RADAR OBSERVATIONS OF WINTERTIME MOUNTAIN CLOUDS OVER COLORADO AND UTAH

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Abstract. Ludlam (1955) postulated that seedable clouds for initiating snowfall are the extensive, shallow orographic clouds. He referred to these as "extensive low clouds". He specifically excluded clouds that contain persistent vertical motions not associated with localities where the airstream flows over mountains. The orographic, randomized Climax, Colorado cloud seeding experiment conducted during the 1960's followed the seeding hypothesis for orographic clouds as proposed by Ludlam (Grant, 1987). This paper presents the results of recent radar observations of the characteristics of differing types of clouds that form over the mountains of Colorado and Utah.

Cloud radar echo observations show that deep, stable and deep, convective cloud systems in the interior areas of the western United States during winter generally extend to elevations higher than the 50 Kpa pressure level where temperatures during winter are sufficiently cold to permit efficient ice nucleation processes to occur. Shallow, orographically forced clouds, on the other hand, almost always occur in their entirety at elevations below the 50 Kpa level where wintertime temperatures are variable with respect to temperatures at which natural ice nucleation can be either efficient or inefficient.

1. INTRODUCTION

The Ludlam (1955) concepts for seedable orographic clouds for initiating snowfall were postulated for extensive, shallow orographic clouds. He referred to these as "extensive low clouds...". He excluded "...clouds (that) contain persistent vertical motions of a magnitude sufficient to sustain any considerable precipitation, except in localities where the airstream containing the clouds flows over the mountains." The Climax randomized cloud seeding experiments were designed and conducted following considerations of orographic clouds as proposed by Ludlam (Grant, 1987). Climax experiments placed emphasis on the generally shallow orographic clouds that form as moisture is advected into the area in association with various weather systems. Large, organized cloud systems passing through the region and deep convective clouds forming over the mountains were considered to be already efficient precipitation producers that could not have their efficiency as precipitation producers greatly enhanced. Consequently, it was assumed for these experiments that the precipitation from these deep cloud systems would be "noise" in the randomized experiment, and that similar "noise" should occur on both seeded and "non-seeded" experimental days. Following Ludlam, the bias in the seeded sample, was postulated for the Climax experiment to occur from a difference in precipitation from the "extensive low clouds."

Detailed, descriptive, and continuous observations of the cloud systems were not feasible at the time of the Climax experiments which were carried out during the 1960's. Descriptive observations of cloud characteristics, estimated depths, and cloud top were limited to (1) visual observations under partly cloudy conditions and from the clear areas to the lee of the barrier, (2) a few direct observations with a modified Navy's SO-12 X-Band search radar, and (3) pilot reports of cloud tops. Other estimates of cloud characteristics were made from analyses of a limited number of upper air soundings made in the vicinity of the experimental area. Descriptive observations of the orographic clouds in the vicinity of Climax, as well as at other locations in Colorado and Utah, have been made during the past few years with the aid of a Ku-Band radar assembled at Colorado State University in the late 1970s. This paper presents the results of some of these recent observations. These results provide climatological descriptions of cloud tops (and consequently cloud depths), maximum and cloud top radar reflectivity, and the cloud elevation of the maximum reflectivity. Data are presented and compared for Tennessee Pass, Colorado (in the immediate vicinity of the Climax experiments), the Park Range of northwest Colorado, and from Beaver, Utah, upwind of the Tushar Mountains. These results are considered in the context of the seedability criteria hypotheses which were utilized for analyses of the Climax statistical experiments.

2. THE OBSERVING RADAR

All of the cloud descriptions presented in this paper are based on observations made with the Colorado State University Ku-Band (1.79 cm) radar. Received echoes are digitized by an eight-bit analog-to-digital converter and thereafter loaded into the memory of a minicomputer. Data are written onto 9-track magnetic tape once every 30 seconds or multiples thereof. Storage of data in an array of 46 pulses by 200 range bins affords access to individual pulse values for statistical

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calculations such as signal variance and bias. The computer also produces a real time display of reflected power, calculated in dBZ, based on averages of 46 consecutive pulses. The real-time display is formated as a horizontal intensity profile with 80 positions, each corresponding to 100 meters vertical distance. The overall effect is to establish a time-height history of the cloud vertical structure from 0.4 to 8.0 km height above ground level. Since water droplets are very small in Park Range clouds and concentrations seldom exceed 300 cm^{-3} (see Part II), the radar return is virtually always due to ice particles. Greeson et al. (1979) have shown that attenuation losses in the low liquid water content clouds and at distances observed with the vertical pointing radar are not serious. Greeson (1983) has confirmed this conclusion with comparisons of radar determined values of cloud top compared with aircraft observations.

