Supercooled Liquid Water Structure of a Shallow Orographic Cloud System in Southern Utah

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ABSTRACT

A case study of an orographic cloud system that developed over the mountains of southern Utah is presented. The storm system contained supercooled liquid water over several hours, and produced almost no precipitation. Because of the high liquid water content, low ice particle concentrations, minimal precipitation, and long duration, the storm appears to have been a good candidate for seeding to augment precipitation. A preliminary analysis of the climatological frequency of orographic cloud systems over these mountains is discussed.

1. Introduction

The federal/state weather modification research program of the National Oceanic and Atmospheric Administration (NOAA) is designed to address weather modification research problems by superimposing research efforts on existing operational weather modification programs. One component of the federal–state program has been to study wintertime cloud systems that form over the mountains of southern Utah. A key research problem has been to identify cloud systems that contain persistent supercooled water, but produce little precipitation. In this note, some preliminary results of this program are discussed. A case study of an orographic cloud system that developed over the Tushar Mountains of southern Utah on 27/28 February 1983 is presented. This storm system contained supercooled liquid water over a long time period and had near-zero precipitation efficiency. Because of excessive snowpack in the Tushar region prior to this storm, it was not seeded.

2. Research site and instrumentation

During the storm, airborne, remote sensing, and ground-based instrumentation were used to study the cloud system structure. Figure 1 shows the location of the study area in Utah and the ground based instrumentation used during the 1983 field program. The primary instruments used in this study include a Forward Scattering Spectometer Probe (FSSP), a Johnson-Williams (JW) liquid water content hot wire device, and a Two-Dimensional Cloud Optical Array Spectrometer (2DC), all mounted on a Cheyenne II cloud physics aircraft supplied by Colorado International Corporation, and the NOAA Wave Propagation Laboratory dual-channel microwave radiometer. Additional observational support was provided by a Ku-band (1.79 cm) vertical radar supplied by Colorado State University, a surveillance C-band (5 cm) radar, rawinsondes, and precipitation measurements provided by North American Weather Consultants. The aircraft, ground based instrumentation and data reduction techniques have been described in other papers (Hogg et al., 1983; Rauber et al., 1986; Rauber and Grant, 1986; Sassen et al., 1986).

3. Storm of 27/28 February 1983

At 1200 (all times UTC) on 27 February 1983, a surface cold front had moved into Nevada and southern California. The front was associated with a weak upper trough located well off the West Coast. As the front approached the study area in southwest Utah, it weakened. The front reached the Tushar mountain region in Utah at 0300 on 28 February. The 50 kPa shortwave axis moved over the region shortly afterward. Virtually all precipitation associated with this storm fell after the front arrived in the study area and the upper air trough moved over the Tushars. However, for nearly 11 hours prior to the arrival of the surface front, a shallow orographic cloud system was present over the Tushar Range. During part of the time, convective cells were observed emerging from the cloud near the Tushar Crest.

Three hourly special rawinsondes were launched from the valley upwind of the Tushars during the period when this orographic cloud was present. The time section analysis of equivalent potential temperature, dew-point depression and winds derived from these

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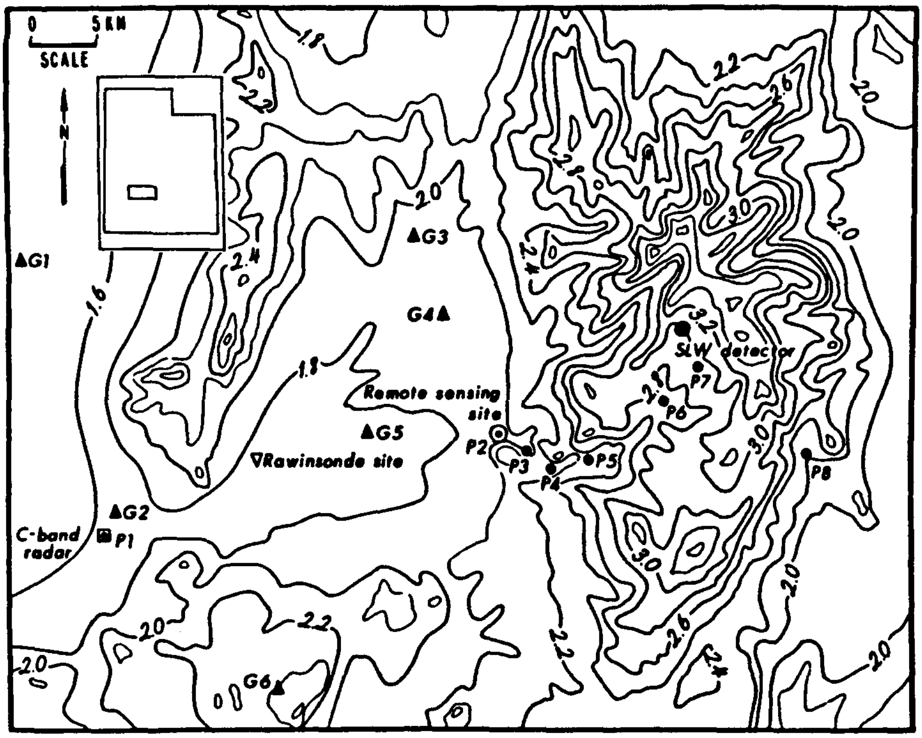

