"REVIEWED"

WINTERTIME CLOUD LIQUID WATER OBSERVATIONS OVER THE MOGOLLON RIM OF ARIZONA

Arlin B. Super and Bruce A. Boe
Bureau of Reclamation
Montrose, CO 81401

ABSTRACT

Liquid water, wind and other meteorological observations were made over the Mogollon Rim of Arizona from mid-January through mid-March 1987. A dual-channel microwave radiometer provided cloud liquid water (CLW) measurements. Winds were sampled by a variety of devices including a doppler acoustic sounder, tower-mounted anemometer and vane, rawinsondes and an aircraft equipped with an inertial navigation system. Temperature observations indicated that the bulk of the CLW was supercooled.

Distributions of vertically-integrated CLW are examined from the thirteen synoptic scale storms that occurred during the observational period. It is shown that most hourly means were less than 0.1 mm, implying limited liquid water contents. While some diurnal variation in CLW occurrence was found, the early morning maximum indicates it was not solar-forced and may have been the result of the random passage of storms. The durations of CLW episodes are shown to have varied from an hour to over a day.

The majority of CLW occurred with southwest winds although a secondary maximum was apparent with northeast flow. Both are upslope for the observing site.

The horizontal flux of CLW was estimated hourly over the crestline of the Rim, just upwind of the lee subsidence zone. Total flux per storm varied widely and three large storms produced three-quarters of the total (two month) flux. However, it is shown that the low hourly values of CLW produced much of the total flux because of their frequent occurrence. The cumulative frequency distribution of the 260 h with flux estimates is shown to be similar to that previously reported for the Grand Mesa, CO, 600 km to the north.

The total CLW flux for the two month sampling period is estimated to have been roughly half the mean annual streamflow from the same area. This suggests that significant potential may exist for winter precipitation augmentation through cloud seeding on the Mogollon Rim.

1. Introduction

It has long been recognized that supercooled liquid water (SLW) is the required "raw material" for augmentation of precipitation by seeding winter clouds over mountain barriers (Ludlam, 1955). For detailed discussion of the processes involved see Dennis (1980). Some additional but limited potential may exist in conditions between ice and water saturation which will be ignored here. The amount of SLW that can be converted to snow on the ground will also not be considered in this paper. Here we are concerned with the frequency of occurrence of SLW and its magnitude and duration. Also, the flow or "flux" of SLW over the barrier will be estimated as this represents the absolute upper limit for precipitation augmentation potential.

It would be impractical for any cloud seeding program to convert all the seasonal SLW flux to snowfall because of constraints such as timely delivery of seeding agents to desired cloud regions, limited time available for ice crystal growth and fallout, possible suspension criteria imposed during wet periods, etc. However, if observations were to show the seasonal SLW flux to be only a very small fraction of natural annual streamflow from a region, the potential of seeding to augment the streamflow through increased snowfall would likewise be very limited on a percentage basis. Admittedly, even a small percentage increase in streamflow might represent a large volume of water in some drainages (e.g. the Sierra Nevada Mountains). However, small percentage increases are difficult to demonstrate with confidence.

On the other hand, if the SLW flux was found to be a large fraction of annual streamflow, this would suggest a possible large potential for cloud seeding. Estimation of the actual potential would involve consideration of the various constraints already noted, and a seeding program would be required to demonstrate the seasonal precipitation increase practical to achieve. However, observation of SLW and its flux over a barrier is clearly a very important first step toward estimating seeding potential.

While the importance of SLW flux has been recognized for many years, only recently has it been practical to routinely observe it. Development of the microwave radiometer (Hogg et al., 1983) has made possible continuous measurements of the integrated amount of liquid

