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TEMPORAL VARIATIONS OF CLOUD LIQUID WATER DURING WINTER STORMS OVER THE MOGOLLON RIM OF ARIZONA

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Abstract. Several winter storms were observed by various instrumentation systems over the Mogollon Rim of Arizona during early 1987. The storms commonly displayed considerable temporal variability in CLW (cloud liquid water) as monitored by a microwave radiometer. The vertically integrated liquid amounts were often inversely correlated with the height of the cloud tops as measured by radar, suggesting that periods with shallow clouds and warm tops may be the most seedable. However, there were important exceptions to this general rule, associated with strong low-level horizontal winds that presumably produced significant uplift and more condensate than nature could convert to snowfall.

Three storm episodes were selected for illustration of the short-term variability in CLW. It is shown that shallow clouds with abundant liquid often occurred at the beginning and ending phases of a storm, and sometimes in the middle portion as well. However, the timing and duration of the CLW periods would be very difficult to forecast, and limiting seeding operations to just CLW periods would usually be impractical. Rather, seeding would probably need to be continuous throughout most storm episodes because of inability to respond to short-term variations in available liquid water. It is suspected that the situation is similar for other mountain barriers of the West.

1. INTRODUCTION

Scientists involved with seeding winter storms over the mountains of the Western United States have long been aware that the storms' temporal variations are often substantial and rapid. Precipitation records or radar cloud top observations are just two indicators of these variations. Yet, in our attempts to understand the processes involved in complex storms, it is often necessary to generalize. References are made to "orographic" storms or "shallow" versus "deep" storms. A storm may be divided into prefrontal and postfrontal phases for ease of comprehension. But a more detailed examination of any storm or phase so designated usually reveals that conditions varied considerably with time and distance and also from storm to storm.

The problem of defining storms or their phases is particularly difficult for randomized seeding experiments, and serious compromises are often made where the experimental unit becomes the 24-hour day or some other rather arbitrary unit. While improvements in instrumentation and knowledge have gradually aided our ability to define portions of storms or cloud systems that are reasonably similar to others, the problem of definition is still difficult, especially if it must be done prior to an episode when a randomized seeding decision is called for. The problem has likely contributed to the limited success of several seeding experiments because quite dissimilar cloud systems may be grouped into the same category for statistical analysis.

This paper illustrates some of this variability in important storm characteristics, specifically over the crestline of the Mogollon Rim of Arizona. In particular, the availability of CLW (cloud liquid water) is addressed. The implications for seeding strategies are also discussed.

2. OBSERVATIONS

The most important characteristic of winter storms for the weather modification operator is CLW, especially the portion that is supercooled, because this is the substance that the operator attempts to convert to snowfall. Those storms or portions of storms that naturally convert all CLW to snowfall cannot generally have their snowfall augmented by seeding. (Some limited potential may exist between ice and water saturation that will be ignored here.) CLW has also proven to be one of the most difficult parameters to routinely monitor. Aircraft measurements must be limited to brief (2 to 4 h) portions of the storms and are usually made at least 600 m above the highest terrain within several kilometers of the flight path. Icing rate meters on towers sample only the lowest portion of the cloud over the particular site, which may not be representative of conditions only a few tens or hundreds of meters higher (Boe and Super, 1986). Yet, recent work has indicated that much, perhaps most, of the CLW in winter orographic storms lies between normal aircraft sampling levels and surface towers (e.g., Holroyd and Super, 1984).

Recently, microwave radiometers have made possible the continuous observation of total CLW along their field of view, which has substantially increased understanding of winter storms over the mountains. Examples of studies using these new instruments, sometimes in conjunction with aircraft measurements, include Holroyd and Super (1984), Rauber et al. (1986), Rauber and Grant (1986), and Boe and Super (1986).

During mid-January to mid-March 1987, a microwave radiometer, a sensitive 5.4-cm radar, and a high-resolution precipitation gauge were collocated at Happy Jack, Arizona, on the crestline of the Mogollon Rim. The crest location is important because CLW passing overhead may be considered excess to that liquid which nature is converting to snowfall. Cloud droplets typically evaporate a short distance downwind in the lee subsidence zone.

