WINTERTIME SUPERCOOLED LIQUID WATER FLUX OVER THE GRAND MESA, COLORADO

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ABSTRACT

Supercooled liquid water (SLW) and wind measurements were made over the Grand Mesa of western Colorado during the period late January through March, 1986. Observations were obtained with an instrumented aircraft, a tower-mounted icing rate meter, and an acoustical sounder. These data were used to estimate the flux of SLW over the Mesa top, just upwind of the lee subsidence zone, during nine aircraft flights. The SLW flux calculations for a one meter width perpendicular to the wind ranged from 124 to 2707 g s^{-1} with a median value of 600 g s^{-1}. These values compared favorably with previous flux calculations over the Mesa from microwave radiometer and tower wind measurements. Maximum possible precipitation rates were calculated from the flux estimates by assuming all available SLW was uniformly precipitated over 10 km. These precipitation rates varied from a low of 0.04 mm h^{-1} to a high of 0.97 mm h^{-1}. Observed precipitation rates during the aircraft missions were in the same general range. However, marked variations occurred among storms in both observed and calculated precipitation rates which suggested that the natural precipitation efficiency of the sampled clouds varied widely. Several cases may have had significant cloud seeding potential.

1. Introduction

The fundamental importance of supercooled liquid water (SLW) to wintertime orographic weather modification has been recognized for many years. Yet, relatively few observations have been reported concerning the flux of SLW over mountain barriers during winter storms and the implications of that flux for potential snowfall increases. That is largely due to the observational difficulties associated with SLW measurements, especially in obtaining vertical profiles near mountain barriers.

A number of recent studies have indicated that SLW is often concentrated in the lower layers over the windward slopes and crest of mountain barriers (e.g. Holroyd and Super, 1984; Rauber and Grant, 1986). Aircraft observations are impractical in the lowest several hundred meters above many mountain regions. Recently developed microwave radiometers are providing integrated SLW measurements along their field of view, but little information on the vertical distribution of SLW (e.g., Boe and Super, 1986).

Several aircraft missions were flown in orographic clouds over the Grand Mesa of western Colorado during January through March, 1986. These were in support of experiments conducted by the Bureau of Reclamation's Colorado River Augmentation Demonstration Program. Wind and SLW measurements obtained during these flights make possible the calculation of SLW flux over the Mesa. Because of the flat top of the Mesa and lack of nearby higher terrain, a special waiver was granted permitting flight within 300 m of the highest ground. The unusually low-level in-cloud aircraft observations were supplemented by a tower-mounted icing rate sensor at 70 m agl. These combined observations provided good information on SLW and wind through the entire vertical extent of the orographic clouds.

The flux of SLW was calculated from these measurements on nine different missions. These flux estimates are compared to previously reported estimates from a microwave radiometer and tower wind observations on Grand Mesa. Using simplifying assumptions, they are also converted to maximum possible precipitation rates, which are then compared to observed snowfall rates.

2. Data Collection Procedures

Airborne SLW measurements were obtained from a Johnson-Williams (J-W) liquid water sensor recently reconditioned by the factory. Once zeroed outside of cloud, it exhibited little drift, and appeared to have a resolution near 0.02 g m^{-3}. As shown by Strapp and Schemenauer (1982), a properly maintained J-W system can yield measurements of reasonable accuracy.

Horizontal winds of moderate accuracy were calculated from measurements of position from

