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WINTERTIME CHARACTERISTICS OF SUPERCOOLED LIQUID WATER OVER THE GRAND MESA OF WESTERN COLORADO

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Abstract. Wintertime supercooled liquid water (SLW) observations have been made over the Grand Mesa of Colorado from early 1983 through March 1985. Measurements were made with aircraft, microwave radiometers, and tower-mounted icing meters. Results of analyses of this large data set are summarized. It was found that SLW was produced largely when 70 kPa winds measured by Grand Junction rawinsondes were southwesterly and in excess of 10 m s^{-1}, and when the air approaching the Mesa at the same level was near saturation. Aircraft measurements indicated that SLW was primarily limited to above and just upwind of the Mesa, except during some periods of prolonged synoptic-scale cloudiness. Highest SLW contents were generally recorded at the lowest levels sampled. Over a five month period, microwave radiometers recorded SLW over the Mesa 29% of the time, in a total of 115 episodes. Hourly averages of vertically integrated SLW were as high as 1.07 mm, but the median was 0.08 mm. Half of all episodes lasted less than 3 h, while 12% lasted longer than 12 h. Eighty percent of the hours with positive average SLW were contained within episodes of 5 h duration or longer. The SLW flux, if converted to snowfall over a 10 km distance, would be approximately half the natural precipitation.

1. INTRODUCTION

The importance of supercooled liquid water (SLW) to wintertime orographic weather modification potential is well recognized (Grant and Kahan, 1974; Cooper and Marwitz, 1980). As part of the assessment of wintertime seeding potential over the Grand Mesa of west-central Colorado, the Bureau of Reclamation's Colorado River Augmentation Demonstration Program (CRADP) has been monitoring liquid water and other parameters of interest on and near the Mesa during the winter months since early 1983. This paper summarizes this work, some of which has appeared in conference preprints, and much of which is documented in Bureau of Reclamation internal memoranda.

The ultimate goal of this applied research is to improve the wintertime orographic seeding technology applicable to the Upper Colorado River basin. Demand for water within the Colorado River Basin is anticipated to exceed present supplies early in the next century due to rapidly expanding population, and increasing useage by industry and agriculture (Lease, 1985).

The Grand Mesa is a high, flat-topped barrier, averaging about 3200 m msl. Upper air flow is not blocked by upwind barriers for flow from the north, west, or south. The top is accessible year-around by an all-weather highway. Airport facilities at Montrose and Grand Junction allow prompt access by aircraft.

Measurements of SLW have been made over the Mesa by aircraft-borne sensors, and on the Grand Mesa by microwave radiometers and tower-mounted icing rate meters.

2. INSTRUMENTATION

The primary sensor used in the measurement of SLW over the Grand Mesa has been the dual-channel microwave radiometer. Two similar units of the type discussed by Hogg, et al. (1983), have been used at different times on the Mesa.

One radiometer was that owned and operated by the Bureau of Reclamation, the other was owned by Utah State University (USU). Both units operate at the 20.6 and 31.65 GHz bands. Blowers were implemented to keep the radiometer reflectors clean. The Bureau unit was used during the months of November and December 1983, and the USU unit was used from January through March of 1985. Both units were operated in the vertically-pointing mode near Island Lake, just south of and about 120 m below the Mesa top (Fig. 1). Thus, measurements represented the vertically integrated supercooled liquid water from the surface to cloud top. The two units were operated side-by-side during May 1985. The resulting liquid water measurements agreed well and were consistent, even during periods of convection.

Airborne measurements of liquid water were made during portions of the months of January, February, November, and December 1983, by the University of North Dakota's Citation II cloud physics aircraft. Data from a Johnson-Williams (J-W) hotwire sensor and a Rosemount icing rate meter were supplemented by integrated FSSP data.