FIG. 1. A topographical map of the study area in southwestern Utah, showing the recording precipitation gages arrayed across the Tushar Mountains (P1–P8), the AgI and indium oxide aerosol generators (G1–G6), the supercooled liquid water probe (SLW), the Minersville C-band radar, the Adamsville rawinsonde site, and the remote sensor site at the mouth of the Beaver Canyon. Contour units are in km.

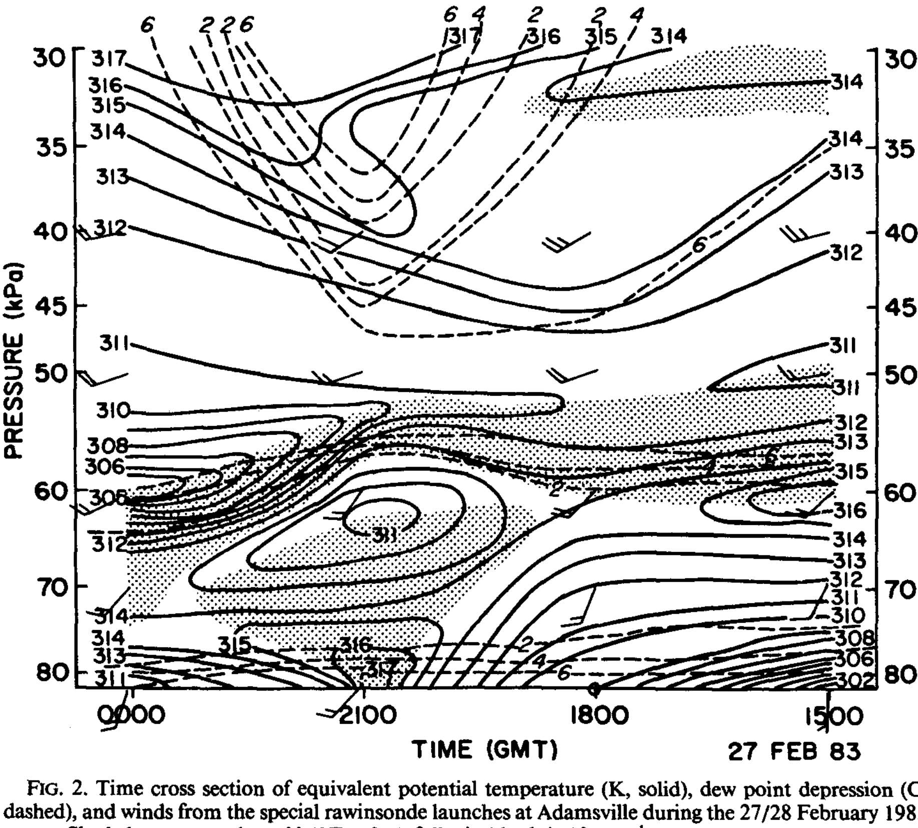

FIG. 2. Time cross section of equivalent potential temperature (K, solid), dew point depression (C, dashed), and winds from the special rawinsonde launches at Adamsville during the 27/28 February 1983 storm. Shaded areas are where $\partial\theta_e/\partial Z < 0$. A full wind barb is 10 m s^{-1}.