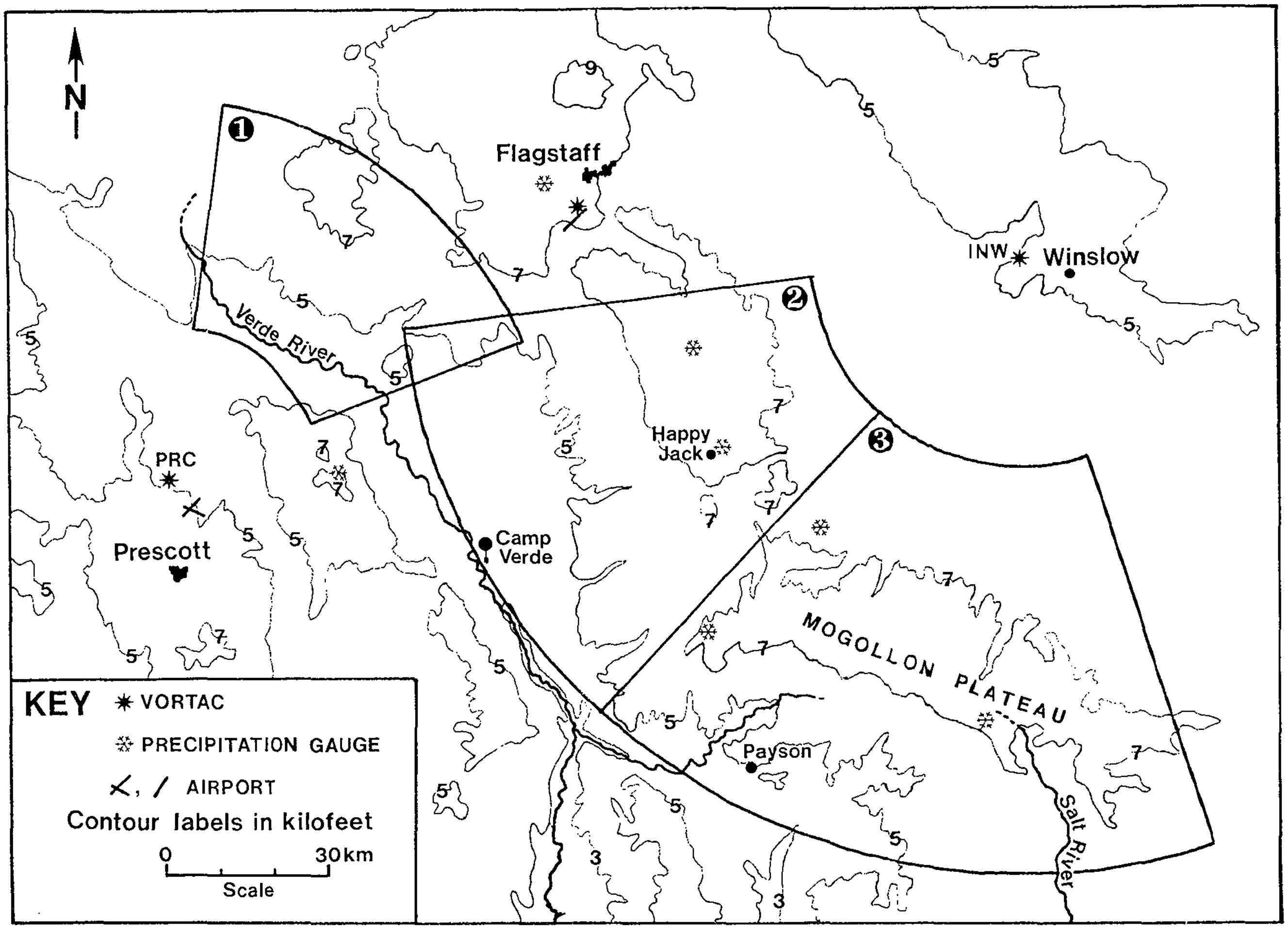

Fig. 1. Map of the Mogollon Rim project area in Arizona. Aircraft operations were concentrated in Area 2, especially near Happy Jack.

water above the instrument. When the liquid water is known to consist entirely of cloud droplets and not rain drops we will refer to it as cloud liquid water (CLW). When the CLW is supercooled, the radiometer measurements can be combined with wind speed and SLW flux estimates can be made as reported for the Grand Mesa, Colorado, by Boe and Super (1986), and Thompson and Super (1987).

2. Observations

A cooperative agreement between the U.S. Bureau of Reclamation (Bureau) and State of Arizona made possible initial observations and analyses of CLW over the Mogollon Rim. A field program was conducted from January 14 to March 17, 1987, at the Happy Jack Ranger Station, about 55 km south of Flagstaff, Arizona (Fig. 1). The Happy Jack (HJ) site was chosen primarily because of its location on the crestline of the Mogollon Rim, with electrical power availability and ease of access important secondary considerations. The site is at an elevation of 2290 m msl on a portion of the Rim that has its long axis extending NNW-SSE. The terrain gradually slopes toward the Verde River Valley to the SW and Little Colorado River Valley to the NE.

Bureau instrumentation operated at HJ included a microwave radiometer similar to that described by Hogg et al. (1983), a doppler acoustic sounder, a sensitive 5.4 cm radar (SWR-86, sensitivity -27 dBz at 3 km range), an aspirated Particle Measuring Systems (PMS) 2D-C probe, a high resolution precipitation gage and sensors for monitoring near surface air temperature, dewpoint temperature, wind vector and icing rate. The last three instruments were located about 30 m above the top of a small hill near HJ. In addition, two technicians lived at the site and made routine weather and pilot balloon (pibal) observations from about 0600-2400 (all times MST) each day.

The University of Wyoming King Air 200T cloud physics aircraft sampled several cloud systems during the field season in the HJ vicinity. Horizontal passes were typically flown at height intervals from cloud top or 5200 m (17,000 ft) msl, whichever was lowest, down to the lowest permissible flight altitude of 2930 m msl. Passes were generally parallel to the wind and directly over HJ. These observations showed the distribution of CLW, winds, and temperature, among other parameters.

The radar system was operated in an RHI mode and made one scan per 5 min from the zenith to 6 deg elevation angle toward the north. These observations showed the cloud (radar) top and top character, whether stratiform or convective.

The microwave radiometer (hereafter radiometer) was used in a vertically-pointing mode to provide the integrated amount of liquid water and water vapor passing directly above the unit. Radiometer data collected during cloud-free (and thus liquid water-free) conditions were examined to determine the magnitude of the drift of the instrument. Much of the time baseline drift was sufficient to necessitate a correction of ±0.01 to 0.03 mm, but care was taken to maintain a zero or slightly negative baseline for liquid water. Thus, in all cases with positive readings, liquid water actually existed above the instrument.