The Happy Jack site, located about 55 km south of Flagstaff, and its instrumentation have been described by Super and Boe (1988). Nearly continuous records of vertically integrated CLW, cloud top height and structure, and precipitation rate were obtained through several storm episodes. Three episodes have been selected to illustrate some common features and some differences among the storms, as well as their temporal variability over the observing site.

3. STORM VARIABILITY

Examination of the several 1987 storms revealed that their character usually changed considerably with time. The Arizona storms were almost all associated with synoptic scale disturbances. They contained such diverse cloud forms as cirrostratus, altostratus, stratus, orographic stratus or stratocumulus, downwind anvils, and embedded convection. Such clouds can be with or without the presence of CLW or of precipitation.

The presence of high clouds (above 6 km or 20 000 ft m.s.l.), physically connected to lower clouds by particles producing a radar echo, was usually a good indicator that CLW values would be suppressed. Such high clouds will frequently have tops colder than -30°C and therefore may be contoured in typical nighttime satellite infrared images. Analysts with the Sierra Cooperative Pilot Project in California have identified the "cirrus passage" (the advection of the rear edge of a high cirriform cloud band over the project area) as a frequent indicator of the initiation of greater values of CLW in the lower clouds (Reynolds, 1988). But high tops themselves have no effect if the ice particles do not fall into the lower clouds. The same inverse correlation of cloud tops and CLW frequently was apparent in the Mogollon Rim clouds, but there were exceptions in the observations.

In a similar fashion, the presence of high concentrations of ice particles and associated increased precipitation usually precluded the presence of abundant CLW as shown by Rauber et al. (1986). The ice particles rapidly grow at the expense of such CLW and consume it. Such high concentrations are typically associated with periods in which the cloud tops are high. Nucleation of ice particles is commonly thought to be more efficient at the cold temperatures found in high cloud tops, although factors other than temperature may be important (Hobbs and Rangno, 1985).

Figure 1 and two similar figures to follow plot three important storm characteristics on the same time axis for the entire storm episode. The hourly precipitation amounts from the high-resolution gauge are plotted at the bottom of Figure 1. The radiometer vertically integrated CLW, showing three general periods of liquid in the clouds above Happy Jack, is plotted in the middle of the figure. A time-height diagram of echoes from the 5.4-cm Skywater radar is plotted at the top of the figure.

The radar echo plot in Figures 1, 2, and 3 was constructed from RHI (range height indicator) scans made to the north of Happy Jack every 5 minutes. The equivalent radar reflectivity factor was averaged for the 0.1 km by 1.0 degree range bins located within 2.2 to 3.3 km horizontal distance of the radar. This range was chosen to maximize radar sensitivity while minimizing the ground clutter return. Up to four levels of equivalent reflectivity factor are shown on all radar plots: Any values exceeding 0 dBz are shown in black; those between -10 and 0 dBz are gray; the next lighter shading represents -10 to -20 dBz; and the lightest, -25 to -20 dBz, represents the weakest echoes detectable with the particular radar system. While the greater dBz values generally indicate higher precipitation