rawinsondes is shown in Fig. 2. Prior to 2300, potentially unstable layers were present between the 60 and 50 kPa level. During this time, condensation occurred only in the low levels associated with the orographic cloud present over the Tushar Ridge. Around 2300, a strong minimum in equivalent potential temperature developed at the top of the saturated layer. Orographic lift near ridgetop, afternoon heating, sufficient moisture and potential instability all contributed at this time to the development of convective elements emerging from the orographic cloud along the ridge line. Some of these convective cells reached as high as 6000 m (all heights with respect to mean sea level), but most had lower tops. The orographic cloud and convective elements present over the Tushars between 2300 and 0300 produced no precipitation upwind of the crest, trace amounts downwind of the crest, no echoes on the scan surveillance radar, and weak scattered echoes on the Ku-band radar. However, radiometric measurements and aircraft penetrations through this cloud system indicated that it contained supercooled water. At 0230, the approximate time of arrival of the surface front, a high layer of clouds developed over the Ku-band radar. By 0330, strong convection developed and precipitation began to fall. This note is concerned with the supercooled liquid water structure during the orographic period of this storm between 1500 and 0300.

4. Aircraft measurements

A schematic of the 27/28 February 1983 orographic cloud system showing the topography, approximate cloud boundaries, aircraft track, and radiometric beam positions at 90° and 270° azimuth is shown in Fig. 3. Approximate cloud boundaries were drawn based on aircraft and remote sensing measurements, as well as visual observations from the aircraft crew. The locations within the cloud system where the supercooled liquid water content exceeded 0.05 g m^{-3} are shown by the heavy lines along the track. Regions where ice particles were observed are noted by slanted lines. The temperatures measured during the soundings at 2345–0002 and 0057–0104 are also shown. Johnson-Williams liquid water content, 2DC particle concentrations in three size ranges and temperatures for the complete flight are shown in Fig. 4.

The aircraft operated in the area from 2344 to 0104. This was the period when emergent convective cells were present over the Tushars, an orographic cloud was present in the low levels, and no significant cloud cover was present over the western valleys. From the cross section shown in Fig. 3, one can see that the aircraft sampled the upper regions of the cloud system. The sounding performed west of the mountain was in clear air over the valley, primarily to melt ice accumulated during the flight.

Three distinct regions of supercooled liquid water were observed in the storm by the aircraft. The first and primary region was in the cells emerging from the shallow orographic system over the windward side of the Tushar Mountains. In this region, JW liquid water content measurements were as high as 0.68 g m^{-3} with many measurements above 0.20 g m^{-3}. Liquid water content measurements by the FSSP showed similar structure, but averaged 1.8 times larger than those measured by the JW during the entire flight. The reason

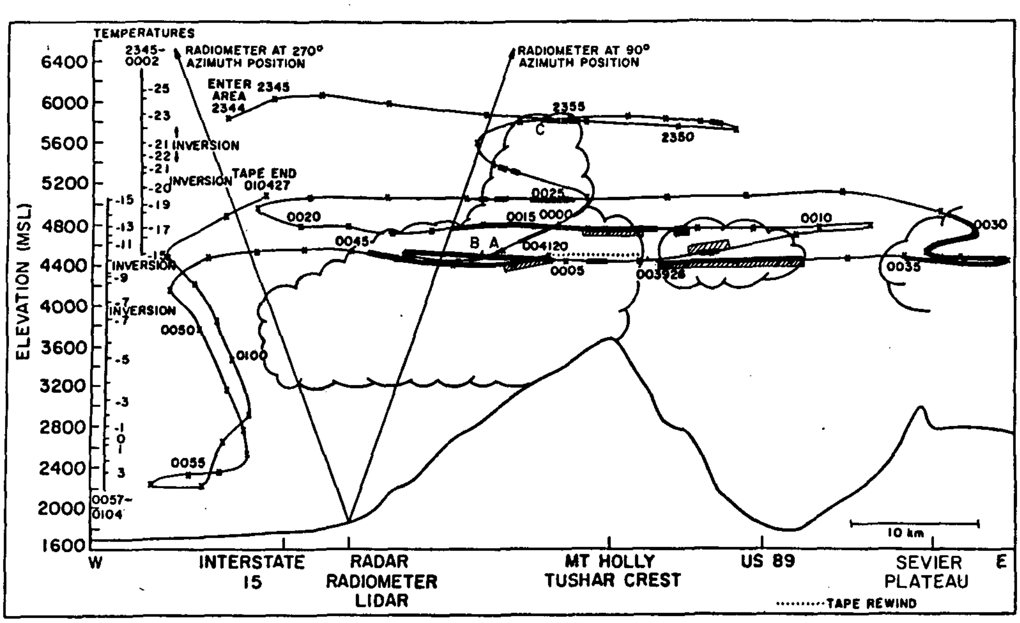

FIG. 3. Aircraft flight track, radiometer beam positions at 90° and 270° azimuth, topography and approximate cloud boundaries for the 27/28 February 1983 storm system. The topography is taken under the flight track which was approximately parallel to the mean wind direction at flight level.