It is noteworthy that the work of Heggli et al. (1987), partially based on the radiometer used in this study, indicated that radiometer-measured values of water vapor are very likely within 15% of actual values. Further, two similar radiometers operated near one another yielded very similar liquid and vapor values. The absolute accuracy of the liquid values is difficult to independently verify because of the lack of a suitable standard.

Other instruments provided wind measurements so that CLW flux could be estimated. These included tower-mounted sensors and a doppler acoustic sounder, all at HJ, rawinsonde observations from Camp Verde west of HJ (see Fig. 1), and aircraft-measured winds provided by the University of Wyoming King Air during some storms. Rawinsondes were released at normal synoptic times (1200 and 0000 GMT) on most days, with additional soundings at about 6 h intervals during periods of special interest. Since the observations were just upwind of the crestline in the prevailing southwesterly flow, the flux estimates approximate the amount of liquid water naturally available just prior to depletion in the lee subsidence zone. This can be thought of as nature's surplus water, not converted to precipitation due to the inefficiencies of the precipitation process in the winter clouds over the Mogollon Rim.

The radiometer does not respond to dry snow in the atmosphere or on the reflector, but wet snow on the reflector can cause serious overestimates of both liquid and vapor (Hogg et al., 1983). Both air temperature near the radiometer and the temperature of the reflector itself were monitored at 5 min intervals from January 29 to the end of the field season. Further, the type of snow and condition of the reflector were frequently noted during all storms, and the reflector was kept essentially clear of snow and water by a large blower and manual wiping when required. Even so, three brief periods with the wet snow problem existed during one storm. These three periods were obvious because of abrupt, several-fold increases in liquid and vapor values. Linear extrapolation from adjoining periods with valid data was used to estimate the CLW in these cases.

A more serious problem occurs when rain is present. While Hogg et al., (1983) used spraying tests to show a wet reflector has little effect on the readings, the presence of rain in the atmosphere above the unit can result in large increases in liquid water. The radiometer is unable to distinguish between that liquid water in the form of tiny cloud droplets (CLW of interest to cloud seeding potential) and that due to much larger rain drops. The mixed cloud droplet/rain drop condition was a problem during all or portions of only three storms as indicated by air and radiometer reflector temperatures above freezing, measured precipitation at HJ and/or observer notes of rain or melting ice hydrometers. The mixed cloud droplet/rain drop observations were excluded from the analysis to be presented. Section 3 will discuss the additional exclusion of a limited number of hours typed as mesoscale convective. A total of 260 h remained with CLW observations of which 225 h occurred after continuous temperature measurements started at HJ on January 29. (The earlier CLW data were supercooled according to National Weather Service hourly observations from Flagstaff or aircraft measurements).

Of the 225 h with temperature measurements at the radiometer site, 76% had mean temperatures from -7.4 to 0.0°C so the CLW was totally supercooled. The HJ site was rarely in cloud so CLW was above it and, therefore, almost always colder than the surface during storms.

Of the remaining 24% of the hours with the radiometer site warmer than 0°C, only 10 h were above 5.0°C. Assuming a typical lapse rate of 0.6°C per 100 m, the 0°C isotherm would be within 800 m of the radiometer with surface temperatures between 0.1 and 5.0°C. The vertical distribution of CLW was observed only when the aircraft was present and then only higher than 640 m above HJ. However, it appears reasonable to assume that at least some of the radiometer-observed CLW was supercooled in all but a small portion of the hours.

Happy Jack precipitation data and observer notes were examined for all hours with the radiometer site above 0°C when CLW was observed. Most of these hours had no observed precipitation. Those that did usually had very light precipitation. Frequent manual checks of the radiometer reflector kept it dry in such instances so the CLW observations to be discussed are believed to be valid; that is, not due to a wet reflector or rain. Virga may have been above the radiometer in some few cases but CLW observations accompanying surface temperatures above 1°C rarely exceeded 0.2 mm. Therefore, the large majority of CLW values are believed to be due to tiny cloud droplets, usually supercooled. Thus, while further discussion will usually refer to CLW, it can be considered a first approximation of SLW.

3. Storm Typing

A classification scheme was developed for the Arizona storms observed during mid-January to mid-March 1987. A storm episode was defined by the nearly continuous presence of CLW over HJ and/or hourly precipitation recorded by any gage in a seven gage network (see Fig. 1), having no interval >2 h during which neither SLW nor precipitation was observed. Precipitation gage resolution was 0.13 mm except at HJ where it was 0.05 mm. Some additional brief (<2 h) periods with CLW and/or precipitation were detected but were considered too insignificant to be classified as storms. These episodes were excluded from the analyses to be discussed.

Storm episodes were categorized by two characteristics, the scale of the storm and the presence or absence of convection. Convection was identified by examining the following: radar time-height and range-height indicator plots, the character of the liquid trace recorded by the radiometer, aircraft observations, hourly weather reports from Flagstaff, time lapse movies taken from Payson (Fig. 1.), stability parameters derived from Camp Verde soundings, visual satellite imagery, and observations by the HJ crew. Those storms clearly associated with synoptic-scale features were so classified while the others were categorized as mesoscale. If an episode had convection present for half or more of its duration, it was classified as convective, otherwise it was termed stratiform.

