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RELATIONSHIPS BETWEEN STORM TOTAL SUPERCOOLED LIQUID WATER FLUX AND PRECIPITATION ON FOUR MOUNTAIN BARRIERS

Arlin B. Super
Bureau of Reclamation
Denver CO 80225

and

Arlen W. Huggins
Desert Research Institute
Reno NV 89506

Abstract. There is a commonly held view that large winter orographic storms tend to be efficient in converting supercooled liquid water to snowfall while small storms tend to be inefficient and, therefore, are more susceptible to cloud seeding. To test this conceptual picture, supercooled liquid water flux and precipitation amounts were compared for 4 different mountain regions in Arizona, Colorado and Utah. Supercooled liquid water flux totals were estimated for entire storm periods from vertically-integrated microwave radiometer measurements and wind speeds within about 1 km of the mountain crest, corresponding to the layer expected to contain most of the supercooled liquid water. Per storm precipitation totals were measured near the radiometer sites.

Comparison of storm total supercooled liquid water flux with total precipitation revealed apparent significant relationships between the two variables at all sites. The larger supercooled liquid water flux-producing storms tended to have larger precipitation amounts. When the effect of storm duration was removed, partial correlation coefficients between supercooled liquid water flux and precipitation were significant at 3 of the mountain sites. None of the data sets supported the concept that large precipitation-producing storms are highly efficient in converting supercooled liquid water flux to snowfall. This suggests that large storms are efficient during some phases when abundant snowfall is produced, but inefficient during other phases when supercooled liquid water flux is abundant. This hypothesis was tested for one well-observed storm. Precipitation efficiency was estimated throughout the storm's duration by comparing snowfall with upwind supercooled liquid water flux plus ice flux. The prefrontal phase was very inefficient and produced most of the total supercooled liquid water flux. The frontal phase was more efficient and about half the flux of liquid and ice was converted to snowfall. The postfrontal phase had little supercooled liquid water flux but significant ice flux. However, it was inefficient in converting cloud ice to snow on the ground.

One to a few storms at each site produced most of the seasonal total supercooled liquid water flux. From 50 to 67 pct of all storms at each site produced small amounts of supercooled liquid.

1. INTRODUCTION

The most important observation for assessing winter orographic storm seedability is supercooled liquid water (SLW) flux. The flux of SLW over a mountain barrier, just prior to the descent of cloudy air into the lee subsidence and evaporation zone, is the absolute upper limit for precipitation augmentation by winter cloud seeding. It is likely that seeding could convert only a fraction of the flux to snowfall under most circumstances. Seeding would certainly not produce more snow than the available SLW flux could support (ignoring possible limited growth between water and ice saturation in some situations).

Routine SLW observations have been practical during the last decade, since the development of the microwave radiometer (Hogg *et al.* 1983). However, a limited number of suitable microwave radiometers exist, and SLW measurements have been made only intermittently and over a small number of mountain ranges in the West. None of the measurement periods have been long enough to constitute a climatology with which to estimate normal conditions over many winters. However, existing observations allow examination of the total SLW flux per storm as related to total precipitation at four different mountain ranges in the intermountain West. Supercooled liquid water flux estimates were made over the Grand Mesa of Colorado, the Tushar Mountains and Wasatch Plateau of Utah, and the Mogollon Rim of Arizona. Total observational periods per site were only 2 or 5 mo, but several to many storms were sampled in each location.

2. SLW OBSERVATIONS

Microwave radiometer observations of SLW were made on the Tushar Mountains of southern Utah during 3 different periods. Measurements were made for 2 mo during early 1985, and for 1.5-mo periods during 1987 and 1989, providing a total of 5 mo of observations. These measurements were reported by Long (1986), Huggins (1990a) and Huggins (1990b), respectively.

A 2-mo field program was conducted during early 1991 on the Wasatch Plateau of central Utah, 175 km northeast of the Tushar Mountains.

The SLW flux observations from that project have not previously been reported.

Microwave radiometer observations were made on the Grand Mesa of Colorado, located about 290 km east of the Wasatch Plateau, as reported by Super *et al.* (1986) and Boe and Super (1986). Two months of data were obtained during late 1983 and 3 mo of observations exist from early 1985. Thompson and Super (1987) presented SLW flux estimates over the Grand Mesa, based on 1986 aircraft and tower measurements, and found them to be in reasonable agreement with the earlier microwave radiometer estimates.

The final data set is from a 2-mo period of early 1987, obtained on the Mogollon Rim of Arizona. These observations have been reported by Super and Boe (1988). The more general term "cloud liquid water" was used in that paper because the air temperature at the radiometer level was above 0°C during portions of some storms. The large majority of observations were totally supercooled, however, and the term SLW will be used in this paper. Almost all liquid water observations at the Utah and Colorado sites were supercooled because of their more northerly latitudes and higher elevations.

