

STUDIES OF CLOUD STRUCTURE AND MICROPHYSICS WITH GROUND-BASED MULTI-SENSOR MEASUREMENTS

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1. Introduction

Clouds modulate the Earth's radiation budget and climate, and they are the key element in the global water cycle. The radiative impact and precipitation potential of clouds depend on their macrophysical properties such as layering, heights and temperature, and, most importantly on their microphysical properties that include liquid and/or ice water content (LWC or IWC), characteristics of the cloud particle size distribution, cloud particles shapes and types (habits), and cloud phase. These microphysical properties determine cloud optical properties such as extinction, phase function and the single scattering albedo. The ability to measure/retrieve cloud microphysical properties is crucial for many weather and climate studies including weather modification applications.

Although in situ aircraft-based sampling can provide valuable cloud information on a limited scale, remote sensing measurements have become a very powerful and indispensable tool for studies that require continuous cloud information on differing scales. While cloud observations with passive instruments such as microwave (MW) radiometers or surface radiation sensors have been in use since the 1960s, it was not until about mid the 1980s to early 1990s when active sensor and active-passive sensor based cloud measurements became widely available to the scientific community and multi-sensor cloud microphysical retrieval methods for vertically pointing and scanning observations began to be developed.

These retrieval methods and observation capability developments were mostly due to the introduction in practical use of specialized cloud lidars and radars that were able to provide high resolution measurements. The multi-sensor cloud retrieval approaches combine advantages and overcome limitations of individual remote sensors and can be roughly divided into radar-radiometer methods (e.g., Matrosov et al. 1992, Frisch et al. 1995, Mace et al. 1998), lidar-radar methods (e.g., Intrieri et al. 1993, Donovan et al. 1997, Wang et al. 2002, Okamoto et al. 2003), and lidar-radiometer methods (e.g., Platt et al. 1987). Radar methods that use Doppler or polarimetric information (e.g., Matrosov et al. 2001, Matrosov et al. 2002, Mace et al. 2002, Shupe et al. 2004) can be considered as multi-parameter methods since they use multiple input measurements of different kinds (although often from a single remote sensor).

2. The ESRL suite of cloud remote sensing methods

The NOAA Environmental Technology Laboratory (ETL), which recently was absorbed in the newly created Earth System Research Laboratory (ESRL) is a pioneer in the field of multi-sensor cloud remote sensing development. The history of retrieval method developments during the 1990s have been described by Matrosov et al. (2000). The ESRL now maintains a suite of remote sensing methods that are applied to the continuous cloud data sets obtained by semi-permanent Cloud Observatories such as the one maintained by the U.S. Department of Energy's Climate Research Facility at Barrow, North Slope of Alaska (NSA). These observatories are typically equipped with a suite of remote sensors including vertically pointing cloud radars (K_a- or/and W-band), infrared (IR) and MW microwave radiometers and often lidars. While the scope of ESRL's interest includes clouds from different geographic regions, the priority is given to Arctic clouds which are among the most challenging for retrieving.

A choice of a particular microphysical retrieval method is dictated by a cloud scene (phase mask) and the applicability range of this method. The radar - IR radiometer method (Matrosov 1999) is used for optically thin ice clouds that are unobstructed by liquid layers as viewed from the ground. The radar - MW radiometer method (Frisch et al. 1995) is used for the liquid water clouds that do not contain ice particles. Ice clouds that are obscured from the surface by the cloud layers containing liquid and the ice component of mixed-phase clouds are retrieved using the Doppler moment method (Matrosov et al 2002) if there are no indications of significant upward and downward air motions. When such motions are present, simple radar reflectivity based regression methods are used for ice microphysical retrievals in such clouds. It should be mentioned, however, that the coefficients in these regression methods vary depending on a number of factors (e.g., season, cloud temperature) and they are "tuned" based on available comparisons between results of these methods and multi-sensor approaches. While the lidar data are not directly utilized for the routine microphysical retrievals, these data (when available) are used for determining the cloud phase. The cloud scene (mask) is determined using available information from the remote sensors and temperature soundings.