Ten storm episodes were designated synoptic stratiform (SS), three were synoptic convective (SC) and three were mesoscale convective (MC). Mesoscale stratiform cases were not observed. The SS and SC cases will be considered together because of similar characteristics; they were generally stratiform clouds with some (usually weak) embedded convective elements in the SC cases. The SC cases contributed little to the overall population because only three episodes occurred and most of the hours from two of these were excluded because of rain-caused ambiguities in CLW values. It will be shown in Table 1 of Sec. 7 that the total horizontal flux of water from the two latter cases, including their likely predominate contribution from raindrops, was about 14% of the flux due to cloud droplets alone from the other storms observed.

The few MC cases were markedly different from the SS and SC storms. They were predominately convective with isolated or semi-isolated turrets, and were sometimes induced by solar heating. These cases contributed little to the seasonal precipitation and CLW flux, and they will be ignored in the discussion to follow.

4. Temporal Distribution of CLW

The frequency distribution of hourly mean amounts of vertically-integrated CLW is given in Fig. 2. For the 260 h with measured CLW, 66% had amounts less than 0.1 mm. Only 1 h exceeded 0.6 mm. This distribution is similar to the distribution of SLW reported by Super et al. (1986) for the Grand Mesa of west-central Colorado. To put these values into perspective, a cloud of 1 km vertical extent with uniform CLW content of 0.1 g m^{-3} would yield a vertically-intergrated liquid water amount of 0.1 mm. This suggests that most clouds over HJ had mean liquid water contents of no more than a few hundredths to one or two tenths gram per cubic meter of air. The King Air aircraft observations over HJ usually showed values in this range. Such values are typical of winter orographic clouds at a number of locations in the Rocky Mountain (Cooper and Marwitz, 1980; Rauber and Grant, 1986; Super and Heimbach, 1988).

The diurnal variation of CLW was examined by noting the number of times during the field program the hourly mean CLW amount exceeded zero for each of the 24 hours of the day. The range of occurrences was from 8 to 16. The period from 1700-2300 (all times MST) was a relative minimum with 8-9 occurrences per hour. While the maximum was 16 at 1100-1200, values of 10 existed only 2 h earlier and later. A broad general maximum was apparent from about 0300-0900, with 12-13 occurrences per hour. On average this maximum ws 46% greater than the evening minimum.

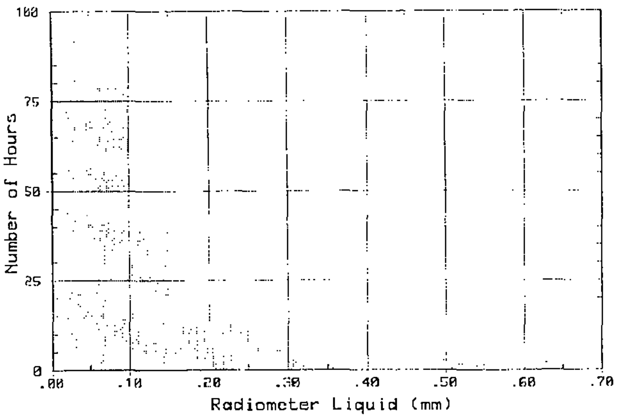

Fig. 2. Distribution of 1 h means of vertically-integrated cloud liquid water amounts.

It is not apparent whether the diurnal variation is significant, or simply the result of the random passage of synoptic scale weather disturbances during the limited two month observational period. Additional measurements would be needed to clarify this issue. At any rate, no pronounced afternoon maximum is apparent so solar heating was not a strong factor in CLW production. This adds credibility to the storm typing method as all these cases were classified as synoptically triggered.

A CLW (not storm) episode was defined, somewhat arbitrarily, by the near-continuous presence of CLW as indicated by the 1 h mean radiometer data. Periods up to 2 h without detectable CLW were allowed to occur within an episode. This definition resulted in 21 episodes from the 13 SS and SC storms.

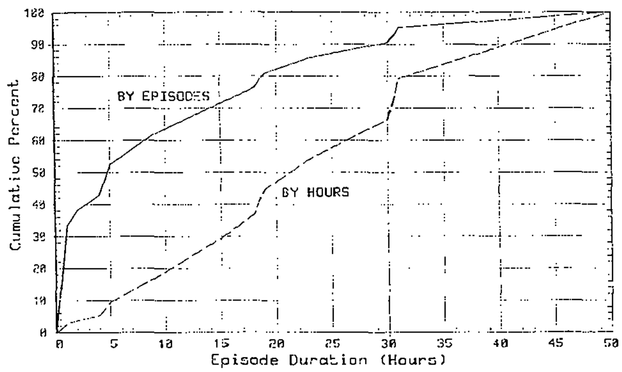

Fig. 3. Cumulative distributions of cloud liquid water (CLW) episodes (solid line) and hours with CLW (dashed line) as functions of episode duration.

The cumulative distributions of the 21 CLW episodes, and the hours with CLW present, are shown on Fig. 3 as functions of episode duration. Only 242 h of CLW observations are considered here, as opposed to 260 h in Fig. 2, because missing data prevented definition of episode durations in some cases. It is seen that about half the episodes were less than 5 h duration. Only 14% (3) of the episodes lasted over 24 h while 33% (7) lasted only 1 h. Over half of all hours with CLW were associated with the 4 episodes of duration $\geq$23 h. Conversely, the 11 shortest episodes, $\leq$5 h duration, yielded only 10% of all hours with CLW.