Additional SLW measurements were obtained by a tower-mounted Rosemount model 871CB1 icing rate meter. The icing rate meter consists of an exposed metal rod, upon which airborne supercooled water accretes. When a given mass (determined by wind tunnel calibration) has accreted, the sensor "trips", heating sufficiently to shed the ice. The icing rate meter was affixed at the 70 m level to a tower atop the Grand Mesa, and yielded data through the winter of 1984-85.

3. METEOROLOGICAL CONDITIONS THAT PRODUCE SLW

A number of dynamic and thermodynamic variables were examined to define those meteorological conditions most likely to result in the production of significant SLW. Data obtained by National Weather Service (NWS) rawinsondes released from Walker Field (GJT) near Grand Junction, Colorado, were utilized to obtain the 70 kPa winds, temperatures, and dew points. Additional wind data collected at the 70 m level on a tower atop the Mesa, as well as temperature

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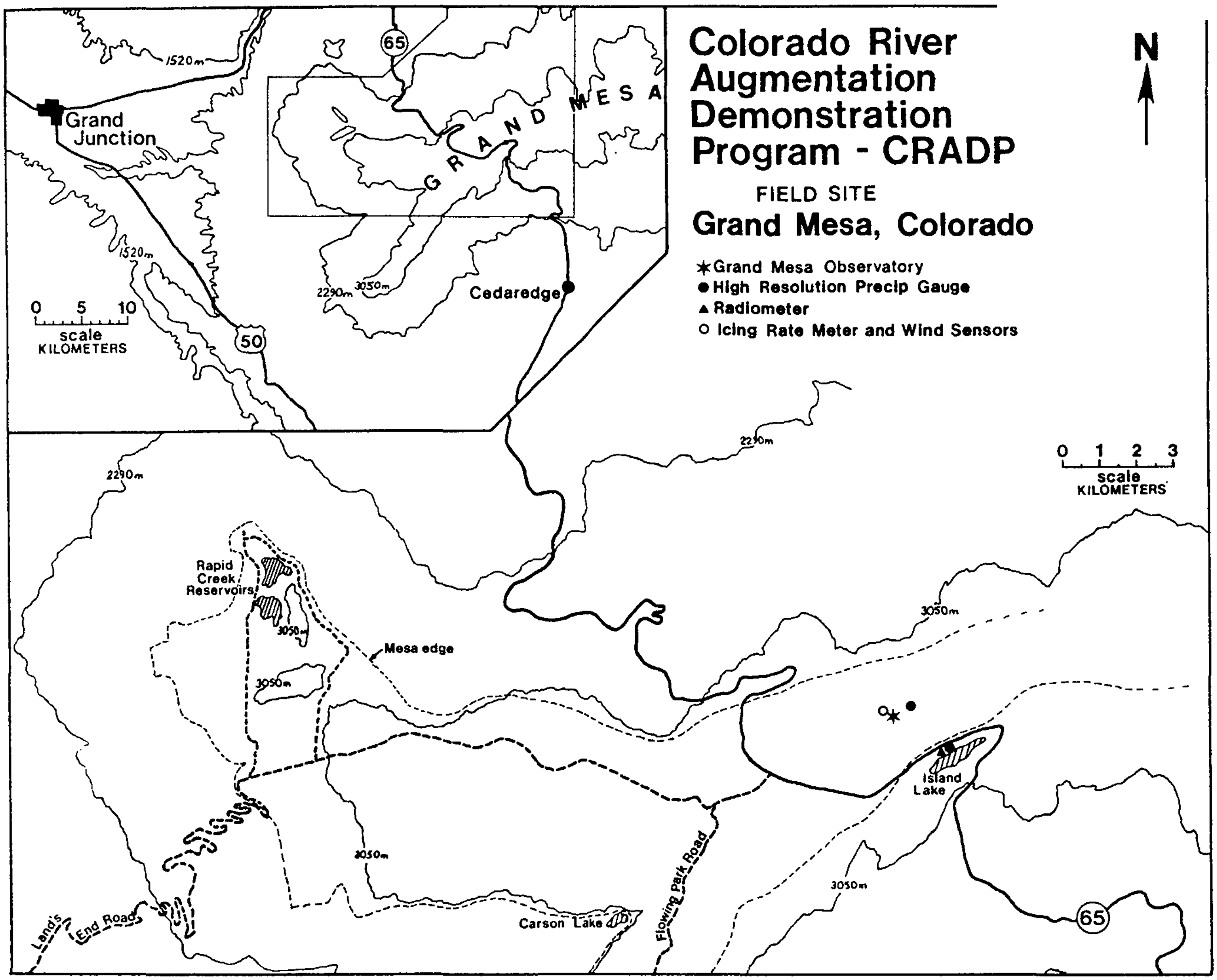