3. An example of cloud microphysical retrievals

An illustration of cloud microphysical retrievals using the ESRL method suite is presented below. The case observed on 2 September 2003 at the NSA observational facility was a rather complicated one. Multi-layer clouds including a precipitating system were observed over the course of 24 hours.

a. Input information

Figure 1 shows time-height cross sections of the first three moments of the Doppler spectrum (i.e., the reflectivity factor, the mean Doppler velocity and the spectral width) as measured by the vertically pointing K_a -band radar. Figure 2 depicts the time series of measured radiometric information including brightness temperatures of downwelling radiation at the IR window (10.96-11.27 μm) and at the microwave frequencies of 23.8 and 31.4 GHz. The microwave brightness temperature measurements were used to estimate vertically integrated amounts of precipitable water vapor (PWV) and liquid water path (LWP).

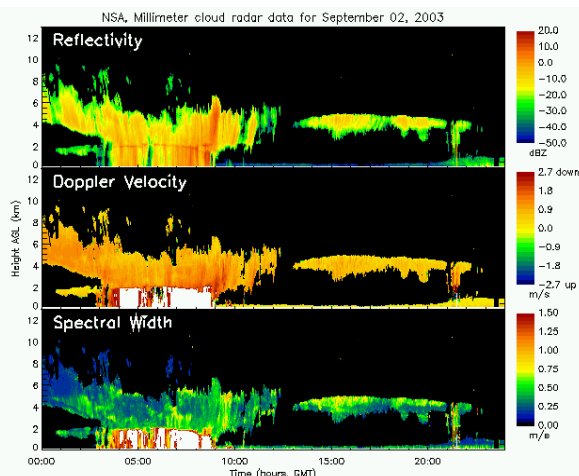


FIG.1. A time-height cross-section of K_a -band radar spectral moments measured at the NSA observatory, 2 September 2003.

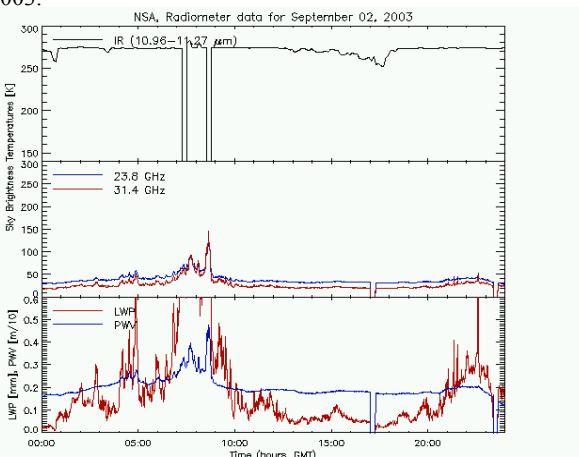


FIG.2. Time series of IR and MW radiometer brightness temperatures and MW radiometer products (LWP and PWV) measured at the NSA observatory, 2 September 2003.

b. Retrieved cloud information

Figure 3 shows the classification of the cloud scene (i.e., the cloud phase mask) for 2 September 2003. During the classification the observed hydrometeors are classified based on available information into ice, liquid and mixed-phase clouds and also in three precipitation classes (rain, drizzle, and snow). The two categories of ice and liquid clouds in the classification schemes separate situations when radar-radiometer methods can and cannot be used (due to multiple layers) for retrievals.

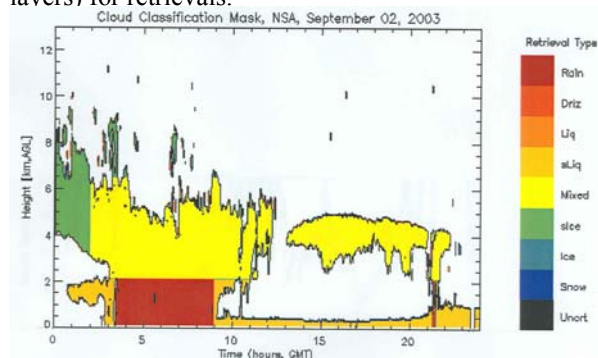


FIG.3. Classification of the cloud scene on 2 September 2003.

