POLARIMETRIC SIGNATURES FROM ICE CRYSTALS OBSERVED AT 95 GHz IN WINTER CLOUDS. PART II: FREQUENCIES OF OCCURRENCE.

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Submitted to the Journal of the Atmospheric Sciences

Second revision July 7 2000

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ABSTRACT

Data are presented, from a large collection of observations in wintertime clouds in Wyoming, which show that the fraction of cloud volumes from which significant radar polarimetric information can be obtained is small. For example, when averaged over all available samples, signals exceeding the chosen limits of 3 dB for Z_{DR} and -18 dB for LDR were found in just a few percent of the observations for radar beam incidence angles of less than 45°. In general, the polarimetric signatures are interpreted as indicators of the prevalence of pristine and lightly rimed crystals, as opposed to more densely rimed crystals, graupel or aggregates. However, specific cases are presented to illustrate exceptions to this interpretation.

The polarimetric signatures provide information regarding ice crystal types from larger cloud volumes than can be observed with in situ probes, and thus may aid in understanding the evolution and possible origin of hydrometeors in the clouds. They may also help to refine assumptions made in the modeling of radiative transfer through clouds.

1. Background

The fundamental factors governing the growth of ice particles in clouds by vapor deposition, riming and aggregation are known from theory and from laboratory experiments. Yet, the full complexity of ice particle growth in clouds remains elusive because of difficulties in predicting and observing cloud composition and conditions with adequate spatial and temporal coverage, and because of large uncertainties about the processes of ice nucleation. In situ probes mounted on aircraft have sufficient resolution to provide adequate detail for most purposes, but these probes sample small fractions of the clouds. Remote sensing measurements, in general, suffer from various inherent ambiguities and do not achieve desirable levels of spatial resolution.

In Part I of this sequence of two papers (this issue, pages ……) we presented evidence that polarimetric measurements with an airborne radar can provide information regarding prevailing ice crystal habits. While this capability is not unique to airborne radar systems (e.g., Reinking et al. 1997), the possibility to bring the radar near the regions to be studied allow aircraft radar systems to sample clouds in a more efficient manner and with higher spatial resolution than can be achieved with ground based radars.

The most general result from Part I is that polarimetric signatures (PLS, to be defined more precisely later) are associated with unrimed or lightly rimed crystals. Heavy riming, and to a lesser degree aggregation, tend to diminish the aspect ratios of the ice particles, which then yield weaker polarization effects. Thus, polarimetric signatures may be used to identify cloud regions that contain unrimed or lightly rimed crystals. In this paper, we present information on the frequency with which polarimetric signatures were detected in a large sample of winter clouds, and then qualify the overall results with specific examples.

2. Field operations and instrumentation

Data were obtained using the Wyoming King Air aircraft with the Wyoming Cloud Radar (WCR) installed in it. In addition to measurements of state parameters and three-dimensional winds, the King Air was equipped with optical scattering and array probes for the detection and sizing of hydrometeors in the size range from 2 μm to several millimeters in diameter. The WCR operates at a wavelength of 3 mm and is configured to obtain backscattered signals along upward or sideways pointing beams of 0.7° beamwidth. Technical details about the WCR are given by Pazmany et al. (1994). Waves of two orthogonal polarizations are transmitted and received. Radar observables relevant for this paper are the co-polar equivalent reflectivity factors at horizontal and vertical polarization (Z_{HH} and Z_{VV}), the differential reflectivity factor (Z_{DR}) and the linear depolarization ratio (LDR). Definitions of these parameters are given in Part I. The volume resolution of the radar is 30 m in range, and few tens of meters (depending on distance from the aircraft, airspeed and averaging time) in the other dimensions. The sample volume for individual data points is 6,000 m^3 at 1 km range. Data were recorded from the WCR to maximum ranges of 1.5, 3 or 4.5 km. .