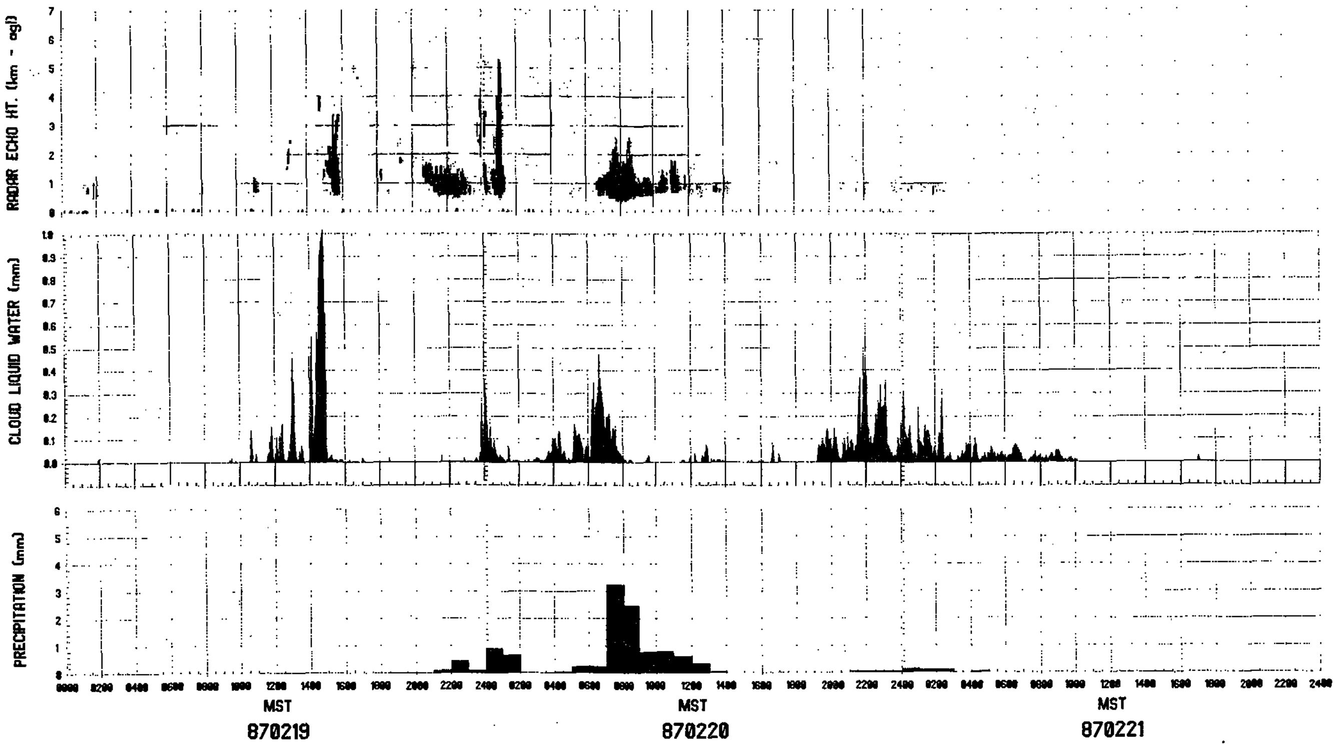

Figure 1. - Time history of precipitation, CLW, and radar echos for February 19-21, 1987.

rates, the relationship can be complex for snow and ice particles, as discussed by Smith (1984).

Figure 1 could also include such variables as temperature, dewpoint, winds, and tower icing rates to show the passages of various synoptic features. Such variables were considered in detailed storm analysis but were omitted from the figures in this paper for the sake of clarity.

The storm episode illustrated in Figure 1 lasted about 48 hours. This episode was chosen for presentation first because it shows wide variations in cloud structure over the storm period. During this storm, a low and trough system over New Mexico retrograded into central Arizona and then resumed a southeastward movement out of the project area.

After the passage of some low cirriform clouds, the episode began with the slow rise of cumulus clouds to the cumulonimbus stage from about 1000 to 1700 [all times l.s.t. (local standard time)] on February 19. Cloud liquid water amounts varied considerably with time, exceeding 1.0 mm at 1445 and then rapidly diminishing to almost zero as the radar echo intensified. The clouds were mostly confined to the higher terrain and therefore appeared to be under mesoscale control, but satellite photos showed enough neighboring clouds to suggest synoptic control.

From about 1700 on February 19 to 0200 on February 20, the clouds were basically stationary debris from earlier convection. This generated a snowfall containing aggregates. Moderate CLW existed for only about 1.5 hours centered near midnight. As the system intensified, CLW amounts increased until almost 0700 on the 20th. Then the high clouds became connected to the lower clouds, and a heavy snowfall consumed the CLW.

After 1200 on February 20, the clouds became towering cumulus until 1800; but the convection was not as tall as on the previous day, and amounts of CLW were quite limited.

At 1800 the low began to pass to the south of the project area as it resumed a southeastward movement. Area winds shifted to being strongly from the northeast. The flow produced a low orographic stratus (upslope) cloud generally confined to the high terrain of the Mogollon Rim. The cloud system produced many hours of CLW and only trace precipitation, suggesting it was very suitable for seeding.