Most of the clouds above the freezing level at about 2 km above the ground (AGL) were classified as mixed-phase because of the relatively large spectral width values (see Fig. 1), which is characteristic of this type of clouds. The upper portions of the cloud observed between 00:00 and 02:00 UTC, however, were characterized by small spectral widths and were classified as ice clouds. Since this ice cloud was observed above the lower level liquid cloud, the radar - IR radiometer method could not be used for retrievals. The persistent lower level liquid water stratus cloud was observed after the rain event ended at about 9:00 UTC.

Figure 4 presents the retrievals of the cloud particle characteristic sizes expressed in terms of the effective radius which is defined by the ratio of cloud content to the extinction coefficient.

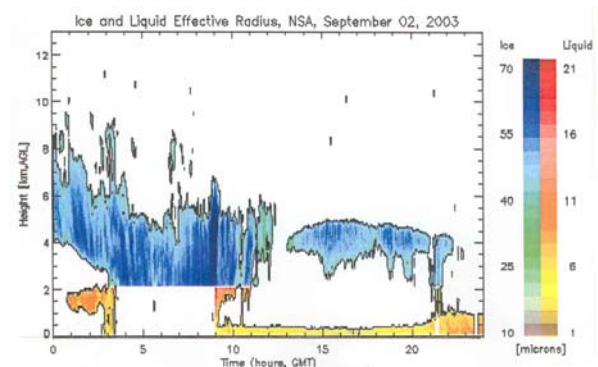


FIG.4. Retrieved effective radii of ice and liquid cloud particle sizes for 2 September 2003 case.

Figure 5 depicts the retrievals of water content (LWC and IWC) for this experimental example. This figure also shows the time series of cloud optical depth which was estimated using the retrieved information on cloud content and characteristic particle size along with an assumption about particle mass-cross-sectional area-size relations (e.g. Matrosov et al. 2003).

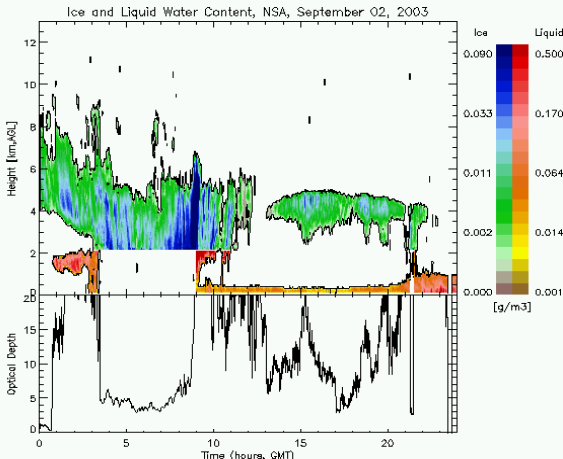


FIG.5. Retrieved ice and liquid water contents for 2 September 2003 case.

Retrieval uncertainties are caused by measurements errors and model assumptions. Theoretical modeling, inter-comparisons of different microphysical retrieval methods for same clouds and comparisons of remote sensing results with in situ cloud sampling provide estimations of these uncertainties. The retrieval uncertainties for typical clouds were estimated at about 30-40% for cloud particle characteristic size and at about 50-70% for cloud liquid and ice water content. The uncertainties could be higher for thinner clouds containing smaller particles since such clouds have very low reflectivity.

At present ESRL Arctic cloud property retrievals do not include rainfall areas as shown by gaps in Figs. 4-5. It is expected, however that in future rainfall retrievals could be a part of the microphysical retrieval suite.

4. Possibilities of rainfall retrievals using vertically pointing cloud K_a -band radars

A novel method has been suggested and tested for retrieving rainfall rates from K_a -band cloud radars measurements (Matrosov et al 2006). This approach takes advantage of the proportionality between rainfall rate and attenuation coefficient in rain at K_a -band and is based (unlike the traditional precipitation radar methods) on attenuated reflectivity measurements and not on absolute reflectivity estimates. This method has been already applied for the vertically pointing cloud radars that are used in warmer climates showing robustness in retrieving rainfall rates that are greater than about 4 mm/h at 1 km resolution. By using a more coarse resolution, lower rainfall rates can also be retrieved. The inclusion of rainfall information can provide a more complete characterization of the vertical atmospheric column.