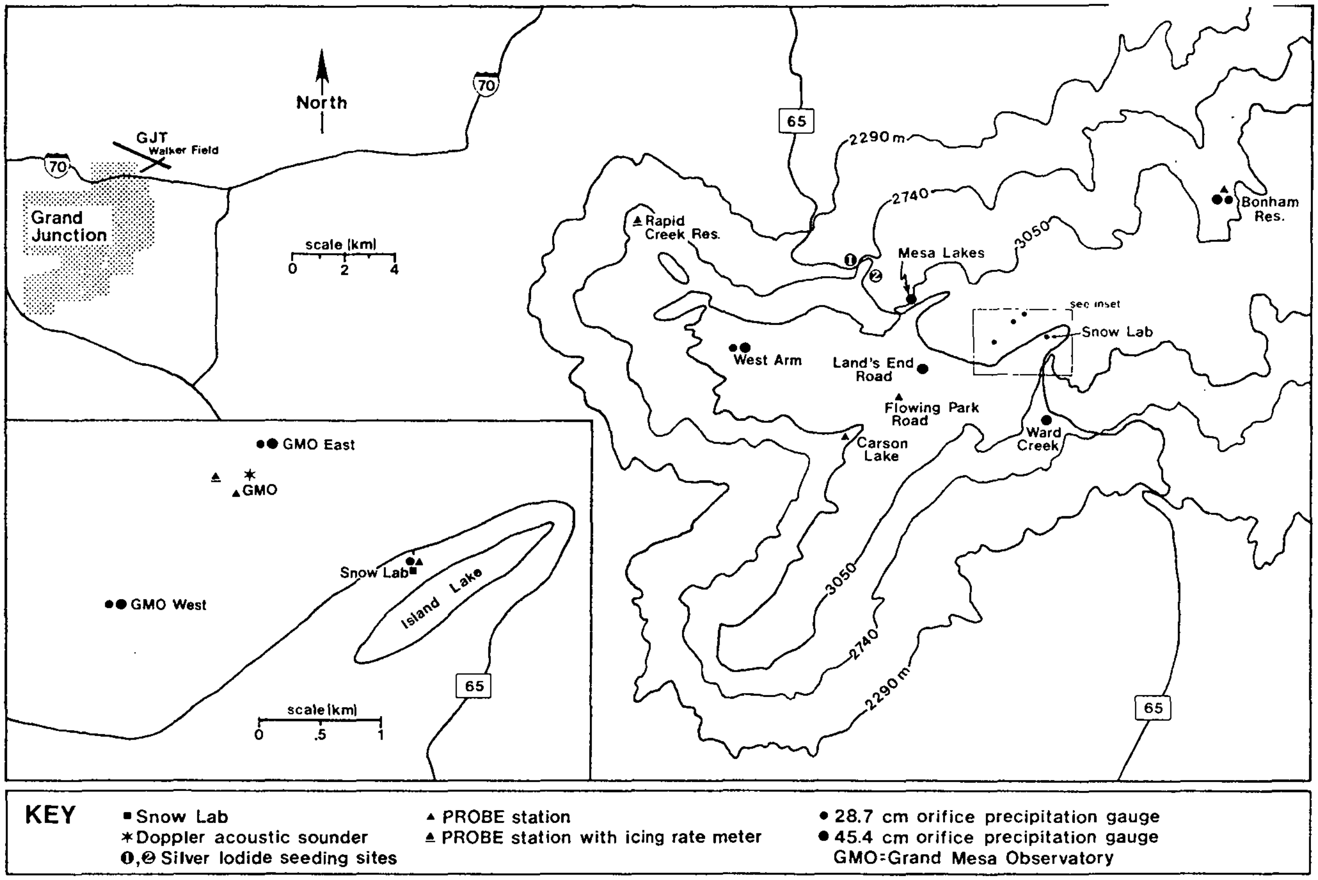

Figure 1. Map of Grand Mesa research area.

Loran-C, and aircraft heading and true air speed. They were usually found to agree within 1-2 m s^{-1} of acoustical sounder winds over the Mesa top. Several other parameters were monitored with the AeroCommander 690A aircraft that are not pertinent to the calculations in this paper.

The concentration of SLW at 70 m agl was calculated using measurements from a Rosemount Model 872B12 icing rate meter on a tall microwave tower near the Grand Mesa Observatory (GMO) shown on Fig. 1, and wind speed measurements for the same level provided by an acoustical sounder located within 100 m of the tower. The icing meter was calibrated in a small wind tunnel and found to recycle ("trip") whenever approximately 0.074 g of SLW adhered to the probe (individual values ranged from 0.060 to 0.085 g in 12 tests using droplets near 10 µm diameter over a temperature range from -6.0 to -10.5°). The mean SLW content was calculated at hourly intervals using the 0.074 g mean value per trip, the number of trips, and the mean wind speed, a technique also used in similar investigations in California (Henderson and Solak, 1983), as well as by Boe and Super (1986). The nominal 90 s deicing time was ignored in these calculations because it was a small fraction of the total time (for 10 m s^{-1} wind and 0.05 g m^{-3} liquid water less than four cycles per hour occur) and corrections would be less than other uncertainties. For example, periods without SLW may exist between instrument trips resulting in some sublimation of ice from the probe. Such events could reduce the calculated SLW content. However, in the absence of a analog output from the device, there is no way to correct for such cases, or even to know whether they occurred.