3. OBSERVATIONAL DATA

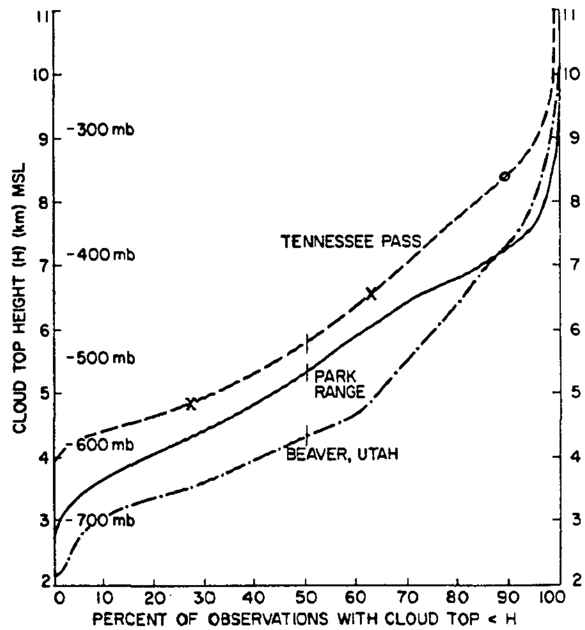
The observations for Tennessee Pass included in this analysis, were made during the late winter and early spring months of the 1979-80 and 1980-81 winter seasons. The site for these observations was at the Ski Cooper Mountain ski area, approximately 9 km WSW of Climax, Colorado. This site is at an elevation of 3201 m msl. The various results presented in this paper are based, respectively, on all usable observations recorded at one minute intervals.

The observations for the Park Range included in this analysis, were made during the 1981-82 winter season. The site for these observations was at the outlying parking area of the ski area at the south end of Steamboat Springs, Colorado. This site is immediately upwind of the Park Range of NW Colorado at an elevation of 2050 m msl. The various results presented in this paper are based, respectively, on all or part of 24,755 observations made at one minute intervals.

The observations for the Beaver, Utah site were made during the 1982-83 winter season. The site for these observations was just east of Beaver, Utah, at the upwind base of the Tushar Mountains, near the mouth of Beaver Canyon. The site is at an elevation of 1890 m msl. The various results presented are based, respectively, on all or part of 11,381 observations made at one minute intervals.