3. SLW FLUX ESTIMATES

The SLW flux can be approximated by multiplying the vertically-integrated SLW amount over a barrier by a representative wind speed for the layer containing the SLW. Microwave radiometers provide no ranging information, so some uncertainty exists regarding the layer containing the SLW, and, therefore, just what wind speed is representative. However, several investigations have demonstrated that the bulk of SLW is usually within 1 km of the barrier top. Evidence that most SLW is located near mountain surfaces includes observations (Hobbs 1975; Holroyd and Super 1984; Hill 1986; Thompson and Super 1987; Heggli and Rauber 1988) and results of numerical model simulations (Young 1974; Blumenstein *et al.* 1987).

The SLW flux values in the following tables are based on somewhat different methods of wind estimation. However, the particular wind speed used is of secondary importance. The majority of wind speeds within 1 km of mountain surfaces have been found to be in the range 5 to 20 m s^{-1}, with 10 m s^{-1} being typical. Vertically-integrated SLW amounts, averaged over 15 min to 1 h, range from 0.01 to over 1.0 mm. As a consequence, a wind speed error of a 1-3 m s^{-1} affects a SLW flux estimate less than natural changes in the SLW amount.

3.1 Tushar Mountains

Estimates of SLW flux were made for the three Tushar data sets. Long (1986) reported on early 1985 data from the Tushar Mountains, based on microwave radiometer and rawinsonde wind speed measurements. During this and following seasons, the radiometer was located about 5 km west of the barrier crest, so some of the SLW flux may have been converted to snowfall prior to the lee subsidence zone. Similar data were presented by Huggins (1990a) for the 1987 field season, and SLW flux estimates for early 1989 were given by Huggins (1990b).

Table 1. - Storm duration, precipitation and SLW flux for three winter programs over the Tushar Mountains.

START (YYMMDD)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg*/m)	START (YYMMDD)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg*/m)
850201	23	2.3	17.9	870211	22	4.8	135.8
850203	8	0.5	3.2	870213	20	13.7	212.7
850204	9	2.8	0.0	870215	22	4.6	6.8
850207	8	0.5	3.2	870223	61	13.5	33.7
850208	31	7.9	253.3	870307	12	0.0	3.5
850212	2	0.0	6.1	870308	19	5.3	53.2
850220	12	6.9	2.3	870313	5	3.1	124.4
850222	9	0.5	0.9	870314	22	7.9	6.2
850302	29	6.9	17.7	**Yr Total**	183	52.9	576.3
850307	10	0.0	12.5	890202	48	29.5	409.6
850310	13	8.4	145.8	890208	104	8.9	216.8
850311	6	0.3	0.6	890218	50	18.8	42.4
850311	7	1.5	49.2	890301	48	59.4	367.6
850312	11	4.3	16.0	890315	72	2.5	11.4
Yr Total	178	42.8	528.7	**Yr Total**	322	119.1	1047.8

* 1 acre-ft of water is 1233.5 Mg (1233.5 X 10^6 gram).

During the above noted Tushar field programs the term "STORM" was used to designate a period with significant cloud cover over the research area perceived to have some probability of producing precipitation. As a minimum that meant a broken to overcast mid-level or lower level cloud deck. Research periods coincided with storm periods. A summary of SLW flux estimates for storm episodes during the 1985, 1987 and 1989 seasons is worthy of consideration.

Table 1 has been extracted from the previously cited final reports for the three winters in question with precipitation data for 1989 compiled since those reports were published. The mass of SLW in Mg (10^6 g) passing over each meter of the north-south oriented ridgeline was estimated for all storms with microwave radiometer observations. The beginning date of each storm with radiometer data and its duration are noted. Whenever SLW data were partially missing, it was assumed that the measured storm fraction was representative of the entire storm, and the estimated SLW flux was adjusted accordingly. Storm precipitation totals are from the same gauge each season, located about 2 km upslope from the radiometer site.

Table 1 shows that storm total amounts of SLW flux varied widely from none to about 400 Mg per meter of ridgeline. Two or three storms produced 75 pct or more of the total SLW flux each field season. Nearly half of the 1985 SLW flux passed over the barrier during a single 31-h storm. Sixty-three pct of the storms had a total flux less than 50 Mg m^{-1}.

To put these SLW flux values into perspective, if 100 Mg m^{-1} were converted to snowfall of uniform depth over a 10 km downwind distance, the resulting snow water equivalent would be 1 cm. Only 1 mm (0.04 inch) of water equivalent would result from 10 Mg flux with the same assumptions, and the precipitation total would be half that if the snowfall were uniformly precipitated over 20 km. Because the flux values in Table 1 are for entire storms, any precipitation increases due to seeding would be very limited with flux values less than 10 Mg m^{-1}.

The cumulative distribution of SLW flux for the 1985, 1987 and 1989 field seasons was presented by Huggins (1990b). He showed that during each project, half the total flux occurred in less than 15 pct of the observational hours. Further, over 90 pct of the flux occurred in just 38 to 47 pct of the observational time.

Although several of the storm periods with large SLW flux amounts lasted about 1 to 2 days, one lasted only 4.5 h (March 13, 1987) and one lasted over 4 days (February 8, 1989). Variability is clearly a common element among winter storms, as has been found in other locations.

Data from Table 1 were used to investigate the relationship between storm total precipitation far up the windward slope and total SLW flux overhead. Figure 1 shows the plotted pairs of observations for the 27 storms, and the linear least squares regression line. SLW flux tended to be larger in the larger precipitation-producing storms. Such storms might be expected to be efficient at converting most of their SLW flux to precipitation. But the observations show considerable remaining SLW flux for most large precipitation-producing storms.