In the absence of cloud droplet size observations, the collection efficiency of the icing meter was assumed to be unity. This should be a reasonably good approximation for the 0.64 cm diameter probe with the range of cloud droplet sizes normally expected over the Mesa, especially since tower winds were 9-10 m s^{-1} in the icing cases to be reported. However, some underestimation of SLW could occur due to flow of small droplets around the probe, but the impact on calculation of of the overall SLW flux is expected to be minor.

On a typical mission the aircraft would take off from the Montrose airport (50 km south of the Grand Mesa) and climb to 17,000 feet (5.2 km), approximately 2.0 km above the mean Mesa elevation, making a sounding of meteorological parameters. Approaching the Grand Mesa the airplane would make a straight and level pass near 17,000 feet, heading either into the wind or with the wind, passing over the Snow Lab at Island Lake (see Fig. 1). A second pass over the Snow Lab would be made at a lower altitude, usually 15,000 feet (4.6 km). Sometimes more than one pass would be made near 17,000 or 15,000 feet and other passes might be made at lower altitudes, but eventually the aircraft descended to 12,400 feet (3.8 km) where most of the sampling would take place. The net effect of this flight pattern was to provide relatively few sampling passes at the higher altitudes, but several at the lowest permissible flight altitude. As shown by Holroyd and Super (1984), most of the SLW is typically found in the lower levels over the Grand Mesa.

To calculate the SLW flux the data were first examined to identify those times when the aircraft was on straight and level flight within the sector north or northeast of the Snow Lab, that is, over the top of the Mesa. The terrain slopes downward south of the Snow Lab area and slightly upward to the west, north, and northeast to the Mesa crest which is about 3 km to the west or north of the Snow Lab and about 7.5 km to the northeast of it.

Airborne SLW measurements, as determined from the J-W sensor, were averaged over a 3 km flight path from over the Snow Lab northward with either SE through SW winds or their reciprocal. With winds from the WSW the 3 km leg extended from 4.3 km ENE of the Snow Lab to the crest 7.3 km away. These sampling paths were chosen to provide observations over the Mesa top. It is important to note that these observations represent the cloud conditions just prior to transport into the lee subsidence zone where aircraft measurements have revealed rapid depletion of the SLW. If the natural precipitation process does not convert the SLW into ice particles prior to passage over the lee slope with associated downward motion, the potential for this conversion is largely lost. Therefore, the SLW flux estimates should closely approximate the "excess flux" that nature has not converted to precipitation. To the extent that it can be converted to snowfall by cloud seeding, it represents the augmentation potential for the orographic cloud.

Measurements of liquid water at one second intervals were used to obtain the 3 km average for each pass at each altitude flown. These SLW content averages for each pass were then averaged for all passes at a given altitude to determine the mean SLW for each sampling level for the flight. Most flights over the Grand Mesa lasted from two to four hours.

Cloud top altitude was determined visually from the aircraft once or twice during each mission. Where weak convective cells existed, the average top was estimated. Certainly tops could vary during the course of a mission, but no other observations are available.

Cloud base altitude was a visual estimate of conditions over the Mesa top, usually made from the aircraft, but sometimes with ground observations as well (e.g., from the Snow Lab). The cloud base was often visible from the lowest flight altitude through breaks in the deck over the Mesa, or when the aircraft was in clear air upwind or downwind of the Mesa.

The average of the SLW (even if zero) for each sampling altitude was assumed to represent the value for the cloud layer one-half the distance above and below the height at which the SLW measurements were made for adjacent altitudes. That is, most cloud layers were defined by mid-points between sampling altitudes. For example, assume the cloud top was at 4.6 km, the base was below the 3.2 km Mesa top and SLW measurements were made at 4.6, 3.8 and 3.4 km (GMO tower). Then the average SLW value determined near cloud top would represent the layer from 4.6 km to 4.2 km, the average SLW determined at 3.8 km would be used for the layer from 4.2 km to 3.6 km and the layer from 3.6 km to 3.2 km would be the average determined at 3.4 km. If the cloud top had been observed at 4.9 km, but no in-cloud observations were taken at that altitude, the average SLW value at 4.6 km would be used for the layer between 4.9 km and 4.2 km.