Field operations were carried out during the period February 6, 1997 to April 4, 1997 in the vicinity of Laramie, Wyoming. Wintertime cloud occurrences in this area cover a variety of synoptic situations and are frequently influenced by nearby mountain ranges. Over the 2-month observation period, flights were launched on 24 days and 52 hours of flight data were recorded. The main criterion for launching flights was the existence of relatively uniform broken to overcast conditions over areas of about 100 km extent within about 200 km of Laramie. Cloud types sampled included altostratus (*As*), altocumulus (*Ac*), cumulus (*Cu*), nimbostratus (*Ns*) and stratocumulus (*Sc*). About 2/3 of the data originate from *Ac* and *Ns*, and roughly 1/3 from *As*, *Cu*, and *Sc.*

Flight plans were decided based on cloud conditions. Generally, flights consisted of a survey of the clouds at various altitudes, at times overlain by repeated sampling of regions of interest. Based on images seen on the onboard radar display, regions of interest were selected by the flight crew when significant polarimetric signatures were indicated in close proximity to flight level so that coincident in situ sampling could be made. Whether repeated sampling of a region was initiated, or not, depended on the strength and uniformity of the detected PLS. The main method employed in collecting radar data in regions of interest was to fly level segments of about 20-40 km length with steady rolling of the wings within ±45°. These maneuvers, with either side-looking or up-looking beam orientations, provided a wide range of incidence angles (α) of the radar beam with respect to the horizontal. A secondary flight pattern was the execution of circles at constant bank angles.

The combination of cloud occurrences, flight occasions and flight plans form a unique set which cannot be construed to form a random sampling of possible conditions. Neither is the data set necessarily representative of conditions at other locations and times. What can be said of the data set is that it is composed of a relatively broad variety of cloud types, that it includes samples from the full range of temperatures common to tropospheric ice clouds, and that it is large enough to eliminate undue influence of any given occurrence on the statistics of the full set. It is difficult to give a good estimate of the degree of bias introduced by repeated sampling of regions where PLS were detected. While some regions were sampled two or three times, these regions represent only a small fraction of all the regions of PLS. The majority of regions of PLS were found during analysis at distances that would have been considered unsuitable for repeated sampling during the flights.

3. Observations

Data were stratified by temperature and by radar incidence angle. Twelve temperature intervals covering the range from -25°C to 0°C were used, divided in such a manner that most interval boundaries coincided with the recognized limits of growth of various crystal habits. Temperatures corresponding to each radar range were extrapolated from the temperature measured at flight level using a rate of –6°C km^{-1}. Thirteen intervals were used for the radar incidence angle. Except between 55^{o} and 85^{o}, the intervals were of 5^{o} width. Data were accepted for this analysis if the measured reflectivities of both polarization channels exceeded the mean noise level by three standard deviations. In addition, in the analysis of the LDR statistics, we required that the cross-polar reflectivity exceed the mean noise level by three standard deviations and that the co-polar reflectivity, which is used to normalize the cross-polar observations, exceed the noise threshold by 17 dBZ. The latter restriction assures that only those samples are considered for which reflectivities were sufficiently high to produce measurable cross-polar values, if the targets produced such signals. Statistics are reported only for temperature/incidence angle stratifications with at least 1000 valid data points, so that the statistical uncertainty in the reported frequencies is less than ±3%. The actual number of data points per bin varied greatly, with the maximum number exceeding 10^7.

In this paper, we present results for four criteria: $Z_{DR} > 3$ dB, $Z_{DR} > 5$ dB, $LDR_{HV} > -18$ dB, and $LDR_{HV} > -16$ dB. These criteria constitute our set of 'polarization signatures', PLS, and are based on results summarized in Fig. 6 of Part I. The $Z_{DR} > 3$ dB threshold can be viewed as separating rimed crystals from unrimed ones, while the $Z_{DR} > 5$ dB threshold isolates what can be considered exceptionally strong differential reflectivity factor. The LDR > -18 dB threshold isolates essentially all crystal types identified in Part I as having LDR values significantly above the minimum values detectable by our system, while the higher LDR threshold focuses on the more uncommon levels of cross-polarization.

a. Combined statistics

The sampling of winter clouds for this study yielded radar data from approximately 600 km^3 of cloud volume. The number of independent records of reflectivity values is of the order of 10^8.