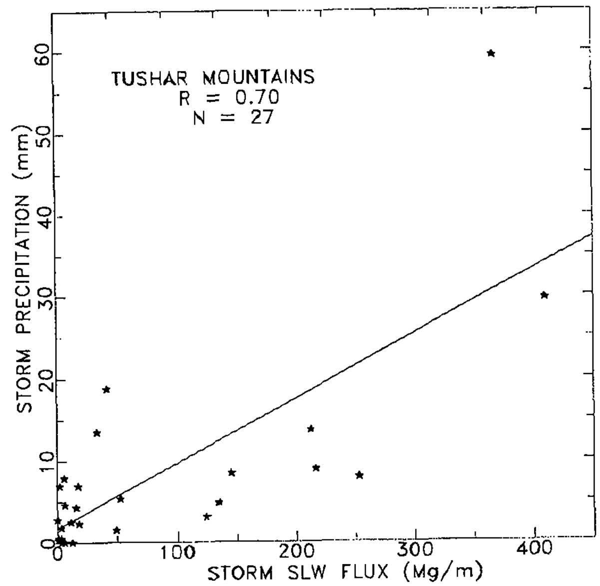

Fig. 1. Storm total SLW flux plotted against precipitation for 27 storms over the Tushar Mountains. A linear regression line is fit to the data. R is the rank correlation coefficient and N is the number of data pairs.

The situation in Utah is probably similar to the northern Arizona storms discussed by Super and Holroyd (1989) which had abundant SLW and limited snowfall during some (inefficient) phases and the converse during other (efficient) phases. The inefficient phases tended to be at the beginning and ending of the episodes when the cloud deck was shallow and cloud tops were warm. Middle portions of storms, associated with frontal passages, tended to have thick clouds with cold tops. These portions apparently produced abundant natural ice particles which converted the low-level, orographically-produced SLW to snowfall.

Figure 1 and similar figures to follow indicate highly skewed distributions with many small values of each variable and few large values. As pointed out by a reviewer, this raises doubts about significance estimates using standard (Pearson product-moment) correlation coefficients. Accordingly, tie-adjusted rank (Spearman) correlation coefficients will be presented because of their advantage that no assumptions need be made about the variable distributions (Mosteller and Rourke 1973).

The rank correlation coefficient for the data of Figure 1 is 0.70, indicating about half of the variance in snowfall was associated with SLW availability. While the relationship is significant at the 1 pct level, about half the variance is unexplained.

Much of the variance in both total precipitation and SLW flux could simply be caused by storm duration. More snowfall and flux would be expected from longer lasting storms. To test the influence of storm duration, the partial correlation coefficient of precipitation and SLW flux, controlling for storm duration, was calculated. A value of 0.52 resulted, still significant at the 1 pct level. The partial correlation coefficient between precipitation and duration (controlling for flux) was 0.57, also significant at the 1 pct level. The conclusions are that larger SLW-producing storms over the Tushar Mountains had a significant tendency to be larger snowfall-producing storms as well, and that snowfall amounts were significantly related to storm duration.

The rank and partial correlation coefficients between precipitation, SLW flux and storm duration are summarized in Sec. 3.5 for all 4 mountain regions discussed in this paper.

3.2 Wasatch Plateau

Measurements were made on the west edge of the Wasatch Plateau from mid-January to mid-March 1991. Storm periods were defined from microwave radiometer SLW observations and precipitation gauge data, the latter from a network of 5 gauges over the Plateau. Storm periods were determined by examining plots of these measurements and requiring a 3-4 h period with no measurable liquid or snowfall to create a break between storms. Sixteen storms resulted from the 2-mo field program as shown in Table 2. Precipitation amounts are averages from all gauges with available data.

The wide range of per storm SLW flux seen in the Tushar data is also evident in Table 2. The Wasatch Plateau field program had more than twice as much flux as the wettest Tushar season. This was primarily due to one very wet storm on March 4-5, which was characterized by strong winds and warm temperatures. Otherwise, the range of per storm flux amounts is similar to Table 2 except that the Tushar Mountains had a greater number of storms with very little flux (<10 Mg).

Figure 2 plots the Wasatch Plateau total storm SLW flux against total storm precipitation. Considerable scatter exists with a rank correlation coefficient of 0.77, significant at the 1 pct level. But a relatively high correlation of 0.76 existed between precipitation and duration. With that effect removed, the partial correlation between flux and precipitation was 0.55, significant at the 5 pct level. Therefore, a significant relationship