4. RESULTS

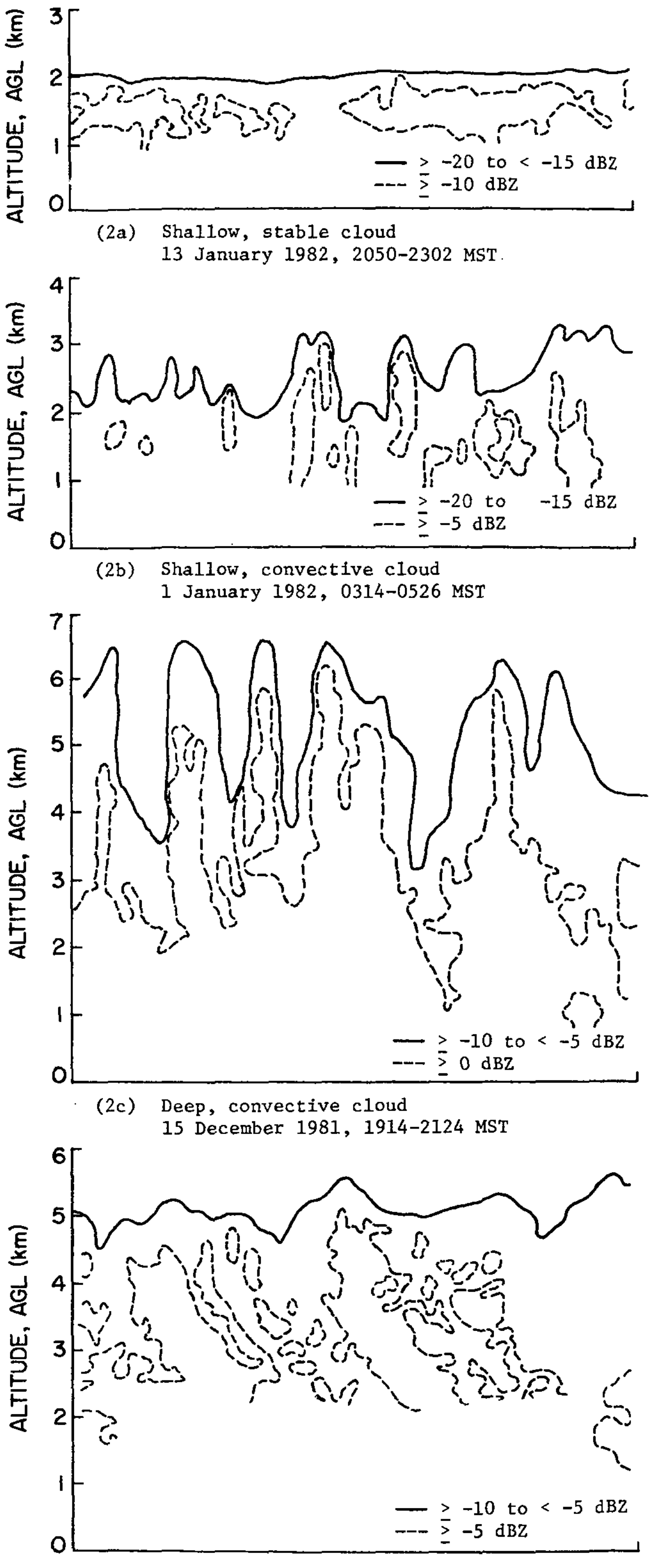
Figure 1 shows the cumulative percent of observations of cloud tops that reach to different elevations for each of the three sites. It can be noted that the median value of cloud top is the lowest at Beaver, Utah: 4280 m msl and near 60 Kpa. The median value of all cloud tops at the Park Range site is higher at 5350 m msl and at a pressure slightly greater than 50 KpA. The highest median value of cloud top was observed at Tennessee Pass at 5850 m msl near 50 Kpa. It can be noted that both the median and mean value of the cloud top elevation at Tennessee Pass are at an elevation slightly above 50 Kpa. These mean values are similar to those observed by Furman (1967) for three storms during the Climax experiments using a SO-12 X-Band radar. He reported mean heights for the three storms to



	Beaver, Utah	Park Range, Colo	Tennessee Pass, Colorado
Number of obs.	11,381	24,755	6824
Obs. frequency	1 min	1 min	1 min
Median	4280 m	5350 m	5850 m
Mean	4760 m	5468 m	6166 m
Standard deviation	1648 m	1393 m	1508 m
Radar elevation	1890 m	2050 m	3201 m

Figure 1. Cummulative frequency of cloud radar echo tops (msl) at three sites in the western United States

range from 4878 m to 6402 m msl with an extreme value of 8232 m msl. The range of the his mean values are shown on Figure 1 as X's and the extreme individual observation which he observed as a circle. The range of the mean values for his storm cloud tops bracket the mean and median values of the much larger Tennessee Pass observational sample. The cloud top climatologies in Figure 1, as in Furman's analysis, are for all cloud types not just for shallow, stable clouds which were the target of the experiment. In Figure 1, as in Furman's data for three storms, different types of cloud systems include shallow, stable clouds as well as convective cells and bands and deep synoptic scale cloud systems. The deeper convective and deep, stable cloud systems, as pointed out earlier, were considered to be naturally efficient and not the basic target clouds during the Climax experiments. The shallow orographic clouds targeted as having a potential for weather modification to augment precipitation during the Climax experiment were those that could be expected to be somewhat lower than the "mean" cloud top observed at the Tennessee Pass site. Grant et al., (1968) concluded that "the cloud system (with weather modification potential) is assumed to be embedded in the 700 mb to 500 mb layer...". The 50 Kpa level was used to index cloud tops for temperature partitioning as one of the criteria for the Climax statistical analyses.



(2a) Shallow, stable cloud
13 January 1982, 2050-2302 MST

(2b) Shallow, convective cloud
1 January 1982, 0314-0526 MST

(2c) Deep, convective cloud
15 December 1981, 1914-2124 MST

(2d) Deep, stable cloud system
21 December 1981, 1132-1340 MST

Figure 2. Radar reflectivity (dBZ) for four cloud types observed over western U.S. interior mountains.

The following sections explore the cloud characteristics for differing types of cloud systems for the present data set for the three western U.S. mountain sites.