The first line in Table 1 lists the observed frequencies of polarimetric signatures for the combined data set and Figs. 1 and 2 indicate the breakdown of frequencies with temperature and with radar incidence angle. The percentages indicated in the figures are with respect to the total number of valid data points in that bin. For example, for the temperature interval $-12°C < T < -10°C$ and radar incidence angles of $10° < \alpha < 15°$ there were 252,688 data points with Z_{HH} and Z_{VV} above their threshold values. Of these 252,688 samples, 121,757 samples, or 48% had Z_{DR} values that exceeded 3 dB. This is the value shown in Fig 1a.

Since the dependence of observed frequencies on incidence angle appears to be relatively weak for $\alpha \leq 45^{o}$, summary histograms are shown for this range of angles in the right-hand panels of the graphs. Frequencies in the histograms are expressed as the ratio of the number of occurrences exceeding the indicated Z_{DR} and LDR limits in the given temperature interval and $\alpha \leq 45^{o}$ to the total number of occurrences at all temperatures for the given Z_{DR} or LDR criterion and for $\alpha \leq 45^{o}$. Thus, while the numbers in the left-hand panels represent the fraction of the total sample volume (for which valid measurements have been obtained) that satisfy the given conditions, the histograms show the temperature distributions of those events for the low incidence angle portion of the data. As a result, the two panels are sometimes in apparent disagreement; in fact, they represent two different aspects of the results.

Looking at the histograms for $\alpha \leq 45^{o}$ in Fig. 1, it is seen that essentially all occurrences of $Z_{DR} > 3$ dB and $Z_{DR} > 5$ dB fall in the temperature range –17 to –8°C, with a significant peak for $Z_{DR} > 3$ dB over the warmer half of this range, –12 to –8°C. The distributions are somewhat broader for LDR (Fig. 2), but the most significant fraction of occurrences fall in the narrower temperature range of -17 to -14°C for both LDR threshold levels.

For high incidence angles, $\alpha > 45^{o}$, the frequencies of occurrences of significant Z_{DR} signatures were less than 0.5% for all temperatures, but LDR values of appreciable frequencies were observed for temperatures > -4°C (from needle crystals and from melting layers).

b. Specific cases.

The frequencies of significant polarimetric signatures were found to differ greatly from one cloud to another. As argued in Part I, crystal habit and the degree of riming are the main determinants of polarimetric signatures, other conditions also influence them. We illustrate this with three examples, for which the summary statistics are given in Table 1, and in Figs. 3 to 5.

CASE 1. Altocumuli were sampled over a period of approximately two hours on February 18, 1997, in a cloud region of about 50 km extent. Cloud depth was approximately 1 km covering the temperature range -17°C to -11°C. Updraft regions of a few hundred meters to over a kilometer horizontal dimensions were found, with maximum vertical velocities of about 2 m s^{-1}. Liquid water contents were up to 0.4 g m^{-3}, droplet concentrations were up to 600 cm^{-3}, and the volume mean diameters of the cloud droplets varied between 6 and 12 μm.

Data from the particle imaging probes indicated that crystals were mainly planar types (P1a, P1d, and P1e; using the Magono and Lee (1966) classification), as expected for the temperatures prevailing within the clouds. Ice crystal concentrations were between 1 and 10 L^{-1}, with sizes up to 2 mm. In a somewhat surprising way, there was a positive correlation between liquid water content and ice concentration. This fact, the relatively small sizes of the cloud droplets, and the shallow cloud depth account for the fact that most of the crystals remained unrimed or lightly rimed, as far as that could be dietermined from the recorded particle images. Radar reflectivity values were between -15 and -5 dBZ for 90% of the data; these weak reflectivities also attest to the lack of heavy riming of the crystals.