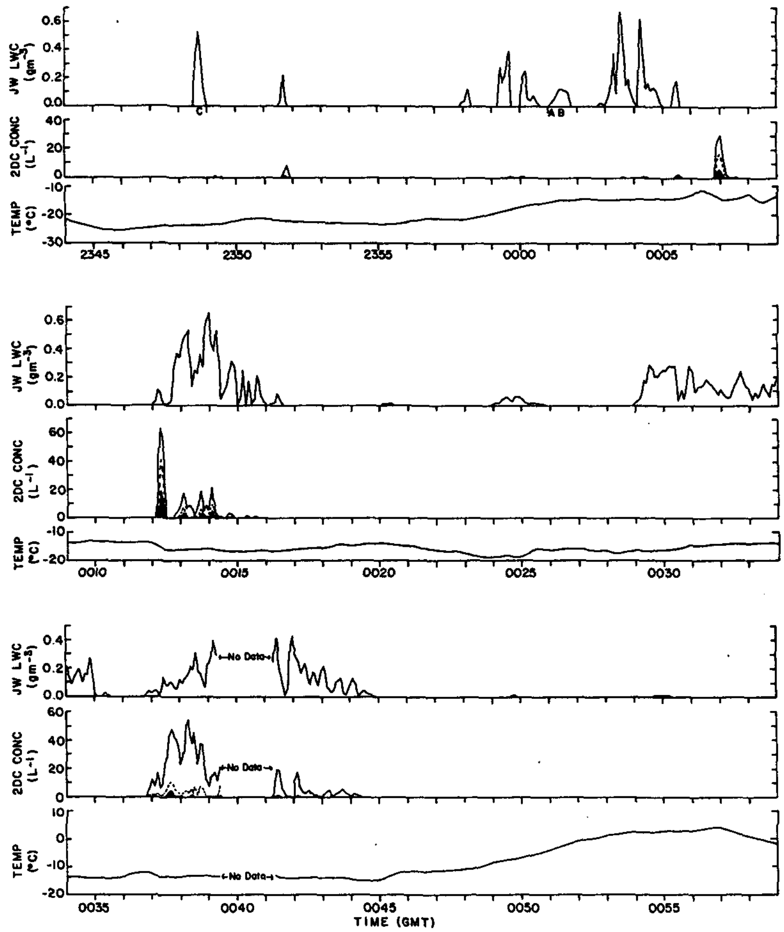

FIG. 4. Liquid water content (g m^{-3}) measured by the JW probe, 2DC particle concentrations (l^{-1}) and temperature measured during the 27/28 February 1983 flight. The 2DC particle concentrations are shown for three size categories. The solid line represents the concentration of particles ≥25 μm diameter, dashed line ≥200 μm, shaded region ≥500 μm. All data are 6 s averages.

for this difference is unresolved. During the penetrations, considerable structure was observed in the liquid water distribution, reflecting a complex vertical motion field. Supercooled cloud water was observed during every cloud penetration in this region.

The second region where supercooled cloud water was observed was in the cloud system over the Sevier Plateau east of U.S. 89 (see Fig. 3). Observations were limited over the plateau because this region was outside the primary study area. However, liquid water contents (JW) as high as 0.28 g m^{-3} were observed in this cloud. The extent of the cloud over the plateau is unknown.

Smaller amounts of supercooled cloud water were also present in a third region, between the Tushar Mountains and the Sevier Plateau but only at the lowest level sampled by the aircraft. Although no visual observations were available for confirmation, it is probable that this region contained scud cloud remains of dissipating clouds that had advected over the mountain.

Figure 5 shows three droplet spectra measured within a 12 min time period over the Tushars. The position of these spectra in time and space are annotated in Figs. 3 and 4. Spectra A and B were measured at −15°C while spectra C was measured at −23°C. The JW liquid water content was 0.54 g m^{-3} in the vicinity of spectra C and 0.03 and 0.12 g m^{-3}, respectively, at A and B. Spectra B and C suggest that broadening of the droplet spectra occurred in this cloud system. Spectra B was about 1 km deeper in the cloud than spectra A during the cell penetration. The large droplets present in this cloud in the vicinity of spectra C suggests that coalescence may have been important. Spectra C may also have been modified by entrainment based on the flat nature of the spectra. Droplet concentrations in most regions were generally between 100–200 cm^{-3}, although some concentrations were as high as 500 cm^{-3} in localized parts of the cloud.