4.1 Cloud Types

Cloud characteristics have been considered for four cloud types. These include shallow-stable; shallow-convective; deep-convective; and deep-stable cloud systems. The classifications are based on radar data but synoptic and precipitation data have also been utilized.

Figure 2a shows the radar display at two-minute intervals for a representative case of a shallow, orographic cloud over the Park Range. This shows the radar reflectivity values from 350 meters above ground level (AGL) to cloud radar top. The same type of display is used in Figures 2b, 2c, and 2d for the other types of cloud systems. All displays are from the Park Range site. The representative example of a shallow-stable cloud system in Figure 2a extends from 2014 to 2302 on 13 January 1982. This particular episode of a shallow cloud extended almost unchanged from 0745 MST on 12 January, through 13 January, to 0650 MST on 14 January. Precipitation for the 24 hour period on 13 January fell at an average rate of .125 mm/hr at the lower upwind elevations to an average rate of .425 mm/hr at the higher elevations.

Figure 2b shows a representative radar presentation for a shallow convective cloud system which occurred on 1 January 1982. The precipitation rate during the period for the display averaged approximately 0.2 mm/hr at the lower upwind elevations and up to an average of approximately 0.7 mm/hr at the higher elevations.

Figure 2c shows a representative radar presentation for a deep convective cloud system which occurred on 15 December 1981. The convective elements on 15 December 1981 went through several repetitions as was the case with the shallow convective cloud system on 1 January 1982. More isolated convective elements are also observed. The precipitation rate during the period of time shown in Figure 2c at the lower, upwind elevations was approximately 0.5 mm/hr and at the higher elevations was at an average rate of about 1.6 mm/hr.

Figure 2d shows a representative radar presentation for the deep, stable cloud system observed on 21 December 1981. The precipitation rate during the period used for this sample was at an average rate of 0.2 mm/hr at the lower upwind sites and up to an average rate of 1.9 mm/hr at the higher elevations. While this sample shows a little over two-hour interval, this particular episode extended for a period of about 6 1/2 hours on 21 December from 0744 to 1416 MST.

4.2 Frequency of Different Cloud Types at the Respective Sites

The frequencies of the different cloud types in this data set are shown in Table 1.

Table 1

Frequency of different cloud types

	Beaver	Park Range	Tennessee Pass
Shallow, stable	58%	53%	33%
Shallow, convective	9%	5%	9%
Deep, convection	15%	7%	21%
Deep, stable	11%	35%	37%

The percentages at Beaver total less than 100% since some of the Beaver, Utah data do not fit the classifications used in this paper. The frequency distributions of cloud types for the Park Range are for 4891 observations at two minute intervals during the periods 13-21 December 1981 and 11-16 January 1982. The frequency distributions for Tennessee Pass are based on 1760 observations at two- minute intervals during the periods 14 February-2 April 1980 and 16 February-27 March 1981 and 5 May 1981.

These frequency distributions show a predominant occurrence of shallow, stable clouds at all three sites. This limited sample suggests that shallow clouds constitute a higher percentage of the total cloud population in the Tushars of southwest Utah than at the Colorado sites. The Colorado sites, show a high frequency of deep, stable clouds as well as the high frequency of shallow, stable clouds. While it is believed that these data are generally representative, it must be remembered that at each site they are based on only a few storms in one or two particular seasons.

4.3 Cloud Top Climatology for Different Cloud Types

Median elevations of cloud echo tops for the respective cloud types are shown in Table 2.

Table 2

Median cloud top elevations in meters for elevation above ground (AGL) and above sea level (MSL).

	Beaver		Park Range		Tennessee Pass	
	AGL	MSL	AGL	MSL	AGL	MSL
Shallow, stable	2100	(3990)	2100	(4150)	2100	(5301)
Shallow, convective	2260	(4150)	3075	(5125)	2180	(5381)
Deep, convective	4320	(6210)	4940	(6990)	4340	(7541)
Deep, stable	4780	(6670)	4004	(6054)	4696	(7897)

The median cloud echo tops AGL are approximately the same at the various sites for the respective cloud systems. The elevation above sea level, consequently generally increases at the higher elevation sites. This would result in colder cloud top temperatures over the higher elevation mountain ranges.

4.4 Cloud Depth

Systematic observations of cloud bases are not available for these radar sites. For purposes of estimating cloud depth in this paper, it is assumed that cloud bases at the Park Range and Beaver radar sites are at around 400 m AGL and that they are 100 m AGL at Tennessee Pass. The primary estimates of cloud base are from estimates of the elevation at which cloud was observed to intersect the mountains. Balloon releases and rawinsonde observations have also been noted. Using these estimates for cloud base, estimates of cloud depths are presented in Table 3.

