hv}(0)$ decreases with increasing diversity of hydrometeor shape and orientation and when mixtures of hydrometeors are present rather than just one type. The lowest values for $\rho_{hv}(0)$ should occur when there
are mixtures of equal amounts of two different types of hydrometeors especially when the size of one varies predominantly in the horizontally and the other varies in the vertically direction (Straka et. al. 2000).

e) $LDR_{vh}$

$LDR_{vh}$ stands for linear depolarization ratio. $LDR_{vh}$ is the logarithm of the ratio of the cross-polar power received to the copolar power received (Straka et. al. 2000). When S-Pol sends out a horizontally polarized wave, a hydrometeor not axis symmetrical in the horizontal plane will reflect a portion of the power as a vertically polarized wave. Hence a cross-polar power is returned from the hydrometeor to the radar. The lowest value for $LDR_{vh}$ from S-Pol as observed from examinations of data collected from S-Pol in Florida in 1998 is -30dB (Hubbert et.al. 1998).

III. AIRCRAFT

A) Instrumentation

The aircraft provides information about the hydrometeors, such as shadow images collected by 2DP PMS probes (refer to Figure 2), but can only fly at specific altitudes allowed by air traffic control. From the shadow images, we can calculate concentration (number of hydrometeor per $m^3$), Flux ($f$) which is number of hydrometeors per $m^2$ and per time, size, shape, and type. From the 2DP PMS probes size distributions as seen in Figure (3) can be derived. From this distribution $z$ was computed using the equation: $z = \sum N(D) \cdot D^6$, where $z$ is equal to the summation of all hydrometeors per with a distinctive diameter $m^3$ times $D$ of the hydrometeors ($i$) to the power of 6.

IV. COMPARING

A) Comparing $z$

As we have seen, there are several calculations that must take place before $z$ for the radar and the aircraft is determined. In order to deduce snowfall rate, we must compare $z$ for each.

B) Matching Data Sets
For this study it was important to use aircraft data to determine exactly what was occurring within the storm at the exact elevation, date, time and azimuth where the radar collected data. We compare hydrometeor type and reflectivity \( z \) from both to deduce an average snow density \( \rho \), use \( \rho \) to calculate \( V_t \) to estimate snowfall rate, and find a relationship between \( z \) and the snowfall rate. The matching program provides an efficient way to find areas where the aircraft is at the exact location or in close proximity to the area sampled by the radar.

\[ a) \quad \text{Aircraft and Radar Match} \]

The matching program looks at the aircraft data first. It matches the aircraft position and time with the closest azimuth and elevation from the radar scans. The aircraft is measured in longitude, latitude, and altitude MSL (above mean sea level) coordinates. The matching program first transforms these coordinates into radar coordinates and determines the closest distance between aircraft position and radar sample volume. The matching program has a time restriction where the radar data has to be collected within -90 to +90 seconds of the aircraft data seeking the best data match. This procedure is repeated every second following the flight track of the aircraft.

A second restriction was to require the distance between the radar beam and the aircraft position to be less than 1 kilometer for proper matching. This program also does a correction for wind flow. This is necessary since the hydrometeors are carried away by the wind and will be at different locations from the radar in scans taken several minutes later. Finally, the matching program provides radar data for the best match along the flight track of the aircraft.

The reflectivity \( z \) calculated from the aircraft data are then compared to the reflectivity \( z_{\text{eff}} \) recorded by the radar. The density of snow and ice particles can be estimated using the following formula: \( 0.93 \ z_{\text{eff}} = 0.197 \ \rho^2 \ z \). The left side represents the reflectivity recorded by the radar-- deduced from the radar equation. This quantity is then multiplied by the refractive index of water. This is necessary since the power received by the radar was divided by \( |K_w|^2 \) in order to obtain \( z_{\text{eff}} \) even in the case where precipitation particles were comprised of ice.

The right side represents the reflectivity calculated from the aircraft data according to \( \sum N_iD_i^6 \) multiplied by the refractive index of graupel. Hydrometer density can be solved if \( Pr \) from the radar and the information from the 2DP PMS probe \((\sum_i N_i D_i^6)\) is known.

\[ b) \quad \text{Density to Calculate Rain Rate} \]

The calculated density for the snow particles was used to estimate snowfall rate. This was done using the following formula: \( S = \rho \ (\pi/6) \sum_i N_i D_i^3 \ V_i \ (\rho,D_i) \), where \( S \) represents the snowfall rate and \( V_i \) the terminal fall velocity of the hydrometeors. The estimated density is used, first to estimate the amount of water in each ice particle, and second to estimate the velocity \( (V_i (\rho,D_i)) \) with which each ice particle of mass \( m = \rho \)}}
\(\pi/6 D_i^3\) falls to the ground. In a final step the estimated snowfall rate is correlated with the reflectivity recorded by the radar. In this study we examined if different Z-R relationships can be deduced for different ranges of density.

C) Various Approach's

a) Locatelli and Hobbs

Locatelli and Hobbs (1974), presented the results of a new set of measurements of the fall speeds and masses of a wide variety of solid precipitation particles. These were obtained during the winter months of 1971-1972 and 1972-1973 in the Cascade Mountains of Washington. In brief, relationships between fall speeds, masses, and maximum dimensions for solid precipitation particles were derived in their paper. Particles were classified according to the suggested Magono and Lee (1966) scheme. All measurements by Locatelli and Hobbs were made between altitudes of 750 and 1500 m above sea level. The fall speeds measured by Locatelli and Hobbs fall in the range of 0.5-3.0 m s\(^{-1}\), where unrimed side planes have the lowest speed and graupel have the highest speed as seen in Figure (4 and 5). This study uses Locatelli and Hobbs (1974) fall speeds, masses, and maximum dimensions for solid precipitation particles as a guide to further determine hydrometeor terminal velocity and density when comparing Electra aircraft data and S-Pol polarimetric radar data.