Ice particle concentrations were determined from 2DC measurements. Images were considered to be ice particles if at least one shadowed bit (25 μm resolution)

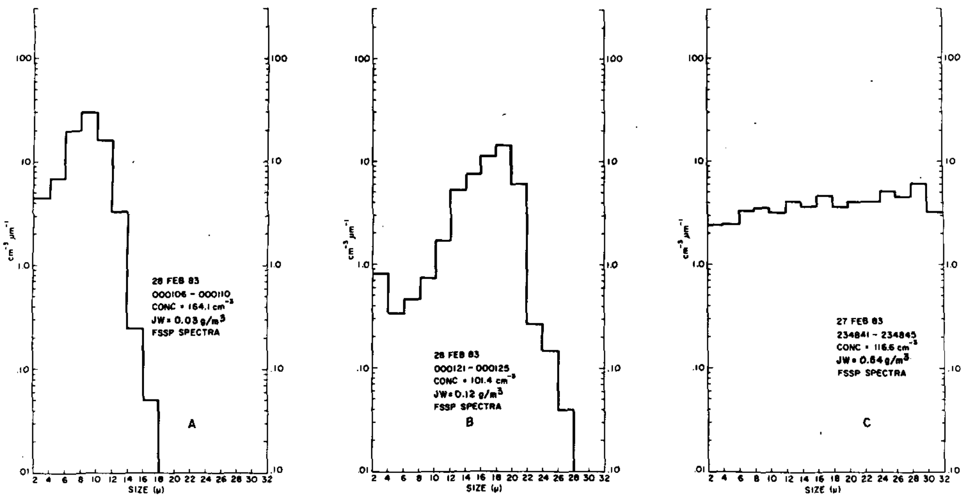

FIG. 5. Droplet spectra measured at three locations in the storm (see Figs. 3 and 4).

was present. Artifacts such as streaks produced by water drops were removed. Figure 3 and 4 summarize these data.

The primary region where ice particles were observed in this cloud system was downwind of the crestline between the Tushars and the Sevier Plateau. In this region, the peak ice particle concentration reached 64 l^{-1} although most were near 20 l^{-1}. However, virtually all of these particles were small. In only one narrow region did ice particles with sizes >500 μm exceed 10 l^{-1}. Generally, these larger particles were present in concentrations <1 l^{-1}. Virtually all ice particles in the cloud were less than 1000 μm in their largest dimension. Upwind of the crest few ice particles were observed. Those which were observed were <200 μm diameter. The same was true over the Sevier Plateau. Apparently, most ice particles formed in this cloud near or at the crest line as the liquid cloud began to entrain dry air or evaporate. Although a fraction of these particles did precipitate, based on the trace precipitation measured on the lee side, the small size of most particles suggests that the majority remained aloft.

5. Radiometric measurements

Scanning radiometric data were available throughout the orographic storm period. The radiometric data are displayed on time/azimuth diagrams in Figs. 6–8. The data were taken along a 20° elevation slant path and were not normalized to the vertical. Radiometric path-integrated liquid water contents are reported in millimeters; 1 mm of water distributed along a 1 km path is equivalent to a liquid water content of 1 g m^{-3}. The measurements reported here should represent supercooled liquid, based on the lack of precipitation at the radiometer site and the cold (<0°C) cloud base.

Prior to 1500, no clouds were present. At 1500, an orographic cloud developed over the Tushar Range and extended back over the valley. Based on the radiometric data, the liquid cloud developed in horizontal extent during the first hour. By 1615, the western edge of the liquid cloud was within the radiometer beam path. Between 1500 and 1900, the integrated liquid water content along the beam path in this cloud varied between 0.0 and 1.0 mm. At 1900, liquid water within the cloud system increased considerably. Two primary zones of supercooled water were present. The largest values were in the northeast quadrant, the region of strongest orographic forcing in the predominantly southerly flow. A secondary maximum appeared to the south-southwest (220°). Values ranged generally between 1 and 4 mm.