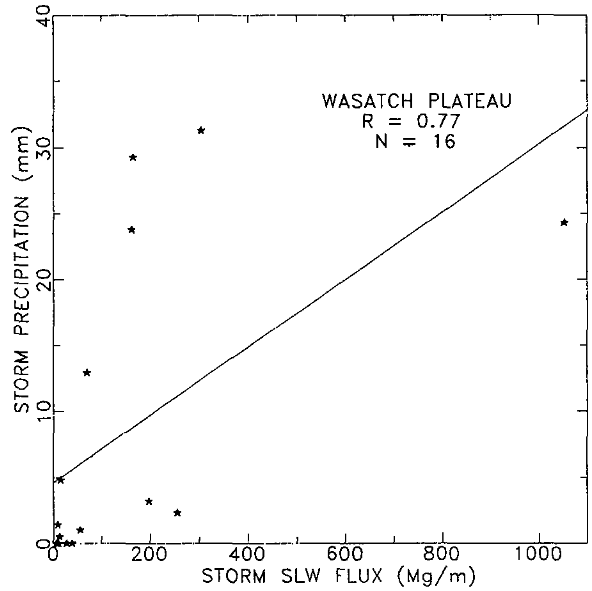

Fig. 2. Similar to Fig. 1 except storm total SLW flux plotted against precipitation for 16 storms over the Wasatch Plateau.

Table 2. - Storm duration, precipitation and SLW flux for 16 Wasatch Plateau storms from mid-January to mid-March 1991.

START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)	START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)
011400	56	23.8	162.9	022405	12	0.0	6.7
011623	36	0.0	39.6	022804	70	31.3	305.2
011905	12	1.0	55.4	030312	20	3.2	197.2
012817	6	0.5	12.1	030414	39	24.3	1052.5
020223	11	0.0	10.8	030610	35	1.4	8.7
021220	50	2.3	254.8	031000	9	0.0	27.8
021604	52	29.3	165.1	031014	34	12.9	69.8
021907	15	0.0	6.4	031400	22	4.8	14.9
				Yr Total	479	134.8	2389.9

between SLW flux and total snowfall also appeared to exist on the Wasatch Plateau.

Half the storm episodes had limited SLW flux (< 50 Mg), and little or no snowfall. The larger flux-producing storms had greater snowfall totals. A single storm produced 44 pct of the total flux for all storms.

3.3 Grand Mesa

Microwave radiometer observations of SLW were collected on the south edge of the east-west oriented Grand Mesa top during November and December, 1983, and January through March, 1985. These observations have been reported by Boe and Super (1986), but not on a per storm basis. The same data set was re-examined for this paper to enable comparisons with the other mountain ranges. Time histories were plotted of SLW and precipitation from a gauge on top of the Mesa near the radiometer. These plots were used in conjunction with hourly tabulations from both instruments to define storm periods. As with the Wasatch Plateau data set, a storm was considered ended at the beginning of any period of at least 3 to 4 h with no measurable snowfall or SLW.

A total of 65 storms existed according to the above definition, as listed in Table 3. While the storm definition was somewhat different than used with the Tushar Mountains data, both attempted to delineate nearly continuous periods with SLW and/or snowfall, separated from other such periods by at least a few hours. Distributions of storm durations are similar in Tables 1, 2 and 3, in which 50 to 70 pct of all storms lasted less than 24 h.

Tower wind speeds were measured above the Mesa, at 16 m above ground in 1983, and at the 70 m level in 1985. Hourly mean tower speeds were compared with 700 mb speeds from Grand Junction, Colorado, located just west of the Grand Mesa. This comparison was done for rawinsonde launch hours with SLW observed over the Mesa (National Weather Service rawinsondes are launched every 12 h). Reasonable relationships existed, with standard correlation coefficients of 0.66 and 0.69 between 700 mb speeds and those measured at 16 and 70 m above ground, respectively. Corresponding linear regression equations were used to estimate the 700 mb speeds from hourly mean tower speeds whenever SLW existed, and these estimates were used to calculate hourly SLW flux. The 700 mb level is approximately 300 m below the Mesa top, and most SLW exists in the lowest km above the Mesa top. Consequently, resulting SLW flux estimates are likely conservative.

All but 10 storms listed in Table 3 had complete radiometer data, and most of those 10 had missing observations for a small fraction of the storm. As in Table 1, flux estimates were adjusted upward in the partially missing cases, assuming the period with measured SLW represented the missing period.

Figure 3 is a plot of storm total SLW flux per meter crosswind vs total precipitation. Considerable scatter exists, with a rank correlation coefficient of only 0.54, but that is significant at the 1 pct level with the 65 available data pairs. However, when the effect of storm duration was removed, the partial correlation was only 0.14, not a significant value. A significant partial correlation (0.65) was found between precipitation and storm duration, controlling for flux, but no significant relationship existed between SLW flux and precipitation when the effect of duration was taken into account.

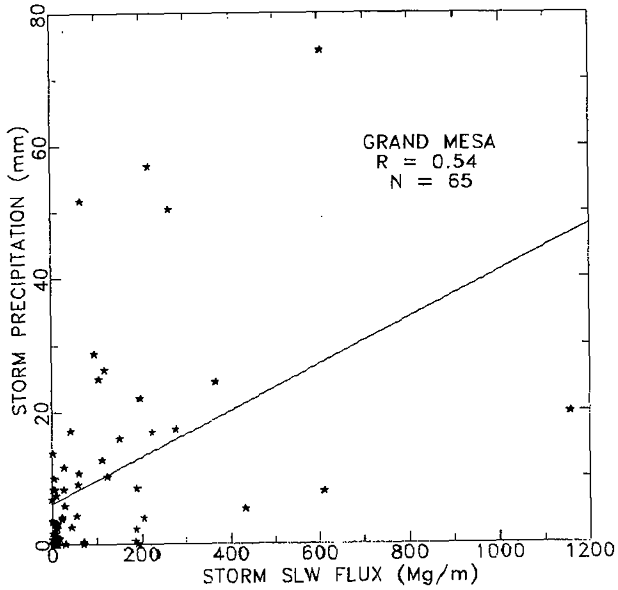

Fig. 3. Similar to Fig. 1 except storm total SLW flux plotted against precipitation for 65 storms over the Grand Mesa CO.