Fig. 1. Colorado River Augmentation Demonstration Program (CRADP) field site on the Grand Mesa of western Colorado.

and precipitation data from near the Grand Mesa Observatory (GMO) were also used (see Fig. 1). The release point of the GJT rawinsondes is 44 km west of the GMO.

The distribution of winds recorded by the GJT soundings was examined for 417 h when the average SLW recorded by a microwave radiometer was ≥0.01 mm. Virtually all hours when SLW was detected had 70 kPa winds from between 195 and 315 degrees true. Within this 120 degree window, 154 of the hours (37%) occurred with winds between 210 and 240 degrees. The mean speed of the SLW-producing winds was 10.4 m s^{-1}.

A second important ingredient for SLW production was, not surprisingly, moisture. Significant SLW was seldom observed when the GJT 70 kPa temperature-dewpoint depression was > 5°C.

Virtually no SLW was observed when temperatures atop the Mesa were colder than -14°C, though 18% of all hours during the 5 month period were at least this cold. The greatest SLW production was always coincident with Mesa top temperatures in the -4 to -10°C range.

In addition, SLW production on the Grand Mesa is linked to the passage of short-wave troughs or low pressure centers. Of the 23 heaviest SLW episodes recorded during the winters of 1983-84 and 1984-85, 17 were associated with short-wave trough passages, and the other 6 were with low pressure centers closed at the 70 kPa level. Nineteen of the episodes were linked to 70 kPa winds from the south or southwest, while only 3 were concomitant with northerly or northwesterly winds.

The vertical motions associated with the upper air features frequently combined with orographically induced motions to produce substantial SLW episodes. In the absence of the troughs and lows, significantly less SLW was observed, if any was detected at all.

Infrequent exceptions to this were some convective cases, which were observed in the absence of significant winds or upper air features. Momentary peaks of SLW near 1.0 mm were occasionally recorded, but the hourly averages in such cases were invariably an order of magnitude less.

Often, the above parameters were at or near their required values, but little or no SLW was detected by the radiometer. Precipitation records from a nearby gauge were examined, only to find that many of these "enigmatic" cases were periods of significant, even heavy precipitation. In plots of hourly averages of SLW vs cross-barrier wind flow (not shown), scatter was greatly reduced by excluding periods when precipitation rates atop the Mesa exceeded

0.15 mm h^{-1}. A large number of hours during which little SLW was observed concomitant with significant cross-barrier wind were thus eliminated from the plots. However, over 50% of the high-SLW data were also eliminated, which demonstrates that much SLW was often present even during periods of significant natural precipitation.

Rauber, et al. (1984), found that in the Park Range of the northern Colorado Rockies, intense storm periods with heavy precipitation had little liquid water. This appears at times to be true also over the Grand Mesa, but the large number of exceptions implies that, unlike the Park Range, significant SLW may exist even during some periods of heavy natural precipitation.