At 2200, the cloud dissipated and liquid water reduced to zero. The Ku-band radar was activated shortly after this time. Clouds began to redevelop around 2300, the time of the aircraft flight. The flight occurred between 2344 and 0104. During this period large values of liquid water were observed over the mountains northeast of the site. These high water contents were most likely associated with convective cells and orographic lifting over the ridge. Values were lower to the west of the site, ranging from 0.5 to 2.0 mm. The cloud in the immediate vicinity was probably composed of supercooled cloud droplets since the cloud produced only scattered weak returns from the Ku-band radar. The high liquid values were maintained between 2300 and 0300. The path-integrated liquid water content reached a maximum of 7 mm to northeast of the site. This corresponded to the region of strongest orographic forcing in southwesterly flow (see Fig. 1).

To provide some perspective on the magnitude of these liquid water measurements, an estimate of the amount of supercooled water passing over the crest during the storm was made and compared to the annual runoff of the Beaver River. The Beaver River drains the target area of the operational program. To perform this calculation, the cloud system was assumed to be homogeneous along the 50 km length of the Tushars

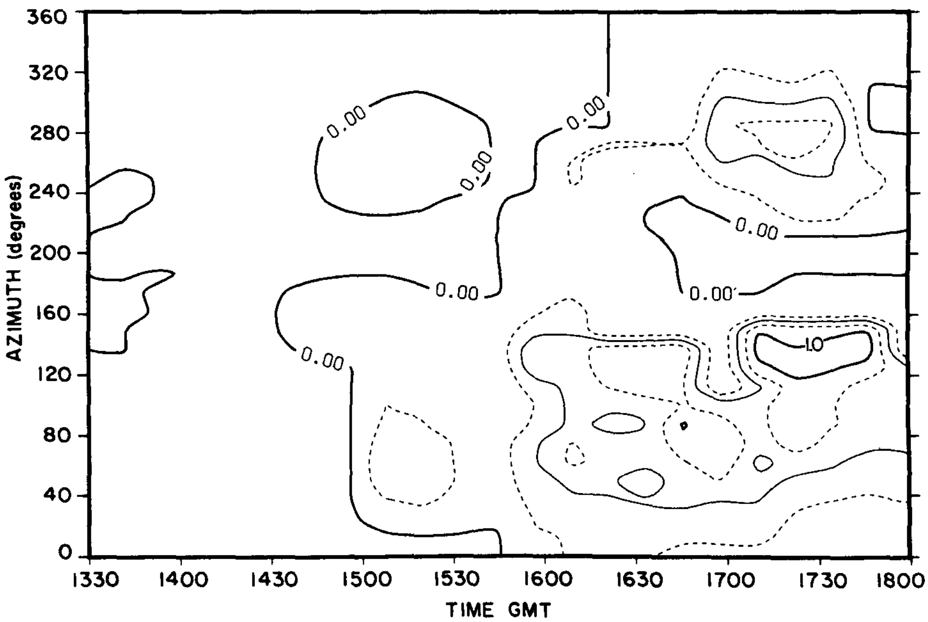

FIG. 6. Radiometric integrated liquid water content (mm) as a function of azimuth angle for 20° elevation scans from 1330–1800 UTC 27 February 1983. Contour intervals are 0.25 mm. The heavy contours are multiples of 1 mm.

that drains into the Beaver River. Supercooled water was assumed to advect across the Tushars at a speed corresponding to the normal wind component at crest height. Scanning radiometric data were normalized to the zenith and averaged over each scan. The total amount of liquid was calculated using the equation

$$F_L = \sum_{\substack{\text{all}\\ \text{scans}}} 10^{-3} LWU_c Yt \qquad (1)$$

where F_L is the amount of liquid passing over the Tushars (cubic meters), LW the average normalized liquid water depth measured during a complete 360° scan (millimeters), U_c the normal component of the wind at crest height (m s^{-1}), Y the length of the Tushar ridge within the Beaver River Drainage (5×10^4 m) and t the time required for a complete radiometric scan (seconds). With the stated assumptions, the total amount of liquid passing over the Tushars during the 13 h period from 1400–0300 was calculated as 6.25×10^6 m^3