As in the similar figures of Utah storms, the same tendency exists in Fig. 3 for most significant SLW-producing storms (>50 Mg) to have at least several millimeters precipitation. Certainly, the inverse relationship does not exist that might be expected if large precipitation-producing storms were consistently highly efficient in converting SLW flux to snowfall and small storms were consistently inefficient. Instead, the data suggest large storms are only moderately efficient overall, probably because they have a combination of efficient and inefficient phases. An example of precipitation efficiency computations for one Utah storm appears in Sec. 3.6.

The total SLW flux for 1983 was 4725 Mg per meter of ridgeline. The 3-mo measurement period in 1985 produced more storms than the 2-mo 1983 period (36 vs 29), and more total storm hours (852 vs 751), but less precipitation (300 vs 336 mm). Most important, the 1985 observational period had less than half as much SLW flux with a total of 2076 Mg. This comparison suggests significant variability in SLW flux from different winter periods as also shown in Tables 1 and 2. This suggests that seeding potential varies markedly from winter to winter.

Similar to results from Utah, the seasonal Grand Mesa flux was caused by a few storm events.

Table 3. - Storm duration, precipitation and SLW flux for 65 Grand Mesa storms from Nov.-Dec. 1983 and Jan.-Mar. 1985.

1983

START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)	START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)
110101	18	.0	70.5	120506	12	.8	.6
110210	9	.0	3.2	120604	11	.9	16.3
110507	10	.0	2.3	120622	25	.4	186.1
111008	17	.3	5.8	120815	2	.0	6.0
111113	7	.3	7.1	120921	29	2.2	187.7
111124	35	10.7	59.5	121123	24	5.3	431.6
111315	17	8.3	26.0	121305	23	7.9	610.6
111719	6	8.3	2.4	121413	35	16.9	224.0
111924	68	56.9	218.8	121621	31	.0	192.3
112410	50	51.6	66.1	121819	38	24.4	366.5
112822	24	5.8	27.2	122213	52	19.8	1155.6
113005	20	1.0	12.2	122419	41	50.3	262.6
120103	48	15.9	151.1	122713	17	11.74	25.9
120310	17	22.0	198.0	122922	48	3.9	205.2
120407	17	10.0	3.8	Yr Total	751	335.6	4725.0

1985

START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)	START (MMDDHH)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)
10103	12	1.7	7.5	22211	25	3.8	20.9
10705	38	28.7	95.8	22511	15	8.3	5.9
11011	8	.3	2.7	22715	10	.2	9.1
11022	20	1.7	1.2	30204	4	.0	8.1
12101	36	17.1	41.1	30212	37	12.7	111.2
12419	6	.0	2.0	30524	11	.1	29.8
12616	26	3.1	11.5	30908	47	24.9	104.5
12801	37	13.8	2.3	31110	47	26.3	117.5
12916	34	6.8	.3	31312	6	.0	9.3
20204	47	7.4	8.7	31505	12	.1	5.9
20407	16	3.6	.0	31711	31	2.5	42.8
20505	38	2.7	9.3	32011	3	.0	12.3
20718	16	4.2	54.4	32110	16	4.1	21.1
20813	35	17.3	276.8	32515	6	.0	3.5
21004	18	2.4	10.4	32602	17	9.0	58.0
21210	15	.3	70.8	32701	76	74.3	605.8
21707	23	3.4	.9	33022	27	10.2	123.3
22001	31	8.4	189.3	Yr Total	852	299.6	2075.6
22201	6	.2	1.6				

For example, almost half the 1983 total flux was caused by 3 of the 29 storms. During early 1985, over half the total SLW flux was caused by 3 of the 36 storms.

3.4 Mogollon Rim

Flux estimates of SLW were reported by Super and Boe (1988), based on microwave radiometer and wind observations taken at Happy Jack Ranger Station on top of the Mogollon Rim of Arizona. Observations were collected over a 2-mo period. Winds were estimated from a combination of acoustical sounder measurements near 600 m agl, and rawinsonde data for higher levels. A storm episode was defined by the nearly continuous presence of SLW over Happy Jack and/or hourly precipitation recorded by any gauge in a 7 gauge network, having no interval greater than 2 h during which neither liquid water nor precipitation was observed.