4. SPATIAL DISTRIBUTION OF SLW

Liquid water measurements recorded by aircraft flights over the Grand Mesa were classified as either along-axis (southwesterly winds) or cross-axis (north or northwesterly winds), based upon aircraft-measured winds in free air upwind. Flight altitudes were normally 3.7 km msl, 300 m above the highest terrain, and sometimes at 300 m increments above that level when cloud depths warranted. Headings were normally parallel to the free air winds.

For each kilometer along each pass over the Mesa, liquid water amounts were averaged and classified as either: (a) no liquid water, (b) a trace to 0.2 g m^{-3}, (c) >0.2 to 0.4 g m^{-3}, or (d) >0.4 g m^{-3}. These values were derived primarily from the J-W probe data, which suffer from zeroing errors and other problems (Strapp and Schemenauer, 1982) and hence have only semi-quantitative validity. The distribution of liquid water for along-axis cases is shown in Fig. 2. Based on about 35 passes at 3.7 to 4.1 km msl, the highest liquid water contents (LWC) were found above the Mesa top, from the southwestern edge to about 30 km downwind. Of the 15 passes made at 4.4 km and above, the greatest LWC was observed near the upwind edge (Holroyd and Super, 1984). Coincident measurements of SLW made by the radiometer were in reasonable agreement with the aircraft values.

Since the greater amounts of SLW were most often recorded on the lowest passes, the possibility exists of clouds being too warm to seed with silver iodide (AgI). Surface temperatures recorded during SLW episodes were most often between -4 and -10°C, and a cloud 300 m thick (the height of the lowest passes above the highest terrain on the Mesa top) would likely be no colder than -6 to -12°C. In the warmer cases, seeding with dry ice might be required.

The cross-axis distribution of LWC varied depending on the cloud type over the Mesa at the time of sampling. November and December 1983 were typified by orographic cap clouds (Fig. 3), and a much narrower distribution was observed with an attendant lee wave cloud downwind. January and February 1983 were dominated by synoptic-scale cloudiness (Fig. 4), and significant LWC was found both upwind and downwind of the Mesa. Subsidence dramatically reduced the LWC within 7 km of the southern edge of the Mesa top in both periods.

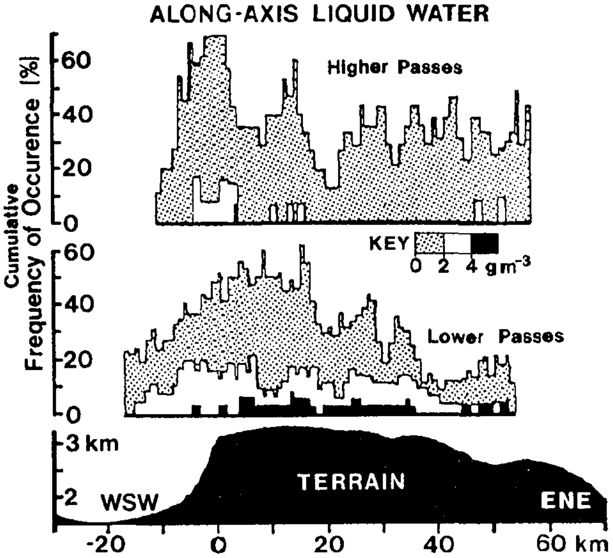

Fig. 2. Distribution of liquid water observed by aircraft during along-axis passes in west-southwesterly flow over the Grand Mesa. Composites of 35 passes between 3.7 and 4.1 km msl (lower passes) and 15 passes between 4.4 and 5.4 km msl (higher passes) are shown.