Wind speed measurements from the aircraft data system were averaged over 6 km distances (approximately one minute) while the aircraft was flying in the vicinity of the Snow Lab-GMO tower area. Fifteen minute mean winds were averaged for the flight duration from the acoustical sounder data to provide winds at the lowest level (3.4 km).

Table 1 summarizes mean SLW contents and wind speeds at each level sampled on each of the nine aircraft missions. The cloud top altitudes and temperatures and cloud base altitudes are also noted. It is shown that cloud tops ranged from 4.6-5.3 km, or only 1.4-2.1 km above the 3.2 km Mesa top. These rather shallow orographic clouds had top temperatures ranging from -11.5 to -24.0°C. In a few cases a higher deck existed that was not connected with the deck sampled.

The mean values of SLW were limited, with a maximum of only 0.12 g m^{-3} (on 10 March). Several mean values were near the resolution limit of the J-W instrument, especially in the upper portions of the clouds. Of course, instantaneous values often markedly exceeded the 3 km means for one or more passes.

Hindman (1986) presented mean SLW content values ranging from 0.14-0.23 g m^{-3} for three high altitude Colorado locations. His higher values may be due to local siting near crestline locations on steep barriers as compared with the flat-topped Grand Mesa, or to instrumentation differences, or both. Moreover, the present study simply assumed unity collection efficiency for the probe in the absence of cloud droplet spectra measurements. Hindman used a relationship between collection efficiency and wind speed valid only for 10 μm droplets. That adjustment, if applied to the GMO tower observations, could more than double the SLW content values of Table 1. The GMO tower SLW measurements, when cloud water extended that low, were in general agreement with the aircraft observations 400 m higher.

Strapp and Schemenauer (1982) showed several J-W sensors agreed within 20% of wind tunnel calibrations. However, several others did poorly, often due to maintenance related problems. The J-W sensor used over the Grand Mesa was factory refurbished before the field season and exhibited very little drift. However, no independent calibration was done so the accuracy of the sensor cannot be stated (a common problem with SLW instruments). The low SLW amounts measured are in general agreement with the airborne FSSP data presented by Rauber and Grant (1986) for northern Colorado winter clouds.

Table 1 indicates that some clouds were very dry at all levels sampled (February 15, March 11). Other clouds had little SLW near their tops but

Date (1986)	1-31			2-15			2-19			3-10			3-11			3-11			3-18			3-18			3-19		
Time period (MST)	1430-1630			1400-1600			1145-1430			1430-1830			1100-1300			1430-1630			0945-1345			1500-1800			1145-1630		
Cloud top (km)	4.5			4.6*			5.0			5.3			5.2*			4.6*			4.6			5.1			4.6		
Top temp. (°C)	-12.0			-11.5			-15.0			-16.0			-20.5			-16.5			-16.5			-24.0			-18.0		
Sampling alt. (km)	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V	N	SLW	V
5.1								.00	36	2	.01	12	1	.02	6							1	.01	8			
4.9					.00	27											.00	6				1	.07	9			
4.6										2	.02	15	1	.02	4	1	.01	7		.00	17	2	.06	10	2	.02	19
4.5	1	.02	12				1	.06	27																		
4.2	1	.04	12	2	.02	22																					
3.95										1	.12	17															
3.8	5	.09	7	4	.02	15	6	.10	22	11	.12	15	4	.02	5	5	.02	8	20	.05	16	14	.06	12	22	.06	12
3.4 (GMO)					.06	9		.03	10		.03	10								.05	10						
Cloud base (km)	3.55			<3.2			<3.2			<3.2			3.6			3.6			3.3			3.5			3.3		

* higher cloud deck existed unconnected with layer sampled.
N = number of observations
SLW = mean supercooled liquid water (g m^{-3})
V = mean wind speed (m s^{-1})

Table 1. -- Summary of mean SLW contents and wind speeds for altitudes sampled on nine flights.

several times more in their lower portions (January 31, March 10). Still other cases had relatively high mean SLW throughout most of their depth (February 19, second mission of March 18).

3. Calculations of SLW Flux and Precipitation Rate

If the vertical extent of the cloud layer representing one sampling level is noted as Z_z, then the vertical plane normal to the wind direction and one unit distance wide represents the area, A_z. The volume flux, VF, represented by each of the layers can be determined by multiplying its area by the average wind speed for the layer, V_z. Thus

$$VF_z = A_z \cdot V_z \qquad (1)$$

The supercooled liquid water flux for each layer, SF_z, can be determined from

$$SF_z = VF_z \cdot SLW_z \qquad (2)$$

where SLW_z is the average SLW content for the layer.