For completeness, the SLW flux estimates for the 11 northern Arizona storms published by Super and Boe (1988) are listed in Table 4 which includes storm total precipitation measured at the radiometer site. These data are plotted in Fig. 4 for which a rank correlation coefficient of 0.69 was calculated, significant at almost the 1 pct level. The partial correlation between precipitation and flux was 0.75 with the effect of duration removed. The partial correlation between precipitation and duration (controlling for flux) was 0.87. Both partial correlations are significant at the 1 pct level suggesting that precipitation is related to both flux and duration. However, sample size is limited (N=11) so further cases should be obtained to test this suggestion.

The total flux for the 11 storms of Fig. 4 ranged from 1 to 419 Mg per meter of ridgeline. Three of the storms exceeded 230 Mg m^{-1} and the rest were under 95 Mg m^{-1}. Once again, a few storms produced most of the total SLW flux for the field season, and these were heavy precipitation producers as well. Storm durations tended to be longer in Arizona than at the other sites considered as only 3 storms were shorter than 24 h. Limited duration, local orographic storms were the exception on the Mogollon Rim (Super *et al.* 1989), unlike the case for more northern mountain regions.

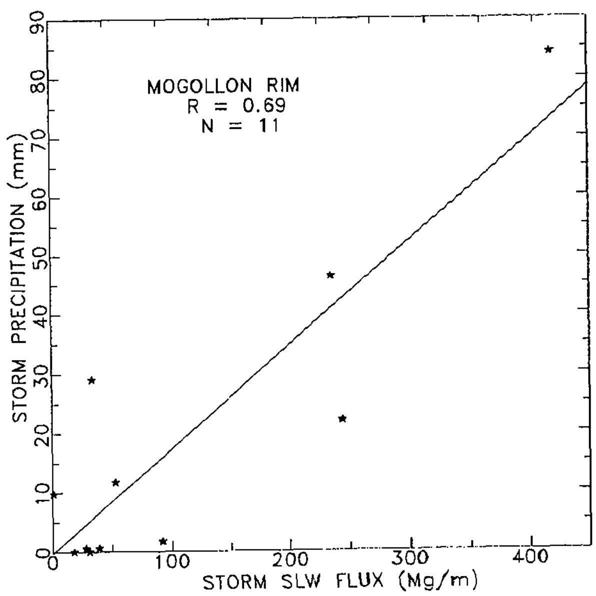

Fig. 4. Similar to Fig. 1 except storm total SLW flux plotted against precipitation for 11 storms over the Mogollon Rim.

3.5 Summary of Rank and Partial Correlation Coefficients

Table 5 presents a summary of rank and partial correlation coefficients for storm duration, precipitation and SLW flux for all 4 mountain regions previously discussed. All but 2 noted values are significant at the 5 pct level (almost all others at the 1 pct level).

Significant relationships appear to exist between precipitation and SLW flux, when the influence of storm duration is removed, at 3 of the 4 mountain regions. The exception is the Grand Mesa which has the largest storm population and, therefore, might be expected to be most representative of longer-term conditions. This exception, and the limited available populations from the other mountain regions, suggest some caution is in order before concluding that a positive relationship generally exists between storm precipitation and SLW flux. Further

Table 4. - Storm duration, precipitation and SLW flux for 11 Mogollon Rim storms from Jan.-Mar. 1987.

START (MMDD)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)	START (MMDD)	DURATION (h)	PRECIP. (mm)	SLW FLUX (Mg/m)
0115	64	29.1	34	0215	25	0.0	18
0119	26	9.8	1	0217	31	0.6	28
0128	5	0.0	31	0219	48	11.7	53
0130	26	22.0	244	0223	80	84.1	419
0204	16	0.6	39	0315	50	46.3	235
0213	22	1.7	92	Yr Total	393	205.9	1194

investigation of this possibility is warranted. However, the available data certainly do not support the hypothesis that storms with large snow amounts tend to have limited SLW flux.

A significant relationship between storm duration and precipitation amount is evident at all 4 mountain regions. This simply means that longer lasting storms tend to produce more snow.

Partial correlation coefficients between flux and duration, with precipitation's effect removed, are not shown. However, only the Grand Mesa's value was significant and the correlation was weak (0.38). Consequently, SLW flux does not generally appear to be related to storm duration. This suggests considerable variability in the efficiency of storms in converting flux into snowfall.

mass flux can be made over the radiometer site. SLW flux amounts computed for 3 h periods centered on rawinsonde launch times were available in Long (1986).

Ice flux estimates were made over the same 3 h time intervals. Area-weighted averages of contoured K_a-band dBZ values in Sassen *et al.* (1990) were computed and converted to ice mass concentration using the expression:

$$M_i \text{ (g m}^{-3}\text{)} = 0.032 \times Z_i^{0.505} \quad \text{(Sassen, 1987)},$$

where Z_i is the equivalent radar reflectivity factor for ice scatterers. No attempt was made to vary the expression for ice mass concentration with the types of ice particles that were observed at the surface. The expression was derived from data taken in deep ice clouds where Z_i varied from -15 to 25 dBZ; a range encompassing

Table 5. - Correlations between storm duration (DUR), precipitation (PPT) and SLW flux (FLUX).