5. Relationships Between CLW and Wind Direction

Hourly mean wind directions were recorded at 30 m agl on a tower located atop a 70 m hill near HJ. These observations were not available until January 28 so only 233 h exist with both wind direction and detectable CLW data for SS and SC storms. These were used to construct Fig. 4 which shows the frequency distribution of occurrence of detectable CLW, whatever its magnitude, vs wind direction. Clearly most hours with CLW present were with SW winds, with 53% of all cases between 195-255° true. A secondary maximum existed for NE flow, with 24% of all cases having winds from 30-90°. Both SW and NE flows are approximately perpendicular to the axis of the Mogollon Rim in the HJ vicinity, so both represent upslope flow. Such flow should force orographic lifting and thereby enhance CLW production.

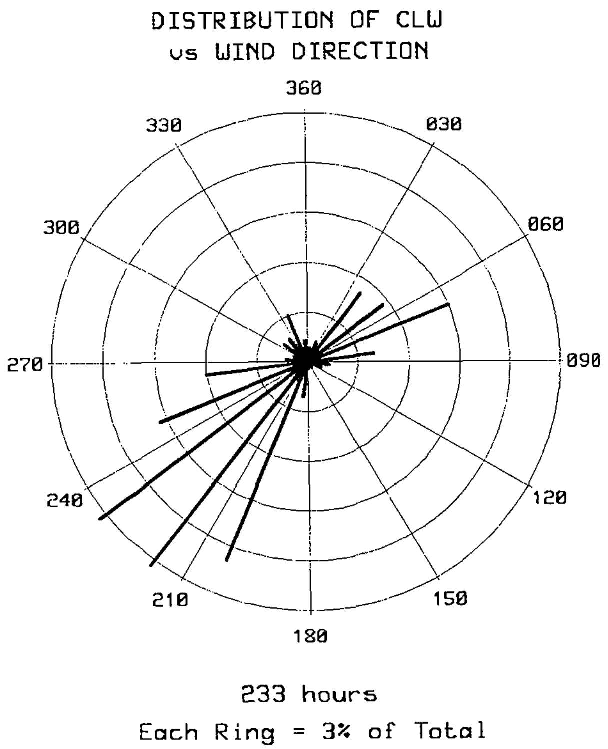

Fig. 4. Wind rose showing the distribution of hours with cloud liquid water vs wind direction in degrees true.

A plot like Fig. 4 (not shown) was constructed using winds observed by rawinsondes released at Campe Verde 42 km WSW of HJ. It showed a similar distribution for SW flow but only 8% of the CLW hours were associated with 700 mb winds from the 30-90° sector, far below the 24% shown for HJ tower winds in Fig. 4. This suggests the NE upslope cases are primarily a low-level, local phenomena over the Mogollon Rim, not usually observed near 3 km altitude over the Verde Valley to the west. The 700 mb distribution showed a secondary maximum of 15% of all cases from 285-300°, unlike the tower wind distribution.

6. CLW Flux Estimates

The horizontal flux of CLW has been estimated for each hour of the storm episodes observed during the 1987 winter field season. To convert measurements of integrated radiometer CLW to flux, it was necessary to make assumptions about both the vertical wind speed profile and the vertical distribution of the CLW.

A basic calculation of the volume flux VFz for any layer at mean height z having wind speed Vz and cross-sectional area Az can be given by

$$VFz = Az \times Vz \qquad (1)$$

(after Thompson and Super, 1987). The CLW flux CFz for each layer can then be calculated by

$$CFz = VFz \times CLWz \qquad (2)$$

where CLWz is the vertically integrated CLW for the layer. The total CLW flux is then the summation of the flux for all layers. Since one gram of CLW is equivalent to 1 cm^3 liquid water, Fg, the flux in g s^{-1} per meter crosswind, is

$$Fg = CLWz \times Vz \times 1000 \qquad (3)$$

where CLWz is in mm, and Vz is in m s^{-1}.

Neither the vertical distribution of the wind speed nor that of CLW were routinely measured throughout the entire cloud layer over HJ. Therefore, it was necessary to make some assumptions about these distributions which were based on periodic observations taken throughout the field season.

In the case of wind speed, the doppler acoustic sounder usually provided data in the lowest 570 m agl. An investigation using all available wind measurements indicated the highest level observed by the acoustic sounder was often representative of the mean wind speed in the lowest 1-2 km. Therefore, whenever acoustic sounder data near 570 m agl were available, they were assumed to represent the lowest 2 km layer above HJ with possible adjustment whenever aircraft winds were also observed in that layer.

All wind estimates above 2 km agl were based upon either upwind rawinsondes, or the preferred aircraft observations over the HJ vicinity when available. These two measurement systems also provided estimates for the lowest 2 km when acoustic sounder data were occasionally unavailable. Upwind rawinsonde winds were found to usually provide good to very good estimates of actual winds over HJ as measured by the aircraft.

Knowledge of the vertical distribution of CLW over HJ was obtained exclusively from aircraft sampling. For reasons of safety, the aircraft was not flown in cloud within 300 m (1000 ft) of the highest terrain, which resulted in a minimum flight altitude of 2930 m msl. Thus, the cloud layer in the lowest 640 m over HJ was not sampled by aircraft. However, many clouds were sampled at and above the minimum altitude, providing information of the CLW distribution further aloft.