The polarization data for this flight is summarized in Fig. 3. As the figure indicates, $Z_{DR} \geq 3$ dB was observed a high proportion of time for all incidence angles less than 45°. The frequency of LDR occurrences was also high but somewhat below the frequencies of Z_{DR}, perhaps due to inadequate sensitivity of the radar. Combining all angles $\alpha \leq 45°$, the overall frequency for $Z_{DR} \geq 3$ dB was 73%, and for LDR_{HV} >-18 dB it was 31% (see Table 1). For $\alpha > 45°$, the frequencies of PLS were negligible.

Special interest in this case is the high frequency of PLS, which could have been thought incompatible with the presence of substantial quantities of supercooled liquid water.

CASE 2. A nimbostratus was sampled on February 11, 1997 over a 40-km region, at altitudes between 3 and 6.5 km, and temperatures from –30 to –6°C. There was no liquid water detectable at any point in the cloud and vertical air velocities were essentially zero everywhere. The cloud consisted totally of ice crystals whose concentration remained in the range 5 to 50 L^{-1} at all altitudes. Observed ice crystal habits included columns, capped columns, hexagonal plates and irregular (graupel-like) crystals.

Figure 4 presents a summary of the polarization data for this case. Very few occurrences of $Z_{DR} > 3$ dB were found. The highest frequencies are only 2 to 4%, and these correspond to cloud volumes that contained plate and columnar crystals. Two zones of T-α combinations, at different values than the zone of appreciable Z_{DR}, exhibit significant LDR occurrences. One zone is for small incidence angles and temperatures of –17 to –12°C , the other is for high incidence angles spanning a wider temperature range. These occurrences derive from cloud regions containing columnar crystals and capped columns. Because these observations are for high incidence angles, contrary to the other figures, the histograms in the right-hand panels of Fig. 4 are for $\alpha > 45°$.

The specific interest in this case is that the absence of liquid water, and therefore of riming, did not ensure high frequencies of PLS. Complex three-dimensional crystal shapes (bullet rosettes) generally expected in clouds whose tops are near -30°C provide the main explanation for the observations. Yet small areas within nimbostratus, at temperatures within a fairly large range, can have simpler crystal forms and produce LDR signatures.

CASE 3. Figure 5 shows a summary of polarization data from a cumulus congestus sampled on April 4, 1997. The cloud was sampled at temperatures of –20 to +6°C. Vigorous updrafts of up to 7 m s^{-1} were encountered and some lightning activity was noted. Cloud droplet concentrations up to 500 cm^{-3} were measured with liquid water contents to 0.8 g m^{-3}. Ice and water regions tended to be alternating. Ice particle concentrations >100 L^{-1} were frequently recorded by the 2D-C probe. The dominant ice particle type was graupel which reached up to 6 mm in size (cf. Fig 5 of Part I).

As shown in Table 1, only 0.1% of all the data with $\alpha \leq 45^{o}$ have $Z_{DR} \geq 3$ dB. Frequencies for $Z_{DR} > 3$ dB were < 3% at any T-α class. In contrast, frequencies up to 48% were observed for LDR > -18 dB in the vicinity of –10°C. In addition, depolarization was also pronounced in the melting layer.

The evidence for this case is consistent with the prevalence of graupel particles in the cloud, and as expected the roughly symmetrical shape of most graupel led to the paucity of nonzero Z_{DR} values. The large frequency of LDR values has no clear explanation at this time, and indicates that the presence of significant LDR signatures may also be due to ice particles other than unrimed crystals. It may also be supposed that small needle crystals were involved (perhaps via the Hallett-Mossop splinter mechanism), although no needle crystals were large enough to be detected in the particle imaging probe data. More information about this case is given in Part I.

This case also adds a caveat to the interpretation of the results presented in Section 3a, indicating that those results overestimate the fraction of cloud volumes occupied by unrimed or slightly rimed crystals. In this data set the overestimation is a few percent of the reported frequencies, based on a comparison of the number of data points included in the combined data set with the number of observations of high LDR from graupel.