		Rank Corr. Coeffs.			Partial Corr. Coeffs.	
Mountain region	No. pairs	PPT/FLUX	PPT/DUR	FLUX/DUR	PPT/FLUX (without DUR)	PPT/DUR (without FLUX)
Tushar Mtns.	27	0.70	0.72	0.55	0.52	0.57
Wasatch Plateau	16	0.77	0.76	0.66	0.55	0.53
Grand Mesa	65	0.54	0.76	0.62	0.14*	0.65
Mogollon Rim	11	0.69	0.84	0.38*	0.75	0.87

* not significant at 5 pct level

3.6 <u>SLW Flux, Ice Flux and Precipitation Efficiency in One Utah Storm</u>

In the discussion of SLW flux and precipitation, it was speculated that large precipitation producing storms also generally had large amounts of SLW flux because some phases of the storms were inefficient. For one storm in the Tushar Mountains, data existed to compute not only SLW flux, but ice flux as well, and to allow a computation of precipitation efficiency throughout most of the storm. The storm occurred on February 8-9, 1985, and has been well documented by Long *et al.* (1990) and Sassen *et al.* (1990). This storm produced the largest total SLW flux and second largest total precipitation of all storms sampled in the Tushar Mountains in 1985.

The microwave radiometer was positioned about 5 km west of the mountain crest, and collocated with a Doppler K_a-band radar during this storm. SLW flux passing this site could have been incorporated into precipitation in the region downwind of the radiometer. Likewise cloud ice passing overhead could have fallen as precipitation downwind of the radiometer and radar. So, the precipitation falling downwind of the radiometer can be used to estimate precipitation efficiency (over this portion of the barrier) if estimates of both SLW flux and ice

nearly all of the Utah data. A flux was determined by multiplying this average cloud depth ice concentration by the average westerly wind speed in the cloud layer. The flux was then converted to a mass per unit of barrier length by multiplying flux by the average 3 h echo depth and the length of the time period. Over the duration of the storm in question the estimated average 3 h ice mass concentration varied from 0.0112 g m^{-3} to 0.0788 g m^{-3}, and the wind speed varied from 8.2 m s^{-1} to 14.6 m s^{-1}. SLW flux, ice flux and precipitation all peaked during the period bracketing the surface cold frontal passage.

Finally, for each 3 h SLW flux period a 3 h average precipitation amount was computed from the three recording precipitation gauges available downwind of the radiometer-radar site. One gauge was 2 km northeast from the site, a second was 6 km east-northeast near the barrier crest, and the third gauge was about 12 km east-southeast on the lee slopes of the Tushar Mountains. It was assumed that the mean precipitation observed by these gauges represented the snowfall over a 15 km downwind distance from the radiometer and radar. The average precipitation depth was converted to a mass per meter of barrier length using the expression:

F_p (Mg m^{-1}) = P (mm) x 1000 (g m^{-2} mm^{-1}) x D (m)/10^6 (g Mg^{-1}),

where P was the average downwind precipitation depth and D was the downwind barrier distance (15 km) over which precipitation was assumed to be distributed. No attempt was made to vary the distance by period, and it is quite likely that precipitation fell downwind of the furthest downwind gauge during some periods. This would result in an underestimate of precipitation efficiency as it is defined below.

Here precipitation efficiency is estimated entirely from the condensed phase water budget, and evaporation and condensate production within the volume in question are ignored. For each 3 h period the precipitation efficiency was computed as the ratio of the precipitation mass flux downwind of the radiometer-radar site to the total horizontal SLW plus ice mass flux measured above the remote sensing site. Table 6 shows the 3 h flux totals and precipitation efficiency estimates for the February 8-9 storm. Table 6 clearly demonstrates that, for this particular storm, the prefrontal period was very inefficient in precipitation production where SLW flux generally contributed more than 70 pct of the total condensed flux. Although the frontal period was two to four times more efficient, the estimated efficiency peaked at about 60 pct. The relative contribution of SLW flux decreased in the postfrontal period, and efficiency remained similar to the frontal period. It is interesting to note that, by this definition of efficiency, a period with minimal SLW flux can still be relatively inefficient due to cloud ice not falling to the ground as precipitation. The final postfrontal period was "efficient" at converting cloud water to ice but the precipitation efficiency remained below 60 pct. Table 7 summarizes fluxes and efficiency by storm stage.

Although this storm produced only a moderate amount of precipitation, it does tend to verify the earlier speculation about SLW flux varying within a storm, with the greatest contribution coming from a particular storm stage. In this example the inefficient prefrontal stage provided the greatest total SLW flux, although the rate of production in the briefer frontal stage was highest (Table 6). A declining rate of production and greater efficiency in converting cloud liquid to ice resulted in the lowest SLW flux in the postfrontal stage. Sassen *et al.* (1990) and Long *et al.* (1990) discuss the specific mesoscale kinematics and cloud structure which, in large part, forced the distributions of water mass noted in Tables 6 and 7.

Table 6. SLW, ice and precipitation fluxes, and precipitation efficiency estimates for the Tushar Mountains storm of 8-9 February 1985.