The total SLW flux over the Mesa, SF_t, is the sum of the SLW flux for each of the layers, namely

$$SF_t = \sum_{z=1}^{n} SF_z \qquad (3)$$

where n is the total number of layers.

Calculations of SF_t were made for nine aircraft flights (on seven days) during the period from January 31 through March 19, 1986. These flights were chosen because measurable SLW existed (a few missions detected ice cloud only), and a reasonable number of horizontal passes were made through most of the vertical extent of the cloud.

The clouds sampled during the missions in January, February and the first flight on March 11 were not seeded. The second flight on March 11 included the airborne release of silver iodide (AgI) but the acetone generator was operated for only three minutes and little or no seeding effect was detected by the aircraft instrumentation. The missions on March 10, 18 and 19 all included airborne AgI seeding resulting in observed microphysical changes within the clouds. However, only 1-4 lines of AgI were released on these dates so any reduction of the mean SLW content due to seeding should have been limited.

An upper limit on cloud seeding potential can be estimated by assuming that the entire SLW flux over the Mesa could be converted to precipitation. The actual distribution of snowfall caused by seeding would be dependent upon several factors such as nucleation rates, ice particle growth and fallout rates, and the vertical and horizontal motion fields. However, one can crudely estimate the maximum possible precipitation accumulation by assuming all the SLW flux could be converted to snowfall of uniform distribution over the width of the Mesa. For cross-barrier (generally north or south) flow the zone with a seasonal snowpack accumulation is approximately 10 km across.

4. Results of SLW Flux and Precipitation Rate Calculations

Precipitation rates for the nine sampling flights have been calculated by assuming conversion of all SLW flux into uniform snowfall over a strip 10 km long (downwind) by 1 m wide (crosswind). These are listed in Table 2, along with the SLW flux calculations, also for a 1 m crosswind width. The table also contains the observed precipitation rate from a project operated network of seven high resolution gauges (see Fig. 1), and the average for the three gauges closest to the Snow Lab, both for the time periods corresponding to the SLW flux estimates. The three-gauge average was included as a separate listing since these gauges might be more representative of the SLW measurements made in their vicinity. These gauges were about 2 km NW, 2 km W and 4 km S of the Snow Lab.

Table 2 shows that the SLW flux calculated for the nine flights covered a wide range from a low of 124 g s^{-1} to a high of 2707 g s^{-1}. The average value for all flights was 874 g s^{-1} and the median was 600 g s^{-1}.

Aircraft Flights Date (1986)	Time (MST)	SLW Flux* (g s^{-1})	Precipitation rate** (mm h^{-1})	Mean gauge network obsvd. precip. (mm h^{-1})	Mean observed precip. - 3 closest gauges (mm h^{-1})
1-31	1430-1630	487	.18	.25	.47
2-15	1400-1600	600	.22	.20	.35
2-19	1145-1430	2707	.97	.03	.03
3-10	1430-1830	1657(s)	.60	.64	.94
3-11	1100-1300	154	.06	.95	1.15
3-11	1430-1630	124(s)	.04	.80	.39
3-18	0945-1345	630(s)	.23	.05	.07
3-18	1500-1800	1000(s)	.36	.16	.21
3-19	1145-1630	584(s)	.21	.06	.09
	AVERAGE	874	.32	.35	.41
	MEDIAN	600	.22	.20	.35

* for 1 m crosswind width.

** Assumes conversion of all SLW flux to uniform precipitation over 10 km.

(s) Denotes some aerial seeding was conducted.

Table 2. - Grand Mesa SLW flux and precipitation rate calculations and precipitation gauge observations.

Calculated precipitation rates ranged from a low of 0.04 mm h^{-1} to a high of 0.97 mm h^{-1}. The average value was 0.32 mm h^{-1} and median was 0.22 mm h^{-1}. In the case of the lowest rate, a 12 hour precipitation period would produce a negligible amount of additional precipitation, only 0.48 mm. The highest rate would produce 11.6 mm of additional precipitation during a 12 hour period. For comparison, Super et al. (1986) reported a median hourly snowfall rate of 0.7 mm h^{-1} and a median daily amount of 3.7 mm for a two-winter period on the Grand Mesa. Only about one-third of the 1204 hours with measurable snowfall exceeded 1.0 mm h^{-1}.