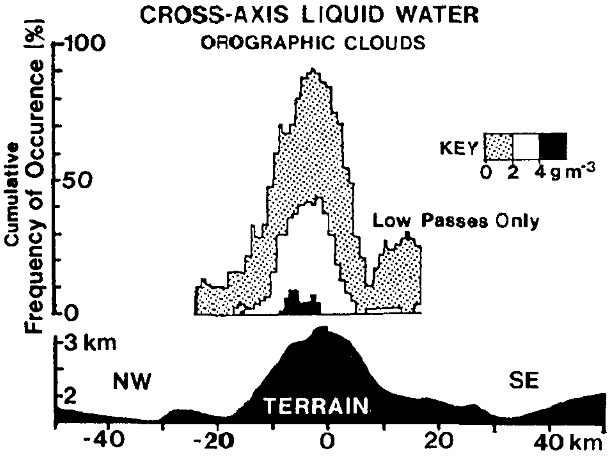

Fig. 3. Cross-axis distribution of liquid water observed in northerly flow cases that produced local orographic clouds. All passes were made at 3.7 km msl.

Wind roses (not shown) were constructed from data collected by sensors 70 m and 16 m agl at the GMO for periods of SLW production. Whereas the mean GJT 70 kPa wind vector for this period was 210 degrees at 12.4 m s^{-1}, the vector recorded by the 70 m sensor was 180 degrees at 7.9 m s^{-1}, a rotation of 30 degrees. The 16 m sensor recorded a vector of 165 degrees at 5.2 m s^{-1}, which is perpendicular to the Mesa axis at the GMO. Some turning of the winds was observed in the aircraft wind data, which also suggested deceleration (damming) on the upwind side, and acceleration in the lee.

Thus, a southwest wind upwind of the Mesa will likely become a southerly, or even southeasterly wind at lower levels over it. SLW

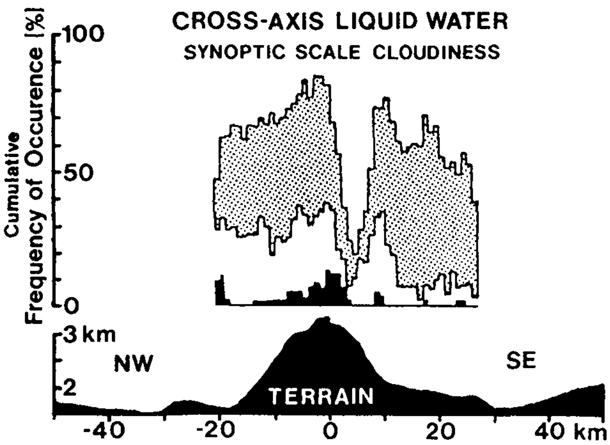

Fig. 4. Cross-axis distribution of liquid water observed during northerly flow cases with predominantly synoptic-scale cloudiness. Passes were made at 3.7 and 4.1 km msl.

generated in such cases probably does not remain over the Mesa as long as Fig. 2 suggests, but rather passes over the Mesa in a more direct fashion. Similar effects were observed on the north side of the Mesa; the lower winds became perpendicular to the Mesa as they approached it. Even southwest flow entering the "convergence notch" between the arms of the Mesa probably crosses the Mesa and descends on the north side relatively quickly. This rapid transit and descent may pose a targetting problem, as the time available for newly nucleated crystals to grown in an SLW-rich environment will be relatively short, on the order of 0.5 h given an average cross-barrier wind component of $10\ m\ s^{-1}$.

None of the aircraft LWC data were collected during any of the 23 previously-identified episodes of heavy SLW, though two flights were made in conditions that later developed into major episodes. Most of the heavy SLW episodes occurred with GJT 70 kPa winds from more southerly directions than sampled by the aircraft. Significant icing did occur on several occasions, and in one instance a flight was terminated due to heavy icing, which suggests that research aircraft may not be able to remain on station during the heaviest SLW episodes.

5. TEMPORAL DISTRIBUTION OF SLW

Radiometer data were recorded as two-minute averages, and subsequently averaged to the nearest 0.01 mm for 1 h intervals for the periods of November and December 1983, and January through March of 1985. Periodic tipping curves were constructed to maintain proper calibrations. The radiometers were always operated in a vertically-pointing mode. In the absence of liquid water, the liquid values recorded were slightly negative or zero. Thus, any positive 1 h average represented the actual presence of liquid water.