Figure 1 illustrates the general tendency for clouds with tops under 6 km m.s.l. (mean sea level) [3.7 km a.g.l. (above ground level) in the figure], not connected to higher cirriform clouds, to have CLW. It illustrates a case with CLW at both the start and end of an episode as well as within, all of which appeared in low clouds.

An important counterexample to the more typical storm sequence occurred on January 30-31, 1987, as illustrated in Figure 2. (A power outage after 0500 on the 31st interrupted the radar data for about 3 hours. Further, CLW data were interpolated between 1915 and 2115 on the 30th when melting snow on the reflector gave erroneous readings.) The common appearance of an abundance of CLW from a low stratiform cloud at the end of the episode is illustrated well. But the unusual feature is the very strong CLW signal during the night hours when the radar tops were high and the precipitation rates were moderate. Strong flow over the barrier apparently produced much more CLW than could be consumed by the falling ice particles from the deep cloud system. Acoustic sounder winds at 300 m a.g.l. over Happy Jack were about 14 m s^{-1} from the northeast at the time of peak CLW late on the 30th.

An aircraft mission was flown over Happy Jack (elevation 2.3 km m.s.l.) from shortly before 1000 to 1100 on January 31. The King probe on the aircraft measured mean liquid water contents near 0.15 g m^{-3} with peaks as high as 0.7 g m^{-3}. Ice particle concentrations averaged less than 0.1 L^{-1} in the upper portions of the layer cloud which had a top at 3.8 km m.s.l. where the temperature was -9°C. The University of Wyoming King Air 200T aircraft, certified for flight into known icing conditions, was unable to stay in the cloud for more than several minutes at a time due to heavy airframe icing. Yet the average radiometer vertically integrated CLW was only 0.2 mm during the aircraft mission. This suggests that aircraft sampling would have been impractical during the higher CLW periods experienced late on the 30th and from 1300 to 1500 on the 31st.

Examination of all 1987 aircraft sampling periods over Happy Jack revealed that the surface radiometer never observed a mean hourly CLW amount greater than 0.22 mm when the aircraft was nearby - essentially the amount present during the January 31 flight. While the vertical distribution of liquid water may vary considerably within and between storms, the heavy icing encountered on that mission suggests that aircraft sampling might