4. Conclusions

The principal finding of this study of wintertime clouds in Wyoming is that the fraction of cloud volumes from which significant polarization information can be obtained is small. Overall frequencies were a few percent for signals exceeding the chosen limits 3 dB for Z_{DR} and -18 dB for LDR, for beam incidence angles less then 45° (cf. Table 1). However, in nimbostratus or in altocumulus the frequencies may reach 50 or even 80%. These polarimetric signatures are interpreted, based on results shown in Part I, and in references cited there, as useful though imperfect indicators of the prevalence of pristine (grown by diffusion) and lightly rimed crystals versus more densely rimed crystals, graupel or aggregates.

From an extensive set of in situ observations in Arctic clouds, Korelev et al. (1999) concluded that only 3% of the detected ice particles were pristine crystals, defined by those authors as faceted single crystals evident in the optical array probe data. Their definition is not far from what we referred to as unrimed or slightly rimed crystals. Both definition exclude aggregates. Consequently, the two studies are quite comparable and the two sets of results surprisingly similar, perhaps because both data sets were obtained in wintertime clouds at mid to high latitudes While extrapolation to other cloud conditions is uncertain, it may be surmised that clouds in warmer climates and with higher liquid water contents will have no greater proportions of unrimed crystals. Differences in overall cloud structure and dynamics may, however, override those factors.

Specific cases presented here illustrate that the presence of significant polarization signatures is not incompatible with some supercooled liquid water coexisting with the crystals, that nimbostratus may have widely distributed regions of simple crystal forms, and that graupel in cumulus congestus may produce unexpected depolarization effects.

In a general sense, it may be of some help to future cloud microphyscis studies that polarimetric measurements have been shown to have the ability to determine, within sampling limitations, the relative proportions of cloud volumes where crystals are growing by diffusion due to liquid water content being absent or very low, or due to the samll sizes of the crystals close to their origins, and to locate such volumes with respect to the overall cloud structure.

Acknowledgments. Many people have participated in the data collection and processing. Dr. R. D. Kelly is co-Principal investigator of the project and has contributed generously to all aspects of this study. He, D. Leon and Drs. J. French, S. Haimov have participated in the field experiment and in the data processing. The work of the University of Wyoming KingAir Flight Facility was indispensable for the success of the experiment. K. Endsley, P. Wechsler, G. Gordon, the pilots and technicians supporting the KingAir have done an outstanding job in the field work and data processing. We also wish to thank Drs. A. L. Pazmany and the late R. E. McIntosh from the Microwave Remote Sensing Laboratory, University of Massachusetts at Amherst for their unstinting efforts to make this work possible. This work was supported by the National Science Foundation grant under ATM-9319907 and ATM-9712859. The 1995 coastal stratus study, from which some data were also used, was supported by a DEPSCOR grant from the Office of Naval Research. We appreciate the care taken by two reviewers in improving the manuscript.

REFERENCES

Korolev, A. V., G. A. Isaac, and J. Hallett, 1999: Ice particle habits in Arctic clouds. *Geophys. Res. Lett.*, **26**, 1299-1302.

Mogono, C., and C. W. Lee, 1966: Meteorological classification of natural snow crystals. *J. Fac. Sci. Hokkaido Univ. Ser. VII*, **2**, 321-362.

Pazmany, A. L., R. E. McIntosh, R. D. Kelly, and G. Vali, 1994: An airborne 95 GHz dual-polarized radar for cloud studies. *IEEE Trans. Geosci. Remote Sens.*, **32**, 731-739.

Reinking, R. F., S. Y Matrosov, B. E. Martner, and R. A. Kropfli, 1997: Dual-polarization radar to identify drizzle, with application to aircraft icing avoidance. *J. Aircraft*, **34**, 778-784.

Wolde, M., and G. Vali (this issue): Polarimetric signatures from ice crystals observed at 95 GHz in winter clouds. Part I: Dependence on crystal form. *J. Atmos. Sci*.