Over the five months, valid data were recorded for 3351 h, or 92% of all possible hours, of which 958 h (29%) had average liquid water amounts of 0.01 mm or more. Surface temperatures recorded at the GMO (elevation 3290 m) during periods of liquid water were $<0^{\circ}C$ 98% of the time; therefore, the liquid water recorded by the radiometers can be considered supercooled.

5.1 Distribution of SLW Amounts

The distribution of SLW amounts is shown in Fig. 5. The median value is 0.08 mm. Only 5% of the 958 h were >.50 mm, while 57% indicated .10 mm or less. The greatest hourly average was 1.07 mm (Super and Holroyd, 1985).

To put these amounts into perspective, consider a hypothetical environment that is shear-free, with the wind speed from the surface upward being constant and equal to that measured by the sensor 70 m agl at the GMO. The SLW flux from the radiometer to cloud top and perpendicular to the wind would then be the integrated SLW multiplied by the wind speed. If one assumes that all the SLW flux might be precipitated uniformly within a 10 km distance (approximately the cross-axis width of the Mesa), an upper limit on seeding potential can be estimated.

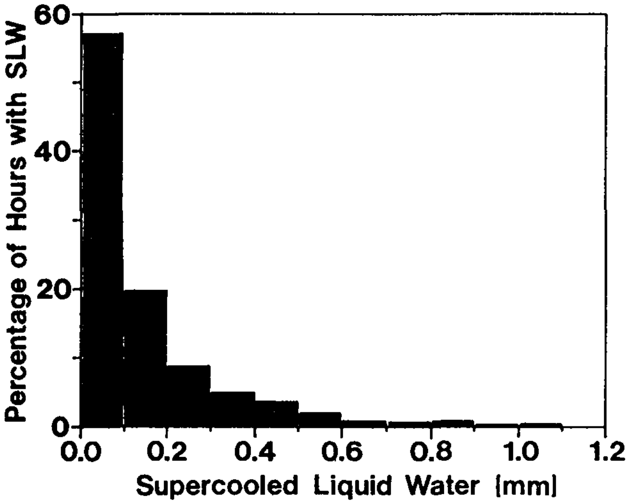

Fig. 5. Distribution of 1 h averages of supercooled liquid water (SLW) recorded by microwave radiometer for 958 h during November and December 1983, and January through March 1985.

For the January through March 1985 period during which the 70 m wind sensor was in operation, 423 h with average SLW ≥0.01 mm were recorded. As measured by a high-resolution precipitation gauge near the radiometer, 275 mm of precipitation actually fell during these three months. The maximum additional precipitation that might be obtained by complete precipitation of the SLW flux within 10 km is 127 mm (Fig. 6). This amounts to an additional 46%, most of which would be derived when SLW amounts of 0.30 mm or less were recorded by the radiometer. The higher SLW amounts did not generally contribute significantly to the total flux. The exception was a single 5 h period in late March during which SLW between .80 and .90 mm was recorded, which accounted for 15% of the total flux.