Figure 6 shows an example of the rainfall retrieval method as applied to the K_a -band radar deployed in Oklahoma. The profiles of retrieved rainfall rates are available at heights where the radar signals are neither in saturation (which prevents retrievals near the ground) nor near the melting layer where melting ice particles contaminate the rainfall measurements. Rainfall retrievals can also be beneficial for retrievals of clouds above rainfall, since the rainfall attenuation of radar signals can be accounted for when estimating cloud microphysics which requires knowledge of absolute values of reflectivity.

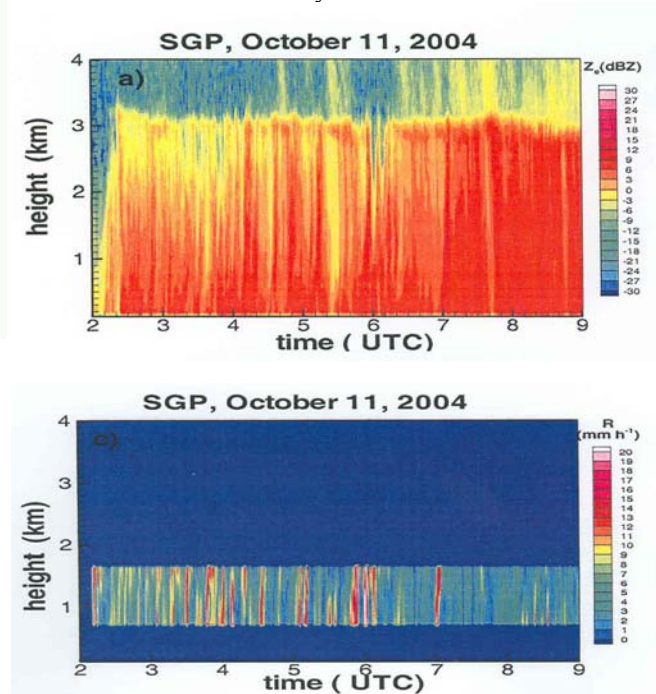


FIG.6. Time-height cross-sections of measured K_a -band reflectivity and retrieved rainfall rates, 11 October 2004.

5. Long term statistics of cloud microphysical retrievals

Long term cloud observations and microphysical retrievals from one site provide the annual cycle of cloud properties as well as typical probability distribution functions (PDFs) and normalized vertical profiles for different cloud parameters. Shupe et al. (2005, 2006) presented the statistical distributions of Arctic cloud properties as obtained from the analysis of one year long ground-based remote sensing measurements and retrievals using the ESRL suite of cloud microphysical retrieval methods.

Figure 7 shows these distributions for all liquid, all ice and the ice component of mixed-phase clouds. These types of clouds were observed in the vertical atmospheric column 19%, 38%, and 41% of the time, respectively. There were also clear signs of the annual cycle in cloud properties with lower values of liquid drop radii and ice particle sizes observed during winter months. Mixed phase clouds were most frequent in spring and autumn.