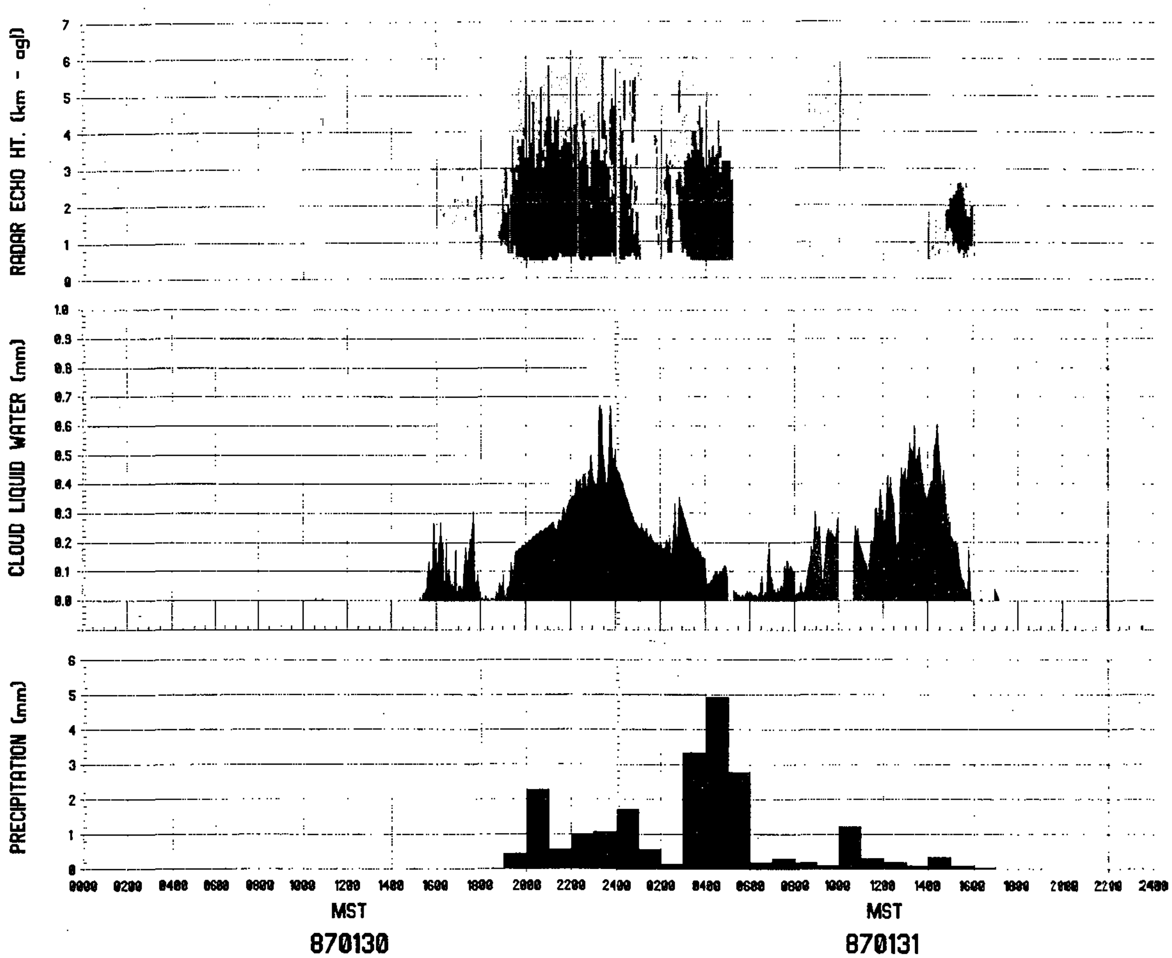

Figure 2. - Time history of precipitation, CLW, and radar echos for January 30-31, 1987.

well be impractical when wetter clouds are present. About 10 percent of all hours with CLW detectable by the radiometer were in excess of 0.2 mm during the 1987 field season. One hour exceeded 0.6 mm. This suggests that aircraft measurements of orographic clouds may underestimate actual liquid water contents for two reasons: (1) the impracticality of flying near the mountainous terrain noted earlier, and (2) the inability to fly in the wetter clouds for more than very brief periods.

The varied character of the storm that brought the largest snowfall to the region in several years is illustrated in Figure 3. The episode began, as usual, with moderate CLW in low clouds. It then changed to high CLW contents from clouds with moderate precipitation and radar tops of a middle height. The presence of light CLW with high radar tops and an extremely high precipitation rate is shown for the daytime hours of February 24. This illustrates that even heavy precipitation may not totally consume the CLW presumably being produced at low levels by the strong winds then present (sometimes exceeding 17 m s^{-1} according to the acoustic sounder). Thereafter, the patterns are similar to those in Figure 1 with high CLW amounts coexisting with shallow clouds.

4. DISCUSSION

Several winter storms over the Mogollon Rim of Arizona were investigated during early 1987 using radar, a microwave radiometer, a high-resolution precipitation gauge, and various other observing systems including a cloud physics aircraft for portions of the episodes. These measurements have revealed a number of important features of interest to cloud seeding.

As has been shown in some earlier studies, there was a general tendency for CLW to be present over the crest within shallow clouds, but limited in amount or absent in the presence of deep clouds having cold tops. The beginning and ending portions of the storm episodes frequently had shallow clouds and relatively abundant CLW, suggesting they were suitable for seeding aimed at snowfall augmentation. Additional periods with CLW were in evidence during the middle of some episodes when high clouds became disconnected with lower cloud decks.

Important exceptions to the general rule were found as illustrated in Figure 2. Very abundant CLW existed for many hours during a period of moderate snowfall from deep clouds. Apparently, the strong near-surface winds produced far more uplift and associated condensate than nature could convert to snowfall. Even the heavy snowfall of February 24 (Fig. 3) failed to fully utilize available condensate although CLW amounts were limited to near 0.05 mm in this case.