The general indication from several storms was that the CLW tended to be concentrated in the lower portions of the clouds. (A similar distribution was found over the Grand Mesa, Colorado, see Holroyd and Super, 1984). For example, aircraft sampling of the Arizona synoptic scale storms generally revealed little CLW at altitudes above 5 km msl (2.7 km agl). Also, CLW was sometimes detected by the radiometer in the lowest 640 m agl when the aircraft was observing exclusively ice crystal cloud at that altitude and above.

The method by which the hourly horizontal CLW flux was estimated was as follows: In the event that cloud tops were generally less than 2 km above HJ as observed by radar or aircraft, the CLW flux was calculated from Eq. (3) using the acoustic sounder speed measurement at 570 m agl and the total integrated CLW amount from the radiometer. If cloud depth consistently exceeded 2 km agl, a second layer was added. In that case, 50% of the integrated CLW was assumed to be in the lowest kilometer (2290-3290 m msl) and the speed for that layer was again considered to be that measured at 570 m agl by the acoustic sounder. The other 50% of the total CLW was assumed to lie above 1 km agl. The thickness of this designated upper layer was variable, depending upon overall cloud tops.

The mean wind speed for the upper layer was estimated using aircraft observations when available and otherwise rawinsonde data. Winds further aloft than 4.9 km (16,000 ft) msl were never used because CLW was infrequently detected that high.

7. Distributions of CLW Flux

Horizonal CLW flux estimates are tabulated in Table 1 for eleven storm episodes with valid data and two with some questionable data. Total flux per storm episode ranged from about 0.1×10^7 g to 42×10^7 g per meter of crosswind distance. The average hourly flux per storm ranged from 10 to 2710 g s^{-1} per meter of crosswind distance.

The character of the episodes varied greatly, from lengthy periods having significant CLW almost without interruption, to episodes with many hours of precipitation but little CLW. The three episodes with the highest total CLW fluxes also had measurable precipitation during more than 50% of the hours.

Table 1 shows that 75% of the total CLW flux for the two month field season (ignoring the two episodes with questionable values due to rain) occurred during only three storm periods which lasted a total of 156 h. Conversely, six of the eleven episodes with valid CLW estimates had a total of 167 h duration but contributed only 9% of the total flux. The three episodes which produced three-quarters of the total flux had SLW maxima associated with cold front passages, either pre- or post-frontal, or both. Secondary maxima were sometimes observed to be related to passage of a surface low or trough aloft.

The largest flux-producing storm, accounting for 35% of the seasonal total, occurred on February 23-26. This storm also produced considerable snowfall over a wide area. For example, the Prescott Airport was closed for a few days due to about 0.5 m of snow on the runways and insufficient equipment to remove it. Sections of Arizona interstate highways were closed for extended periods. The storm was locally reported as producing the heaviest snowfall in 20 years. It seems doubtful that any cloud seeding would be desired or allowed during such a storm.

Table 1. Summary of CLW flux estimates ranked by total flux per storm episode.

Date(s) (1987)	Total Flux*($\times 10^7$ g)	Rank	Average Flux*(g s^{-1})	Rank	Episode Duration (h)	Percent of hours with CLW over HJ	Percent of hours with precipitation at HJ	Cummulative Total Flux * ($\times 10^7$ g)	(%)
Feb. 23-26	41.9	1	1455	3	80	73	69	41.9	35
Jan. 30-31	24.4	2	2710	1	26	96	85	66.3	56
Mar. 15-17	23.5	3	1305	4	50	96	78	89.8	75
Feb. 13-14**	9.2	4	1155	5	22	86	41	99.0	83
Feb. 19-21	5.3	5	305	7	48	58	46	104.3	87
Feb. 4	3.9	6	670	6	16	94	31	108.2	91
Jan. 15-17	3.4	7	150	10	64	33	59	111.6	93
Jan. 28	3.1	8	1730	2	5	100	0	114.7	96
Feb. 17-18	2.8	9	255	8	31	71	13	117.5	98
Feb. 15-16	1.8	10	200	9	25	60	0	119.3	100-
Jan. 19-20	0.1	11	10	11	26	12	69	119.4	100
The following fluxes were overestimated by unknown amounts due to rain above the radiometer									
Mar. 8-9**	13.1	--	1215	--	30	90	67	---	---
Mar. 6-7**	3.7	--	535	--	19	79	37	---	---

* per one meter crosswind distance
** SC type storms, all others were SS

Figure 5 shows the distribution of CLW flux plotted against hourly mean amounts of vertically integrated CLW. It is seen that the low values of CLW contributed much of the seasonal flux as previously found over the Grand Mesa, Colorado (Boe and Super, 1986). This is because of the much higher frequency of occurrence of CLW amounts less than 0.15 mm (Fig. 2). About 44% of the total flux was due to the 81% of all hours which had mean CLW amounts of 0.15 mm or less. Conversely, the 6% of all hours that had CLW amounts in excess of 0.35 mm yielded almost 30% of the total flux.