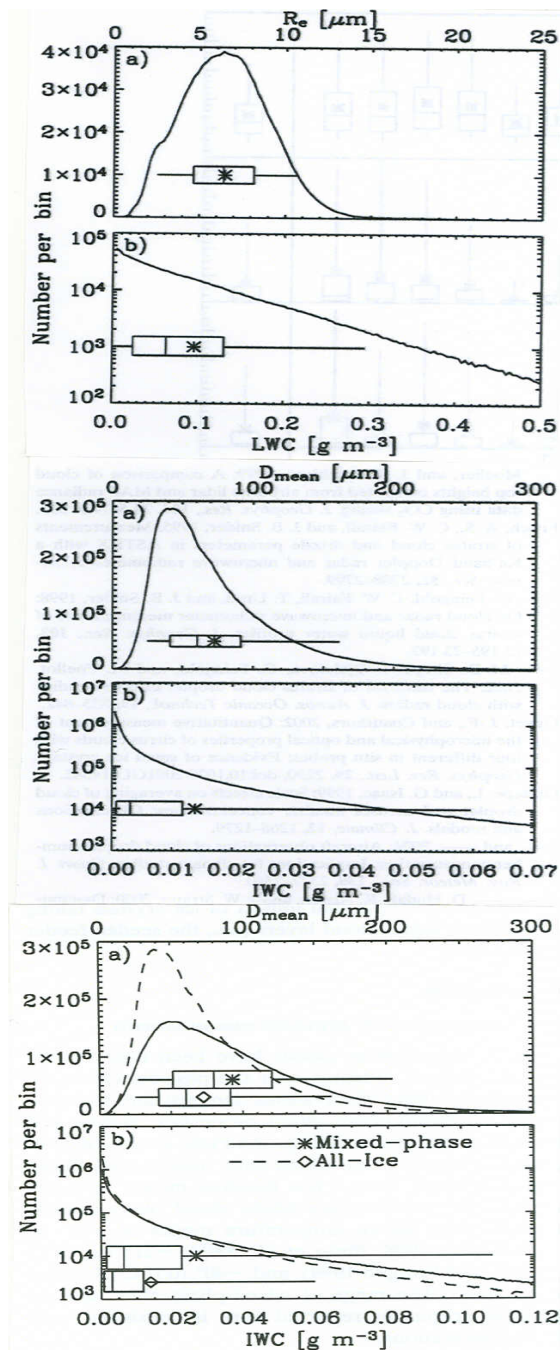


FIG. 6. Annual normalized distributions of effective radii and LWC for liquid clouds (two upper frames), mean particle size and IWC for all ice (two middle frames), and ice parts of mixed-phase clouds (two lower frames).

6. Identification of hydrometeor habits and shapes using polarimetric scanning radars

Polarization information from vertically-pointing radars is rather limited. Scanning polarimetric radars, however, provide a wealth of information which can be used for identifying various types and habits of hydrometeors and estimating their shapes (e.g., typical aspect ratios). Knowing hydrometeor habit is essential

for many practical issues such as aircraft icing detection, cloud radiative feedback modeling, and precipitation enhancement. To address these issues, ESRL operated a scanning polarimetric K_a -band radar for studies of non-precipitating and weakly precipitating clouds.

The main polarimetric parameter used for studies with the ESRL radar was depolarization ratio, defined as the ratio of received radar echoes at two mutually orthogonal polarization states, one of which coincides with the polarization state of transmitted signals. The most common depolarization ratios are the linear depolarization ratio (LDR) measured when echoes are received on both vertical and horizontal polarization when either of these polarizations is transmitted, and the circular depolarization ratio (CDR) obtained when echoes on right-hand circular and left-hand circular polarizations are received when either of circular polarizations is transmitted.

Atmospheric hydrometeors of various growth habits depolarize according to their prevalent aspect ratio, bulk density, orientation, and the polarization state of the incident radiation. It was shown (Matrosov et al. 2001) that CDR does not depend on hydrometeor orientation in the radar polarization plane, and thus is a more useful parameter for studies of particle habits and shapes than LDR which is highly sensitive to particle orientations and also is very small and difficult to measure for hydrometeors that are oriented in the horizontal plane. It was also shown that the slant linear depolarization ratio (SLDR) measured as the ratio of radar echoes on 45° and 135° slant linear polarizations (when either of these polarizations is transmitted) closely approximates CDR for particles that fall with their major dimensions in the horizontal plane. Since this is a common falling attitude for atmospheric hydrometeors due to aerodynamic forcing, SLDR was often used in lieu of CDR for some practical reasons related to the hardware availability.

The hydrometeor type/habit can be determined from the elevation angle dependences of CDR or SLDR. For planar crystals (e.g., dendrites, hexagonal plates) these depolarization ratios are relatively large and they diminish as the elevation angle increases towards 90° which corresponds to vertical pointing. The dynamic range of depolarization changes corresponding to low and high elevation angles decreases as hydrometeors become more spherical, and vanishes for spherical particles (e.g., drizzle drops). The columnar crystal habits (e.g., bullets, needles, columns) are characterized by more or less neutral depolarization dependence when CDR and SLDR do not change much or increase just slightly as the radar elevation angle increases.

Figure 7 shows the elevation angle dependences of SLDR measured by the ESRL K_a -band scanning radar at a constant altitude in a layer of pristine plates and rimed dendrites. Both habits exhibit dependencies that are typical for planar crystals but rimed crystals are more spherical. The hydrometeor images obtained from aircraft sampling are also shown. The mean aspect ratio of the hydrometeors can be estimated from SLDR values measured at an elevation angle of about 40° .