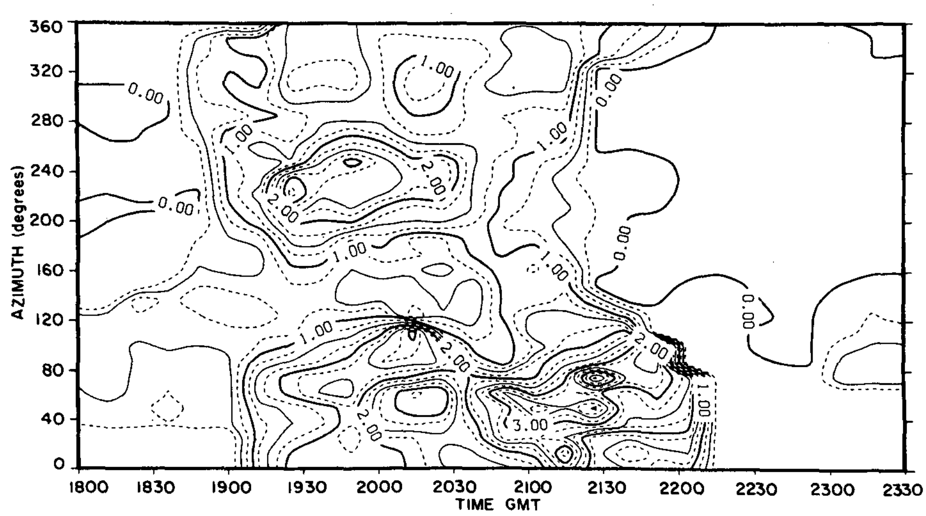

FIG. 7. As in Fig. 6 but for 1800–2330 UTC 27 February 1983.

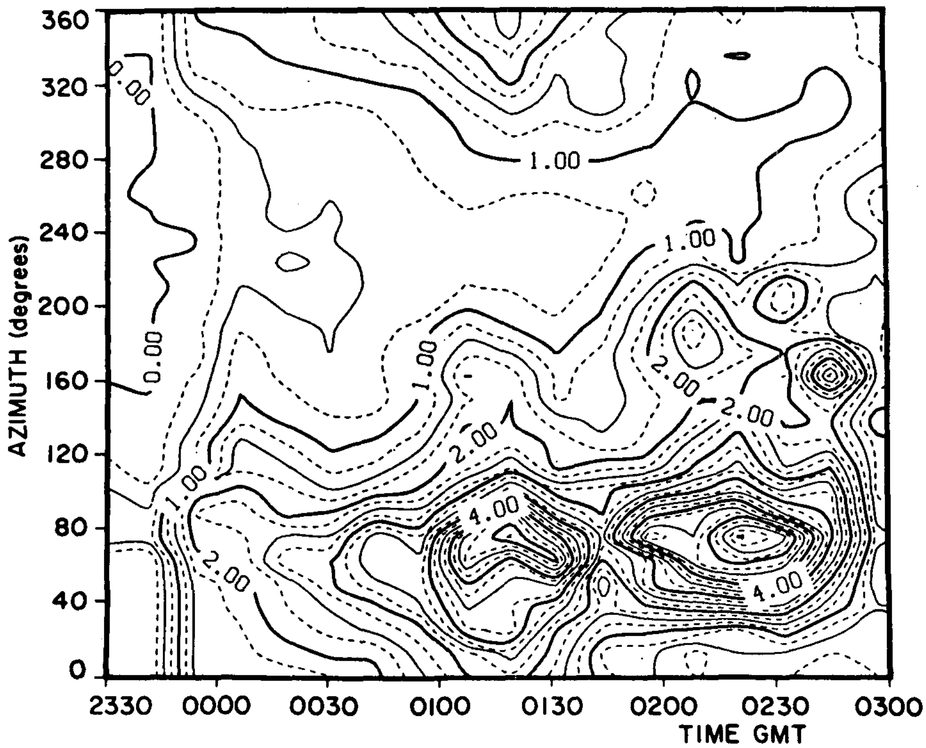

FIG. 8. As in Fig. 6 except for 2330 UTC 27 February to 0300 UTC 28 February 1983.

(5068 acre-ft). To put this value in perspective, the 70-year average annual runoff of the Beaver River is 4.72 $\times 10^7$ m^3 (38,250 acre-ft). Approximately 13% of the average annual runoff passed over Tushar ridge in the form of supercooled liquid during this one storm period.

6. Discussion

The cloud system described was composed primarily of supercooled water. Ice particles observed in the system upwind of the crest were generally present in concentrations of less than 5 L^{-1}. The vast majority were smaller than 500 μm. Ice particles downwind of the crest were in higher concentrations, but few were larger than 500 μm. Liquid water content measured by aircraft in the emergent convective regions often exceeded 0.20 g m^{-3}. Although in situ measurements within the lower orographic cloud were unavailable, radiometric measurements and weak radar reflectivity suggested that this part of the cloud was also composed of supercooled liquid. Despite the long duration of the orographic storm, precipitation was near zero.