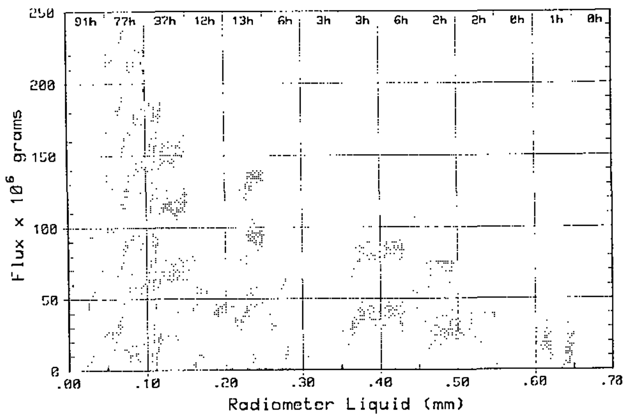

Fig. 5. Distribution of cloud liquid water (CLW) flux per meter crosswind vs vertically-integrated CLW amounts. The number of hours within each amount range are also noted.

It might appear attractive to limit seeding to the wetter (high CLW) periods in anticipation of high snowfall yields. However, the periods with low CLW amounts should not be discounted without further investigation. While their seeding potential may be low in terms of hourly snowfall rates, their seasonal contribution may be significant due to the higher frequency of opportunities. Ideally, both wetter and dryer CLW periods should be seeded if further study indicates both are seedable.

The cumulative frequency distribution of the 260 h with CLW flux estimates is shown in Table 2 along with the Grand Mesa, Colorado estimates of SLW, reported by Thompson and Super (1987). The Grand Mesa data were obtained with a microwave radiometer similar to that used at HJ, but the only wind speed measurement was from a 70 m tower atop the Mesa, while higher level winds tended to be somewhat stronger. Therefore, the Mesa flux observations are throught to be underestimated by perhaps 50-100% depending upon the depth of the CLW (known to be supercooled over the Mesa) and the vertical wind shear.

The Mesa estimates shown in Table 2 are significantly drier at the low end of the distribution where ratios are 2.5 or more, which suggests a higher frequency of clouds with very limited CLW. That might be expected since the Mesa is about 600 km NNE of HJ and 1000 m higher. However, the wetter hours yielded similar flux distributions at the two sites, with ratios less than 2.0. Such differences could be primarily due to the underestimated winds above the Mesa.

Table 2. Cumulative distributions of hourly mean values of CLW flux at Happy Jack, AZ and Grand Mesa, CO.

Percent of total hours	Happy Jack AZ flux ($g\ s^{-1}$)*	Grand Mesa CO flux ($g\ s^{-1}$)*	Ratio Happy Jack/Grand Mesa
5	100	20	5.0
10	140	40	3.5
20	200	80	2.5
30	315	145	2.2
40	435	200	2.2
50	630	295	2.1
60	845	470	1.8
70	1235	700	1.6
80	1750	1190	1.5
90	3035	2155	1.4
95	5250	3475	1.5
100	14,305	15,870	0.9
Total Hours/ Months of Data:	260/2	404/3	

* per one meter crosswind distance

One must be cautious in carrying the comparison too far because both data sets were of limited duration, being only 2 or 3 months long. Further, it is not known how representative these samples are of the normal CLW distributions. It may well be chance that both the mean number of hours with CLW per month, and the distributions shown in Table 2, were similar at the two sites. However, it is possible that the expected greater orographic contribution to CLW production over the steeper Mesa was largely balanced by synoptically-forced lifting of lower-based, hence warmer, and wetter clouds over Arizona.

Using the 260 h HJ data set it was found that about 50% of the total CLW flux occurred with only 12% of the total hours. Conversely, the 50% of the hours with lowest flux values contributed only 11% of the total seasonal flux. Similar distributions are common for mountain precipitation (e.g. Super et al., 1986) which is, of course, derived from SLW flux.

The 233 h with both valid CLW observations and HJ tower wind data were used to partition CLW flux by wind direction. It was found that 31% of the total flux occurred with SSW winds (195-210°). Fifty-five percent of the total flux was associated with wind directions from 195-240°, i.e., generally SW flow. The entire 0-90° quadrant contributed 17% of the total flux while the sector from 255-345° yielded 19% of the flux. Flux from the SE was negligible.

To put the CLW flux values into perspective, they will be compared with streamflow from the area of interest. The region immediately north of HJ is drained to the SW by Dry Beaver and Wet Beaver Creeks, which join the Verde River near McGuireville. Their combined mean annual runoff for the period 1966-1982 was 63,471 acre-ft. The crosswind extent of these watersheds, for SW flow, is about 31 km near the 2130 m (7000 ft) altitude contour. With a CLW flux of about 120 x 10^7 g per meter crosswind (Table 1), a total flux of approximately 3.7 x 10^{13} g results. Because one acre-ft is equivalent to 1.23 x 10^9 cm^3 (or grams) of water, the estimated two month flux across these drainages was near 30,000 acre-ft, or almost half the mean annual runoff from them. A significantly longer period of record would be required to test the representativeness of the mid-January to mid-March 1987 observations for typical Arizona winters. Further, determining what portion of the CLW flux can be converted to snowfall is a different and complex subject. However, it is encouraging that a significant CLW flux was estimated during the initial Arizona field program. It is interesting to note that Rauber and Grant (1987) estimated the amount of SLW passing the crest of a mountain range in southern Utah for a single storm. The total flux for a 13 h period was 12.5 x 10^7 g per meter of crestline, equivalent to about 13% of the mean annual runoff from that target area. Only three storms in Table 1 had more CLW flux, and they were all of much longer duration.