Table 3

Estimated median cloud thickness in meters.

	Beaver	Park Range	Tennessee Pass
Shallow, stable	1700	1700	2000
Shallow, convective	1860	2675	2080
Deep, convective	3920	4540	4240
Deep, stable	4380	3604	4596

The depths of the shallow, stable clouds at these sites, all located along continuous mountain ranges, are deeper than found for the cap clouds over the more isolated peak at Elk Mountain, Wyoming. Rogers and Politovich (1981) reported that typical Elk Mountain cap clouds have bases at 3000 m msl and tops at 4000 m msl and typically depths, consequently, of about 1000 m.

4.5 Cloud Top Radar Reflectivity

Cloud echo top reflectivity value for the Park Range and Tennessee Pass sites are shown in Table 4.

Table 4

Mean cloud top radar reflectivity values in DBZ.

	Park Range	Tennessee Pass
Shallow, stable	-15.0	-9.1
Shallow, convective	-12.7	-13.7
Deep, convective	-9.5	-9.6
Deep, stable	-10.9	-12.3

The median value of cloud top echo reflectivity values with all cloud types fall in the range of -9.0 to -15.0 dBZ at the Park Range and Tennessee sites. The differences between the dBZ values for deep, convective echo systems from other cloud types, is probably significant. Particularly with this radar echo type, and on occasion with other types, the boundary reflectivity value at cloud radar top and "no signal" zone above is much stronger than typical values.

4.6 Cloud Maximum Radar Reflectivities

Median values of cloud maximum reflectivity are shown in Table 5.

Table 5

Median values of maximum radar reflectivity in DBZ.

	Beaver	Park Range	Tennessee Pass
Shallow, stable	9.8	-8.24	-9.8
Shallow, convective	10.8	-5.8	+0.2
Deep, convective	10.8	+4.7	+5.2
Deep, stable	19.7	-2.9	-4.1

It can be noted that there is little difference between the Park Range and Tennessee Pass values but that there is a large difference between the value at these two sites and the one at the Beaver site. At the Colorado sites, essentially all precipitation occurs in the form of snow with a large portion falling as single crystal snowfall. It is believed that the reflectivity values at these sites reflect this form of precipitation. The higher median values at Beaver result from cases with higher reflectivity associated with the occurrence of rain, as distinct from snow, from accreted and aggregated snow crystals that are larger than the single crystals generally observed at the other sites; and from the sometimes presence of a bright band.

Considering the Colorado sites, the reflectivity values for shallow, stable clouds are the lowest and similar. Higher, but still negative values, are observed with deep, stable cloud systems. Still higher median reflectivity values are observed with convective systems and particularly with deep convection.

4.7 Height of Cloud Maximum Radar Reflectivities

The elevations above ground of the maximum radar reflectivities are shown in Table 6.

The median value of the height of the maximum reflectivity is in the lower portions of the shallow cloud systems. The height of the maximum reflectivity in Colorado clouds is, however, considerably more complex. The maximum reflectivity with deep convective clouds frequently occurs both in the lower and upper portion of the clouds. In some cases, highest reflectivity values are observed very near cloud top. It can also be noted with the deep, stable cloud systems that the most common elevation of maximum reflectivity is near mid-cloud level.

Table 6

Median height AGL of maximum radar reflectivities in meters.

	Beaver	Park Range	Tennessee Pass
Shallow, stable	1180	1480	1430
Shallow, convective	1620	1800	1360
Deep, convective	1620	2020 3870*	1690 3000*
Area-wide synoptic scale	1380	1860	2580

*Second zone of maximum reflectivity present in many of the observations.

In many cases with deep, stable cloud systems, and on occasions with shallow, stable clouds, maximum reflectivity values develop at mid-cloud levels and remain essentially at the same elevation for an extended period of time.

5. DISCUSSION AND CONCLUSIONS

Mountain clouds over the interior mountains of the western U.S. are sometimes deep, extensive, area-wide cloud systems. At other times they are shallow, orographically forced clouds that blanket the mountains. At still other times, they can be convective in nature. This discussion follows from the differing characteristics of these respective cloud systems.