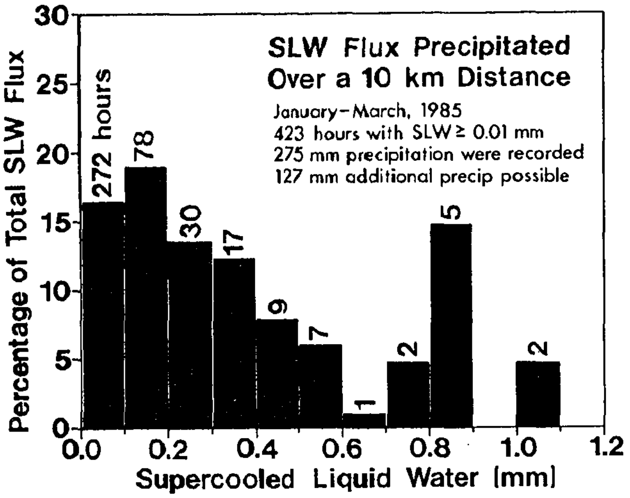

Fig. 6. Flux of supercooled liquid water (SLW) distributed evenly over a 10 km distance downwind of the radiometer. Calculations were based on integrated SLW measured by microwave radiometer, and winds recorded 70 m agl atop the Grand Mesa during January through March 1985. The 127 mm of precipitation calculated was 46% of the 275 mm that was actually recorded by a nearby high-resolution gauge.

5.2 Distribution of SLW Episodes

An episode of SLW was defined as the continuous presence of SLW as measured by the radiometer, uninterrupted for longer than 2 h. If SLW was again detected within 2 h, the episode was considered to be continuous. Using this somewhat arbitrary definition, many hours usually passed prior to the onset of another episode. Periods of missing data were ignored. Hours of valid data immediately preceding or following missing data were not evaluated due to episode length ambiguity.

The cumulative distribution of the 115 SLW episodes recorded during the 5 month period is shown in Fig. 7 (solid line). Fifty percent of the episodes were < 3 h in duration, while only 12% were 12 h duration or longer. The longest episode was 41 h.

If one considers not the number of episodes, but rather the number of hours contained in the episodes of any given duration, the perspective changes considerably. For example, Fig. 7 shows that 50% of all SLW episodes were 3 h, but the number of hours contained within episodes of 3 h and less was only 14% of the total hours of SLW! Thus, the cumulative distribution of hours of SLW shows that 50% of all hours of SLW were contained in episodes 15.7 h and longer (Fig. 7, dashed line).

The SLW episodes longer than 5 h comprised 80% of the total hours, so the time available for an effective seeding response was often greater than originally thought. A 2 h time lapse from the detection of SLW to the onset of effective nucleation (by seeding) would result in 210 h (24%) being "missed". The impact in terms of missed flux might be considerably less, as the greater SLW amounts in any given episode frequently did not occur at the episode onset, but rather some hours later.

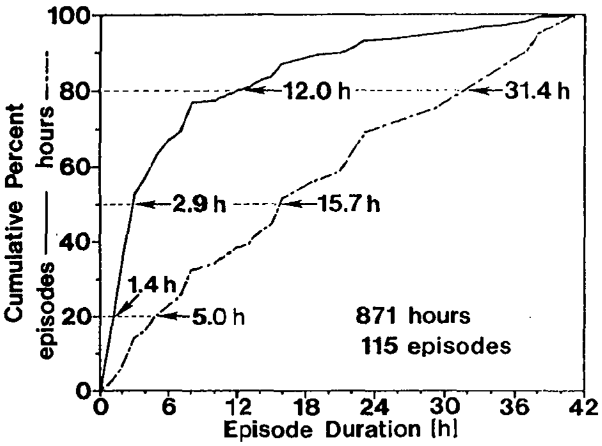

Fig. 7. Cumulative distribution of SLW episodes (solid line) and hours of SLW (dashed line) as a function of episode duration. While over 50% of the episodes were less than 3 h duration, 80% of the hours of SLW were recorded within episodes longer than 5 hours.

5.3 Rosemount Icing Rate Meter

Wind tunnel calibrations showed that the Rosemount icing rate meter would "trip" at an average loading of 0.09 g. Approximate values of liquid water concentration (LWC) were calculated from the number of trips in 1 h, using the formula:

$$LWC = (nm)/(cAs) \qquad (1)$$

where n is the number of trips in 1 h, m is the mass loading constant, herein 0.09 g, c is the number of seconds in 1 h, A is the cross-sectional area of the probe (1.77 cm^2), and s is the wind speed in m s^{-1}. Simplifying,

$$LWC\ (g\ m^{-3}) = 0.141\ n/s \qquad (2)$$

This value is an hourly average and caution must be used in its interpretation. In some cases a portion of the ice accreted prior to a trip may have been deposited during the previous hour. This is highly probable, especially in low icing rates.