8. Summary

Cloud liquid water (CLW) observations were obtained with a microwave radiometer atop the Mogollon Rim of Arizona from mid-January to mid-March 1987. Supporting wind observations allowed estimation of CLW flux over the barrier. Temperature measurements indicate that the large majority of the CLW was supercooled.

It was found that synoptic scale storms produced the bulk of the CLW. The airflow was usually from the southwest during CLW episodes, although northeasterly upslope flow was also an important contributor.

Vertically-integrated mean hourly amounts of CLW were less than 0.1 mm about two-thirds of the time that CLW was detectable. The highest value was under 0.7 mm, which suggests low liquid water contents were common and this was verified by aircraft observations. Nevertheless, more than 300 h with CLW were observed during the field season.

Durations of CLW episodes varied from 1 to 50 h, but the four episodes lasting 23 h or more accounted for over half the observed hours with CLW.

The total estimated CLW flux per storm also varied markedly from 0.1 x 10^7 to 42 x 10^7 g per meter of crosswind distance. About 75% of the total two month flux was due to only three storms. About 35% of the total flux was produced by a single 80 h episode, locally reported as the heaviest snowstorm in 20 years.

The distribution of hourly CLW flux plotted against the vertically-integrated CLW amount (Fig. 5), showed that most of the total flux was due to the many hours with light to moderate CLW amounts. While flux values were relatively low during these hours, their high frequency of occurrence suggests they should not be ruled out for possible cloud seeding potential.

The cumulative distributions of CLW flux from Happy Jack, Arizona and Grand Mesa, Colorado were compared, and found to be remarkably similar. Caution should be used in such comparisons because of the limited observational periods. However, based on the data sets available, the frequency of occurence, vertically-integrated amounts of CLW, and CLW fluxes all appeared similar at the two sites.

The two-month total estimated CLW flux over the Mogollon Rim was compared with mean annual streamflow from the same region, and the flux was found to be almost half the streamflow. This is an encouraging result, suggesting significant winter cloud seeding potential may exist over the Mogollon Rim of Arizona.

ACKNOWLEDGEMENTS

The authors are please to acknowledge the significant contributions to this research made by the following persons: Jack McPartland and Mike Collins of the Bureau of Reclamation, John Thompson, Bill Hauze, Richard Benner, George Wilkerson, and Marty Thorp of North American Weather Consultants, Jim Keller of the U.S. Forest Service, and Wayne Sand and George Bershinsky of the University of Wyoming are all acknowledged for their roles in the data collection program. The cooperation of the U.S. Forest Service in providing facilities at Happy Jack and Prescott, AZ was very important to the field program. Cindy Snook typed the several drafts of the manuscript.

This research was conducted under a cooperative program between the U.S. Bureau of Reclamation and the Department of Water Resources of the State of Arizona.

REFERENCES

Boe, B.A., and A.B. Super, 1986: Wintertime characteristics of supercooled liquid water over the Grand Mesa of western Colorado. J. Wea. Modif., 18, 102-107.

Cooper, W.A. and J.D. Marwitz, 1980: Winter storms over the San Juan Mountains, Part III: Seeding potential. J. Appl. Meteor., 19, 942-949.

Dennis, A.S., 1980: in Weather Modification by Cloud Seeding. 267 pp. Academic Press, New York.

Heggli, M., R.M. Rauber, and J.B. Snider, 1987: Field evaluation of a dual-channel microwave radiometer designed for measurements of integrated water vapor and cloud liquid water in the atmosphere. J. Atmos. Ocean. Tech., 4, 204-213.

Hogg, D.C., F. Guiraud, J. Snider, M. Decker, E. Westwater, 1983: A steerable dual-channel microwave radiometer for measurement of water vapor and liquid in the atmosphere. J. Clim. Appl. Meteor. 22, 789-806.

Holroyd, E., III, and A. Super, 1984: Winter spatial and temporal variations in supercooled liquid water over the Grand Mesa, Colorado. Preprints Ninth Conf. on Inadvertent and Planned Weather Modification, May 21-23, Park City UT, 59-60.

Ludlam, F.H., 1955: Artifical snowfall from mountain clouds. Tellus, 7, 277-290.

Rauber, R.M. and L. O. Grant, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part II: Spatial distribution and microphysical characteristics. J. Clim. Appl. Meteor. 25, 489-504.

Rauber, R.M. and L.O. Grant, 1987: Supercooled liquid water structure of a shallow orographic cloud system in southern Utah. J. Clim. Appl. Meteor., 26, 208-215.

Super, A.B., E.W. Holroyd, III, B.A. Boe, and J.T. McPartland, 1986: Colorado River Augmentation Demonstration Program Technical Report: January 1983-March 1985. U.S. Bureau of Reclamation, Division of Atmospheric Resources Research, Denver, CO, May, 1986. 42 pp.

Super, A.B. and J.A. Heimbach, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana. J. Appl. Meteor., accepted.

Thompson, J.R. and A.B. Super, 1987: Some estimates of supercooled liquid water flux in winter clouds over the Grand Mesa, Colorado. J. Wea. Modif., 18, 92-98.