Another important point emerges from the figures shown. While some periods with abundant CLW were of many hours' duration, others were brief. Further, the transition from periods with abundant CLW to periods with little or none was often very rapid. This suggests that a seeding strategy based on a forecast of suitable conditions will often fail. Even responding to observations of existing conditions would be challenging, especially for airborne seeding with the necessity to

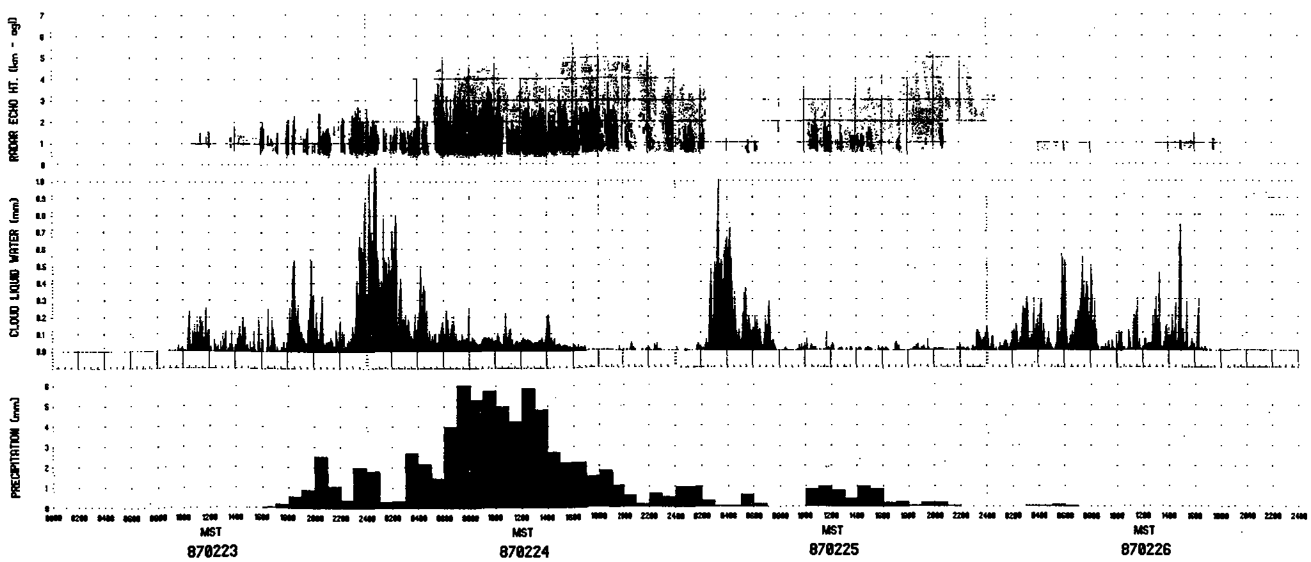

Figure 3. - Time history of precipitation, CLW, and radar echos for February 23-26, 1987.

file flight plans an hour or so before takeoff. The only reasonable approach may be to attempt to seed throughout the storm episode with the assumption that seeding will not significantly decrease snowfall during periods without excess CLW. Fortunately, there is evidence that this assumption may be valid, at least in the northern Rockies (Super, 1986; Super and Heimbach, 1988).

This paper addresses only temporal variability of CLW above a particular observing point. Studies in other regions (e.g., Rauber and Grant, 1986) and aircraft measurements over the Mogollon Rim have demonstrated considerable spatial variability as well. Thus, when the observations above any mountain site indicate abundant CLW, the atmosphere may have no liquid some kilometers away. And, of course, the situation may be reversed a short time later. This further emphasizes the difficulty of attempting to rapidly respond to indications of probable seedability from any practical observing network.

In summary, measurements from several Arizona winter storms have indicated considerable temporal variability in storm characteristics, particularly in the amount of liquid water available. This implies that the seeding potential of the storms also varies markedly with time. Super (1986) suggested that seeding Montana winter storms was highly effective during a small portion of the 6-hour blocks investigated, but had little or no effect for the other periods. That may be partially due to similar variations in CLW. If only limited periods with abundant CLW exist, only those periods have the possibility of substantial snowfall increases when seeded.

Future seeding experiments should routinely monitor the CLW content, preferably with a radiometer. Statistical analysis of randomized experiments should be considerably "sharpened" if experimental periods are partitioned by CLW availability. Physical experiments that attempt to directly detect seeding effects (e.g., Super and Heimbach, 1988) also need to monitor whether CLW is available.

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