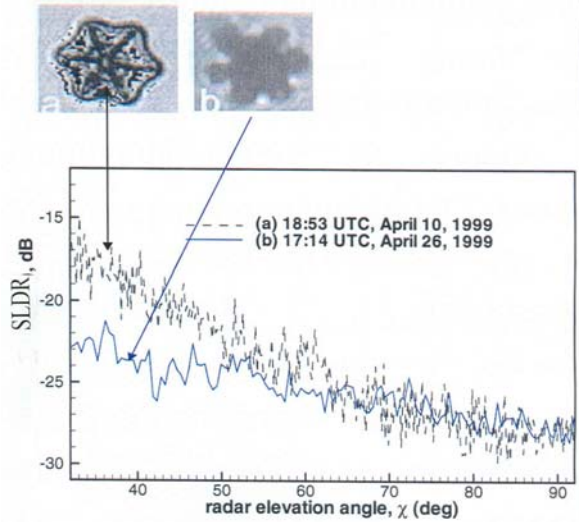


FIG. 7. Depolarization ratios as a function of radar elevation angle for pristine (a) and rimed (b) planar crystals.

Figure 8 depicts depolarization ratios measured in layers of columnar hydrometeors along with the corresponding crystal images. Unlike for planar habits, there is no clear trend in SLDR as a function of the radar elevation angle. The mean depolarization ratio increases as the column aspect ratio decreases. Irregular shaped, graupel-like ice crystals are quasi-spherical and exhibit very low depolarization at around -28 dB. True spheres such as drizzle drops (not shown) provide depolarization ratio values of about -29 dB, level which is specified by the radar polarization isolation.

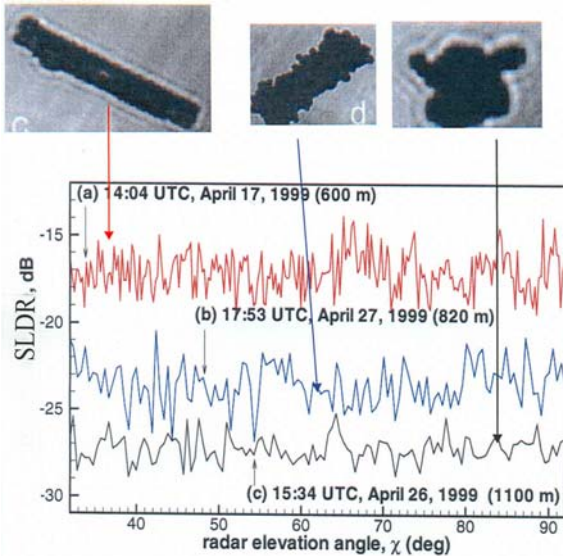


FIG. 8. Depolarization ratios as a function of radar elevation angle for long columns (red), blocky columns (b) and irregular shaped ice crystals (black).

Figure 9 shows a range-height indicator (RHI) radar scan in a cloud that predominately consists of weakly precipitating single pristine dendrites. Embedded in this cloud is a thin layer of columnar crystals which has

a very distinct pattern of depolarization. The results given in the section illustrate that polarimetric scanning radar can be a very effective tool for monitoring hydrometeor habit changes which is an important mechanism in forming precipitation.

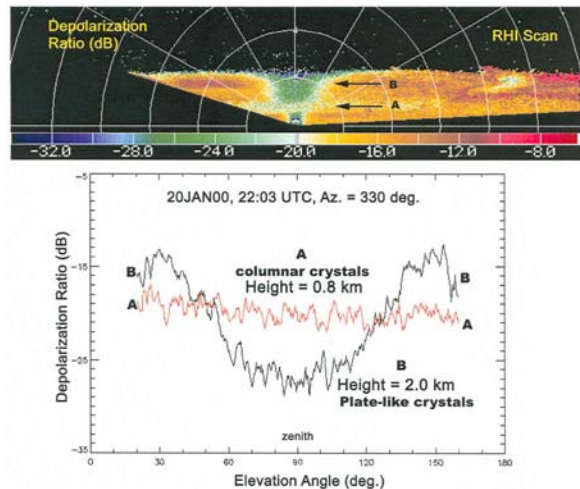


FIG. 9. An RHI of SLDR measurements in a dendritic cloud with embedded layer of columnar crystals (upper frame), and SLDR elevation angle dependencies that at two characteristic altitudes (lower frame).