5.1 Deep, Stable Cloud Systems

The median depth of these cloud systems is typically 4000-4700 meters and they typically extend to 6000 m to 8000 m msl, and occasionally to above 10,000 m msl. They frequently last for a few hours and occasionally for 5-10 hours as a large synoptic scale weather system passes through the region. These deep cloud systems are generally preceded and/or followed by shallow, stable blanket clouds or orograhically forced convective clouds as low-level moisture and/or instability is advected into the mountain regions in association with the synoptic scale disturbance. Deep, stable clouds extend to elevations that nearly always have cold temperatures which favor ice nucleation during winter(Rauber and Grant, 1986; Rauber et al, 1986; Rauber, 1987; Uttal, 1988). Maximum radar reflectivity values in these clouds are consistently greater than in the shallow, stable blanket clouds but still low. These clouds constitute some 30-40% of the orographic cloud cover over the Colorado mountains but apparently, based on the limited sample, a much smaller portion (11%) of the cloud cover in southwest Utah.

5.2 Shallow, Stable, Orographic Clouds

Shallow, stable, blanket clouds are typically the most frequent cloud type over the mountains of Colorado and Utah. The limited data sets suggest that they constitute over 50% of the cloud cover over the ranges directly exposed to approaching airflow and perhaps as little as 30-40% of the cloud cover over complex mountain areas such as Tennessee Pass that are protected from direct low-level lifting from some directions.

The median depth of these orographic blanket clouds is about 1700 m and their cloud radar echo tops extend to elevations from about 4000 to around 5000 m msl. While these clouds are relatively thin, condensate supply rates can be large as horizontal wind flow is rapidly lifted in passing over a mountain barrier. While the median maximum reflectivity is -8.24 DBZ in the Park Range, shallow, stable clouds, for example, values for individual cases range from less than -15 DBZ to greater than +10 DBZ. The median elevation of radar cloud tops in shallow clouds varies from about 2690 m to 4890 m msl at Beaver, 2650 m to 4250 m msl at the Park Range, and 4101 m to 5501 m msl at Tennessee Pass. These cloud radar echo tops for this cloud type were almost always at an elevation below the 50 Kpa level, which was used to index cloud top temperature for this cloud type which was hypothesized for the Climax experiments to have the main weather modification potential (Rauber and Grant, 1986; Rauber and Grant, 1987). The temperature at the 50 Kpa level, consequently, would almost always be equal to or colder than the actual cloud top temperatures. If the statistical partition of -20°C or warmer at 50 Kpa used in the Climax statistical analyses is considered (Mielke et. al, 1981), one can be confident that the actual cloud top temperature for these shallow clouds was at that 500 mb temperature or warmer. These shallow clouds are also the ones generally observed to have significant amounts of sub-cooled water for extended time periods (Rauber and Grant, 1983; Rauber et. al, 1986; Rauber and Grant, 1986).

5.3 Shallow, Convective Clouds

Shallow clouds were much less frequent in all study areas than the shallow, stable, orographic clouds. They were, however, typically only slightly deeper than the shallow, stable clouds. The general conclusions reached with respect to the weather modification potential for the more stable, shallow clouds may also apply to these clouds.

5.4 Deep Convective Clouds

The median depth of the deep, convective clouds in this study were from 3900 m to 4500 m with median cloud tops extending to elevations of 6200 m to 7500 m at the various sites. This cloud type constituted from 7% to 21% of the samples at the respective sites. The greater reflectivity values show the presence of larger hydrometers. Since over 95% of the deep convective clouds observed at the Park Range and Tennessee Pass sites had reflectivity values greater than -5 dBZ (75% > 0 DBZ), it must be concluded that even during their relatively short life span, a significant population of large ice particles form in these clouds either from accretion and/or aggregation.

6. SUMMARY

In summary, the cloud radar echo observations show that deep, stable and deep, convective cloud systems in the interior areas of the western United States during winter generally extend to elevations above the 50 Kpa pressure level where temperatures during winter are sufficiently cold to permit efficient ice nucleation processes to occur. Some liquid water can still occur in the lower portions of these clouds. Other studies, however, using parallel radiometric sensing and aircraft probes have shown, for the cases studied, that the amounts of liquid water present in these deep clouds is not large or present for very long periods of time (Rauber et al., 1986; Rauber and Grant, 1986). Shallow, orographically forced clouds, on the other hand, almost always occur in their entirety at elevations below the 50 Kpa level where wintertime temperatures are variable with respect to temperatures at which natural ice nucleation can be either efficient or inefficient.

7. ACKNOWLEDGEMENTS

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