Figure 4: Shows; a picture of an unrimed side plane and lump graupel particles. (Bently and Humphreys, 1962).

b) Heymsfield et al.

This study uses Heymsfield et al., 2001, a new unpublished approach, (a revision of the Locatelli and Hobbs paper) to derive the mass and terminal velocity of ice particles from airborne and balloon-borne imaging probe data (Heymsfield et al., 2001, abstract).

The Heymsfield et al. approach is to use a relationship between the area ratio \(A_r\); the area of an ice particle projected onto a horizontal surface divided by the area of a circumscribed circle) and diameter of hydrometeors to obtain an estimate of hydrometeor density, then use this estimated density to determine the terminal velocity \(V_t\) through a Best number-- Reynolds number relationship. The density relationships in the Heymsfield approach vary considerable with different habits. Instead, a comparison of the radar-derived habits versus aircraft 2DP PMS images is used to provide an average density. In this study the average density will be reflectivity-weighted rather than mass-weighted, like in the Heymsfield et al., 2001 approach.
The Best number ($X$) versus Reynolds number ($Re$) approach, provides a framework for deriving the $V_t$ in the Heymsfield et al., 2001 approach. The Best number is given by $X = \left( \frac{2g}{\rho_a v^2} \right) D^2 \left( \frac{m}{A} \right)$, where $g$ is the gravitational acceleration constant, $\rho_a$ is the air density, and $v$ is the kinematic viscosity of air. The Reynolds number is given by $Re = \left( \frac{V_t D}{v} \right)$. $V_t$ was determined directly by combining $X$ and $Re$ as given by $V_t = a_f \left( \frac{2g}{\rho_a} \right)^{b_f} v^{(1 - 2b_f)} D^{(2b_f - 1)} \left( \frac{m}{A} \right)^{b_f}$, where $a_f$ is the coefficient and $b_f$ is the exponent in Reynolds number--Best number relationship.

V. RESULTS

a) z-R relationship

This study closely analyzed the September 20, 1999 Intensive Observing Period (IOP), where a good match between aircraft and radar data was found. During MAP Eszther Bartha of the Swiss Federal Institute of Technology (ETH), Zurich reported that this IOP was successful in collecting microphysical data. Three hours of good data were available. Precipitation resulted from a frontal system, was widespread, and mainly of stratiform type. Ice crystals, snowflakes, and rimed particles were observed at the flight level with nearly constant temperature (-16 degrees C).
This study found the following z-R relationship: \( z = 58.141271 R^{1.3907765} \), (refer to Figure 6). This z-R relationship shows that the correlation coefficient for the entire flight of September 20, 1999 is 0.953076. The current z-R relationship, which depicts snowfall rate [mm/h] as a function of radar reflectivity (z) measured in dBZ shows little scattering thus adding polarimetric radar variables did not improve the results. In brief, S-Pol polarimetric variables provide additional information on hydrometeors. By adding polarimetric variables the hope was that for each parameter clearly marked regions of separate z-R relationships can be found for different snowfall. By adding the polarimetric variable, regions of low and high \( Z_{dr} \), \( K_{dp} \), \( \rho_{hv} \), \( LDR_{vh} \) were not clearly separated from each other, which made it difficult to clearly define each polarimetric region separately (refer to Figure 7).

A) Discussion

There are some uncertainties associated with the results provided. These are:

1. The calculation of snowfall rate in terms of reflectivity is uncertain. It has serious problems in measuring corresponding radar and aircraft samples. The estimated snowfall/ rainfall rate provided by this study may vary by a factor of 2 for a distinctive reflectivity. Proof from the ground that the conclusive snowfall rate is accurate is not available. A direct comparison of the provided snowfall rate by a ground-based instrument (i.e., rain gauge) is needed to confirm the deduced z-R relationship in this study.
2. The sample volumes as compared by the aircraft versus radar may be different.

B) Conclusion

Once processed in this way, where matching provided corresponding radar and aircraft data, measured (S-Pol) and calculated (PMS) radar reflectivity were compared to calculate an average density. The density is then used and provide an improved terminal fall speed. The hope was that this study would provide good estimates of the snowfall rate using polarimetric radar parameters. However, the study’s results were inconclusive because the additional polarimetric parameters did not improve the results.

This study is the beginning step in developing a method for estimating snowfall rates using polarimetric radar data and understanding heavy precipitation events including flash-floods. The next step is to continue comparisons of Electra aircraft 2DP PMS data versus S-Pol polarimetric data for different case studies, where a variety of hydrometeor types are present. The final goal of this study is to verify the estimated snowfall rate using ground based instruments.

The timing is right for this research because MAP collected data from the aircraft and radar with good matches and position, and S-Pol is part of the newer generation of radars capable of measuring multiple parameters. A rain rate for snow determined by using multiple radar parameters will help when predicting floods, warning of water resource problems, and planning for agriculture.

Figure 7: Shows that by adding the polarimetric variable to the z-S relationship, regions of low and high $Z_{dr}$ were not clearly separated from each other which made it difficult to clearly define each polarimetric region separately.
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