Because of the storm's high liquid water content, low ice particle concentrations, minimal precipitation, and long duration, this storm appears to have been a good candidate for seeding to augment precipitation. However, a serious question remains concerning the seeding potential of such a cloud system since the time available for ice particle growth is short. For example, a crystal originating between $-10°$ and $-15°$C would have approximately 1500 s to fall 1200 m. This would require a mean fall velocity of 0.8 m s^{-1}, a value which could be attained only through rapid accretion. However, ice particles initiated between $-5°$ and $-7°$C would have nearly 2000 s to fall only 400 m, requiring a mean fall velocity of 0.2 m s^{-1}. The production of ice crystal plumes using CO_2 seeding has been demonstrated at these temperatures by Martner et al. (1983). A seeding technique such as that described by Martner et al. (1983) in the Sierra Nevada of California may have been effective in this cloud system. Questions concerning the mechanism for seeding such cloud systems to utilize the available liquid are currently being addressed by the federal–state program.

The cloud described herein was a shallow orographic system. Based on radiometric measurements, such cloud systems in other geographic regions have been identified as often having high liquid water contents (Heggli and Reynolds, 1985; Rauber et al., 1986; Reynolds and Dennis, 1986). The frequency of such storms over the Tushars is unknown at present. An initial climatology of cloud echo top height based on Ku-band radar data from the 1983 field season has been compiled. These data are shown on Fig. 9. They indicate that clouds with echo tops below the 4 km level were present about 40% of the time that significant cloud cover was present. The high frequency of occurrence of shallow clouds in the Tushar region suggests that shallow cloud systems are present during many storm periods. If several of these shallow storms have similar structure, a potential for seasonal precipitation

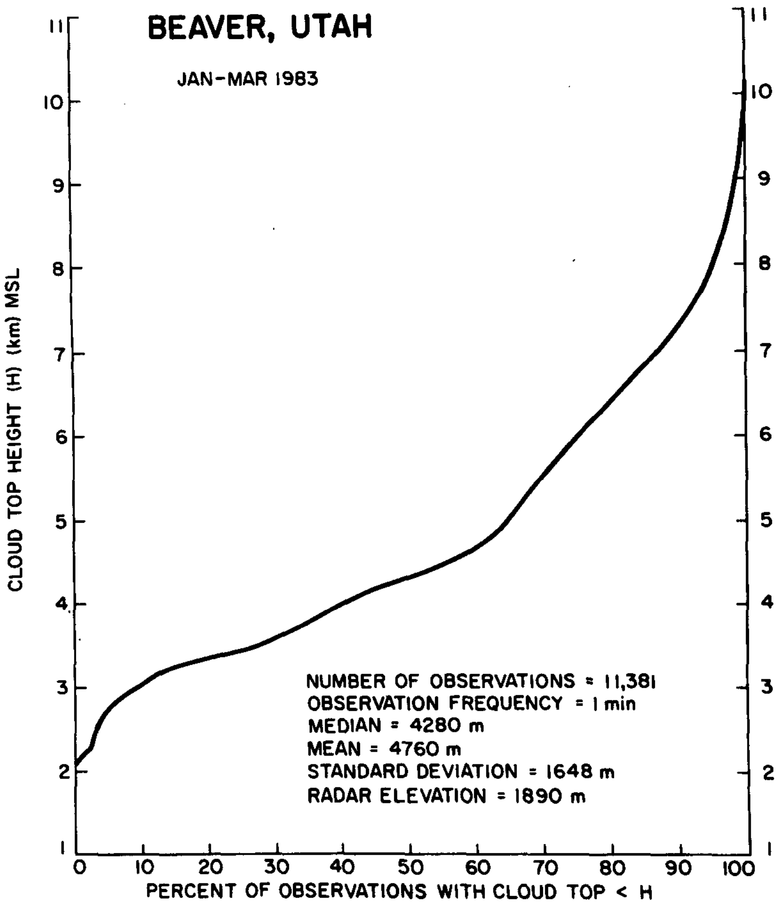

FIG. 9. Radar cloud top climatology for 190 h of significant cloud cover over the Tushar Mountains.

augmentation from such clouds may exist. Questions are currently being addressed concerning the frequency of these storm systems over the Tushars. In addition, investigations are continuing to expand the data base for other cloud systems which may hold potential for precipitation augmentation in this region.

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