Another illustration of ESRL polarimetric radar studies of precipitation formation processes is given by Reinking et al. (2000). They show the influence of gravity waves on orographic clouds in stimulating precipitation. The RHI radar scans in Figure 10 show reflectivity and CDR of a wave-orographic cloud couplet. The conversion of super-cooled liquid contained in a wave cloud (as indicated by low CDR values above the orographic wave) to precipitation is facilitated by ice crystals embedded in the wave cloud.

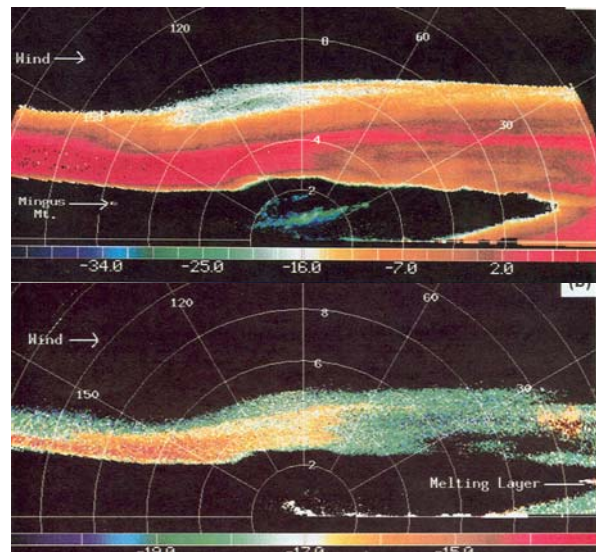


FIG. 10. Reflectivity (upper frame) and CDR (lower frame) RHI scans of a gravity wave - orographic cloud couplet.

7. Air entrainment studies using polarimetric radars

Scanning polarimetric radars can also be used to study processes of air entrainment by developing clouds. Artificial radar targets such as chaff are often used as trackers of the air motions. Typically chaff fibers are dispersed from an aircraft in the vicinity of the study area (e.g., near bases of developing convective clouds). These fibers are very thin aluminum-coated cylinders cut at length that corresponds to half of the radar wavelength, so they produce resonance effects and are very visible by radar. Chaff fibers act as conductive dipoles and have a CDR value that is close to 0 which is almost an order of magnitude larger than any possible CDRs from hydrometeors. Because of these disparities in CDR values, chaff can easily be detected by polarimetric radars in the background of hydrometeor echo. On the other hand, chaff fibers are suspended in air and they practically are tracers of air motions, so by tracking chaff by radar, air entrainments can be monitored and studied.

ESRL polarimetric radars have been used for chaff tracking in conjunction with studies of air entrainment in developing cloud environments for a number of years (e.g., Reinking and Martner 1996). These studies were primarily aimed at understanding ingestions, transport, and dispersion in convective clouds ranging from individual cells to severe thunderstorms producing hail. It was shown that chaff tracking can provide a useful insight in the processes of cloud development.

8. Implication for weather modification studies

The topics discussed above, related to the use of radar and multi-sensor studies of clouds, have a number of implications for weather modification studies. A comprehensive cloud characterization using multi-sensor suites of instruments will definitely aid any weather modification related research. Cloud microphysical retrievals performed before and after seeding can provide information on the effects of this seeding. Trends in different cloud properties (LWC, IWC, characteristic particle size), changes in cloud structure and morphology and in PDFs of different cloud parameters can be used as indicators of seeding results, since it might otherwise be difficult to separate seeding effects apart from natural developments.

Polarimetric scanning radars can be used to monitor hydrometeor habit change and riming in space and time during natural cloud and precipitation developments and as a result of seeding. Seeder – feeder processes and precipitation conversion mechanisms can be studied in much more detail using such radars.

Chaff tracking polarimetric radar techniques could provide an efficient way to determine how to appropriately deliver seeding material to target clouds in an attempt to enhance precipitation or/and suppress hail production. Different ways of delivering seeding material to clouds can be also assessed using this tracking technology.

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