The observed precipitation rates covered essentially the same range as the calculated rates for both the entire gauge network and the three gauges closest to the Snow Lab, but with the three-gauge average generally showing a slightly higher rate. The highest observed rate at any single gauge during the aircraft flight times was 1.9 mm h^{-1}.

Table 2 suggests that nature was very efficient in producing snowfall during some aircraft missions. For example, on both flights of March 11 the calculated precipitation rate (corresponding to the SLW flux) was much smaller than the observed rate indicating that most of the SLW production had already been converted to precipitating ice particles prior to the air reaching the subsidence zone to the lee of the Mesa. Conversely, little natural snowfall was observed on February 19, or the first flight of March 18, both of which had abundant SLW flux over the Mesa top. Such cases would have considerable cloud seeding potential, provided artifical nucleation could produce significant conversion of the SLW flux to snowfall prior to the evaporation/sublimation zone above the lee slope of the Mesa. On several other missions the precipitation rate calculated from the SLW flux was similar to the observed rate. This suggests that some cloud seeding potential may have existed in these cases as well because natural precipitation efficiency was limited. That is, excess SLW flux was passing over the Mesa top and evaporating in the subsidence zone without being converted to snowfall.

5. Comparison of SLW flux estimates

Boe and Super (1986) refer to SLW flux estimates over the Mesa based on vertically-integrated SLW values from a microwave radiometer and the GMO tower wind speeds at 70 m agl. Mean hourly values were available from all but 51 hours during January through March, 1985. Some 404 hours of the 2109 hours with valid observations had non-zero values of both SLW and wind speed. These were used to calculate the frequency distribution given in Table 3 where the SLW flux, in g s^{-1}, is again for a 1 m crosswind distance. These flux values can be expected to somewhat underestimate the actual flux since the 70 m agl winds are usually less than the mean wind for the entire layer containing SLW.

The distribution of Table 3 is approximately log-normal. Ten percent of all hours had values less than 40 g s^{-1} and 10% exceeded 2155 g s^{-1}. The median value was 295 g s^{-1}. Four of the 404 hours (1%) exceeded 10,000 g s^{-1}, thereby contributing a large fraction of the total flux for the three months.

Table 3 shows that the SLW flux estimates based on aircraft and tower observations agree quite well with the radiometer-derived SLW flux values. The lowest aircraft flux measurements are in the lowest 20-30 percent of the radiometer flux values while the highest aircraft value is above the 90th percentile. The bulk of the aircraft flux estimates fall within the 60 to 80 percent range of the radiometer flux calculations. This is likely due in part to the underestimates in radiometer flux values due to using the 70 m agl winds to represent the entire SLW layer. At any rate, the nine aircraft missions appear to have obtained a reasonably representative sample of the cloud types observed by the microwave radiometer over a three month period. The general agreement between the two methods of SLW flux estimation is encouraging.

The aircraft SLW flux values representing flights when seeding was done are indicated by an (s). Four of the five seeded flights had values in the higher range.

Percent	Radiometer SLW flux* (g s^{-1})	Aircraft SLW flux* (g s^{-1})
5	20	
10	40	
20	80	124(s)
30	145	154
40	200	
50	295	
60	470	487 584(s)
70	770	600 630(s)
80	1190	1000(s) 1657(s)
90	2155	2707
95	3475	
100	15,870	

* for 1 m crosswind width

(s) Denotes some aerial seeding was conducted.

Table 3. -- Percent of hours with radiometer-derived SLW flux less than the value noted and distribution of aircraft-derived flux estimates.

The aircraft flights on March 18 and 19 were examined in detail. On March 18 four AgI seeding lines were released during a several hour period at distances between 15 to 25 km north of the Mesa. Each line was normal to the wind and was about 30 km in length. About six minutes was required to produce each seeding line, and between 5-10 g of AgI was dispensed per line. On March 19 two seeding lines were made in a similar fashion. Obviously, the seeding which was done for physical experiments (to be reported) was quite limited. Operational seeding might have produced a different result concerning available SLW.