The icing rate meter tripped during 103 h of January, February, and March 1985. This is just 7.8% of the total hours in the 3 month period, and less than one-third the frequency of events recorded by the radiometer during the same priod. The radiometer often detected SLW when the icing rate meter did not, especially when winds were from the south or southwest. It is improbable that the SLW was being naturally depleted prior to reaching the icing rate meter, as the GMO is less than 2 km from the radiometer, and at a higher elevation. More likely, the supercooled cloud simply lay above the 70 m sensor height, which was thus not exposed to the icing conditions. This has been observed by personnel atop the Mesa in some cases.

A serious drawback to the icing rate meter is that it senses at a single point and relies upon the wind, whereas the radiometer sample volume is a slender cone and independent of the wind. This suggests that such meters should be installed as far above the surface as practical, so that they are subjected to the maximum number of events. In addition, amounts of rime below the instrument threshold of detection may accrete and later sublimate, and thus never be recorded.

In northerly flow the radiometer normally recorded SLW concomitant with icing by the Rosemount sensor. However, the icing rate meter did record significant icing in northerly flow during 9 h when the radiometer detected no SLW. Subsidence of the cloud on the south side of the Mesa may have contributed to the discrepancy (see Fig. 3). If subsidence associated with northerly flow is occasionally sufficient to eradicate the SLW prior to its passage over the radiometer, it is possible that greater seeding potential exists for these cases than is otherwise indicated. Conditions were correct for hoarfrost formation during 4 of the 9 hours, which may have contributed to the icing in those cases.

6. DISCUSSION

The majority of the SLW episodes recorded on the Grand Mesa during the winters of 1983-84 and 1984-85 occurred when moist air flowed over the Mesa from the southwest at speeds of 10 m s^{-1} or more, and the Mesa surface temperature was warmer than -14°C. Usually, an upper air feature (trough, low) was present also, at least in the cases with the greatest SLW.

SLW was most often concentrated in the lower levels above the Mesa top, and usually diminished sharply as the air subsided on the lee side. Because the surface temperature during SLW episodes was normally between -4 and -10°C, the liquid water zone might be too warm for effective silver iodide seeding in many cases.

In cases of southwest flow as defined by GJT 70 kPa winds, the SLW profile was found to be continuous along the Mesa axis. However, because the low level winds over the Grand Mesa tended to be perpendicular to it even when flow upwind was not, transit times were limited near the surface. An ice crystal on the upwind side of the Mesa would be exposed to SLW for about 0.5 h, given a 10 m s^{-1} wind.

Aircraft data are lacking for high-SLW cases in southwesterly flow, but as earlier suggested, flight may become difficult in such cases due to airframe icing.

Half of all SLW episodes lasted less than 3 h, but those short episodes contained only 14% of all hours of SLW. Even if response to SLW detection was no faster than 2 h, over 75% of the hours of SLW could still be seeded.

In a few northerly flow cases, icing was detected by the tower-mounted Rosemount icing rate meter but no SLW was recorded by the radiometer, which suggests that subsidence beyond the south rim of the Mesa may significantly reduce the SLW detected by the radiometer. Somewhat greater seeding potential in northerly flow cases may exist than indicated by existing radiometer data.

The seeding potential over the Grand Mesa appears quite promising, based on radiometer and aircraft data from two winters. More needs to be learned about the flow patterns over and around the Mesa, which are proving to be complex. These patterns are of considerable importance in properly answering questions dealing with targetting of seeding material and the resulting ice particle trajectories.

Transport and diffusion studies, as well as some seeding tests, are among the topics scheduled to be addressed in the near future on the Grand Mesa.

ACKNOWLEDGEMENTS

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