Date	Time (MST)	SLW Flux (Mg m^{-1})	Ice Flux (Mg m^{-1})	Total SLW + Ice (Mg m^{-1})	Precip. Flux (Mg m^{-1})	Precip. Efficiency
2/8/85	1700[1]	39.8	7.96	47.76	2.54	0.053
	2000[1]	30.1	5.97	36.07	5.08	0.141
	2300[1]	7.4	18.16	25.56	3.81	0.149
2/9/85	0200[1]	32.1	9.51	41.61	10.16	0.244
	0500[1]	33.1	11.46	44.56	20.32	0.456
	0800[2]	43.4	43.49	86.89	38.08	0.438
	1100[2]	26.0	10.34	36.34	21.59	0.594
	1400[3]	10.7	8.46	19.16	7.62	0.398
	1700[3]	0.9	12.05	12.95	7.62	0.588

1 = Prefrontal 2 = Frontal with Mesoscale Bands 3 = Postfrontal

Table 7. - Average hourly SLW+ice flux, precipitation flux and precipitation efficiency by storm stage.

Storm Stage	Total SLW+Ice Flux (h^{-1})	Precipitation Flux (h^{-1})	Average Precip. Efficiency
Prefrontal	13.04 Mg m^{-1}	2.79 Mg m^{-1}	0.214
Frontal/Mesoscale Bands	20.54 Mg m^{-1}	9.94 Mg m^{-1}	0.484
Postfrontal	5.35 Mg m^{-1}	2.54 Mg m^{-1}	0.474

4. SUMMARY AND CONCLUSIONS

Storm total SLW flux estimates and precipitation measurements were examined with data sets from 4 mountain regions: the Mogollon Rim of Arizona; the Grand Mesa of Colorado; and the Tushar Mountains and Wasatch Plateau of Utah. Periods with microwave radiometer observations of SLW were limited to 2 mo on the Mogollon Rim and Wasatch Plateau, and to 5 mo at the two other sites.

An apparently significant relationship (rank correlation coefficient) existed between SLW flux and precipitation at each site, with the larger flux-producing storms also having greater precipitation amounts. When the effect of storm duration was removed, the partial correlation coefficient between flux and precipitation was still significant at 3 of the 4 mountain regions. Significant partial correlations existed between precipitation and storm duration (controlling for flux) at all locations.

None of the four data sets support the concept that large precipitation-producing storms are highly efficient in converting SLW flux to snowfall. The reverse was indicated; that is, storms with larger precipitation totals tended to have greater SLW flux. This indication suggests that large SLW flux-producing storms may be efficient in snowfall production during some phases and inefficient during other phases.

One example from a moderate-sized Utah storm supported this conceptual picture. A comparison of precipitation flux to SLW and ice flux was used as a means of computing precipitation efficiency. The prefrontal stage of this storm was very inefficient and contributed most to the total SLW flux. The frontal stage had a higher SLW production rate, but was more efficient and of shorter duration, and thus contributed less to the total SLW flux. The postfrontal stage contributed the least to the total SLW flux. It was also found that the final postfrontal stage was only about 60 pct efficient even though almost no SLW existed. Much of the radar-estimated cloud ice apparently did not fall to the ground as precipitation.

The frequency of small SLW-producing storms (<50 Mg flux per meter) was similar at all four locations, ranging from 50 to 67 pct of all storms. The frequency of large storms, with greater than 400 Mg m^{-1} of flux, ranged from 0 to 9 pct. Both the Wasatch Plateau and the Grand Mesa had a single exceptionally large SLW-producing storm exceeding 1000 Mg m^{-1}. In each area one to a few storms produced most of each season's SLW flux.

The storm frequency was markedly higher for the Grand Mesa, averaging 13 storms per month compared with 8 storms per month over the Wasatch Plateau, 5.5 per month over the Mogollon Rim and 5.4 per month over the Tushar Mountains. However, total observational periods for these mountain areas were limited. While a higher frequency of storm passages would be expected at more northern latitudes (i.e., the Wasatch Plateau and the Grand Mesa), a longer sampling period would be needed to determine if significant differences really exist in SLW episode frequency.

Distributions of storm durations are similar in Tables 1, 2 and 3, with from 50 to 70 pct of all storms lasting less than 24 h. Only 3 of 11 (27 pct) of the Mogollon Rim storms listed in Table 4 were that brief.

Because seeding potential can be expected to be related to SLW flux (among other factors), the major SLW-producing storms obviously should be identified for treatment. Identification can be done with real-time observations of SLW, using icing rate meters and radiometers. Rapid response seeding can be done with remote-controlled generators.

The previous discussion concerning total SLW flux per storm episode may give the impression that the only periods worth seeding have large amounts of vertically integrated SLW. In fact, Super and Boe (1988) examined the 2 mo of hourly (not storm total) microwave radiometer data from the Mogollon Rim to show that 44 pct of the total flux for the season was due to the 81 pct of all hours with mean cloud liquid water amounts of only 0.15 mm or less. Their study also showed that the 6 pct of all hours with liquid amounts in excess of 0.35 mm yielded almost 30 pct of the total flux. Similar results were shown for the Grand Mesa (Boe and Super 1986). These studies suggest that seeding may be appropriate both when SLW is abundant and when it is limited. Hours with large SLW amounts produce significant flux but are relatively rare. The numerous hours with small SLW amounts also produce significant flux over an entire winter.

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