For all 3.8 km aircraft passes across the Mesa on March 18-19, it was determined when the aircraft was in or out of the seeded plume in the vicinity of the Snow Lab, as indicated by markedly enhanced ice particle concentrations. On March 18 the SLW measurements made within the seeded plume averaged 0.06 g m^{-3} on the first flight and 0.04 g m^{-3} on the second flight. Measurements in the unseeded cloud in the same region averaged 0.05 g m^{-3} on the first flight and 0.06 g m^{-3} on the second flight. On March 19 the SLW in the seeded plume averaged 0.04 g m^{-3}, and 0.07 g m^{-3} outside the seeded plume, but there were only four measurements made in the seeded plume. In any case, it would appear that the seeding that was done did not substantially alter the mean SLW content available on these two days, although short-term local depletions may have occurred.

6. Discussion and Conclusions

Observations obtained during nine instrumented aircraft missions were used to estimate the SLW flux across the Grand Mesa. These flux estimates varied over more than an order of magnitude; that is, from 124-2707 g s^{-1} for a 1 m crosswind distance. The flux estimates were converted to a precipitation rate by assuming all the SLW could be converted to snowfall of uniform depth over a 10 km distance (approximately the cross-barrier width). These calculated precipitation rates were compared with the observed rates during the aircraft missions.

The comparisons suggested a wide range in natural precipitation efficiency. The two missions of March 11 had little SLW flux and relatively large observed snowfall rates so the precipitation efficiency was high.

Conversely, the day with the largest SLW flux (February 19) had only a trace of snowfall. (It is noteworthy that seeding was suspended on that day due to avalanche warnings over much of Colorado.) Most of the cases had observed precipitation rates similar to the rates calculated from the SLW flux. Thus, while some snowfall occurred, approximately equivalent amounts of SLW flux passed over the Mesa top and likely evaporated over the downwind slope. Cloud seeding might have been able to convert some of the remaining SLW to additional snowfall on several of the days sampled. Detailed analyses of the March 18 seeding experiments, yet to be reported, are providing strong physical evidence that airborne seeding did produce snowfall on the Mesa.

The SLW flux estimates based primarily on aircraft data were shown to be in reasonable agreement with earlier estimates based on microwave radiometer observations over a three month period. This encouraging result increases confidence in both approaches. Both sets of SLW flux estimates indicate that about 90% of the cases were less than 2500 g s^{-1} for a 1 m crosswind distance. With reasonable assumptions this amount of SLW flux converts to a maximum snowfall rate near 1 mm h^{-1}, or little more than the median rate of 0.7 mm h^{-1} observed on the Mesa over two winter seasons. This implies that cloud seeding could produce, at best, only moderate snowfall amounts in the large majority of cases with available SLW. However, just as nature produces much of the Rocky Mountain seasonal snowpack through many hours of light to moderate snowfall, successful cloud seeding might augment the snowpack by providing many hours with modest increases.

A small fraction of the hours with SLW flux provide much of the total seasonal flux according to the radiometer observations. This accounts for the fact that a large fraction of the total seasonal precipitation occurs with a limited number of large storms. If periods with high SLW flux could be successfully seeded, a marked snowpack enhancement might be quickly achieved. However, there are several drawbacks to this approach. It may be difficult to detect and respond to these rather rare events. Further, they tend to be associated with strong SW winds (on the Mesa) so ice nucleation/growth/fallout times are limited making successful targeting difficult or impossible. Often storm warnings accompany these episodes (or avalanche warnings as in the February 19 mission) so seeding may be suspended.

In summary, the best strategy for snowpack augmentation may be to seed the many hours with limited SLW flux. The probable requirement for prolonged seeding makes ground generators attractive some of the time. Fortunately, the SLW is often concentrated at low levels where ground-released AgI is more likely to be transported. Further, temperatures are often cold enough at these lower cloud levels (in the central and northern Rockies) for AgI nucleation to occur. Transport and dispersion investigations and physical seeding experiments (both with ground-released AgI) were conducted on the Grand Mesa during February-March, 1986. Analyses of these observations, yet to be reported, are encouraging concerning the potential of ground-based seeding from high altitude locations. However, it should also be recognized that a significant fraction of winter storms may be too warm for ground-based AgI seeding, depending on geographical location and barrier altitude (e.g., Super and Heimbach, 1983). The best overall strategy may then be a combination of ground-based and airborne seeding, and consideration of dry ice seeding for the cases where the liquid water is only slightly supercooled.

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