The Spatial and Temporal Distribution of Supercooled Cloud Liquid Water During Wintertime Storms over the Northern Colorado Rockies

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ABSTRACT

The spatial and temporal evolution of supercooled cloud water fields in nine wintertime storm systems occurring over the northern Colorado Rocky Mountain region were examined using data collected by the recently developed scanning dual-channel microwave radiometer. These data were supported by several independent data sets including vertically pointing radar data, mountaintop liquid water content measurements, low and high altitude measurements of crystal rime characteristics, rawinsonde data and precipitation intensity measurements.

The storms examined occurred in pre-frontal and post-frontal enviornments, and varied in degree of stability from purely orographic, stable cloud systems to convective bands. The following conclusions were reached: (1) During individual storm events, the amount of liquid water present in the cloud system was inversely related to storm intensity. During storm events, liquid water contents decreased as the storm deepened (cloud top temperature decreased), precipitation rates increased, and radar reflectivity increased. (2) Liquid water presence in convective bands was generally limited the development stages of the band. Rapid conversion to the ice phase occurred rather quickly after the onset of the band due to highly efficient ice crystal production processes in the cloud. (3) The distribution and amount of liquid water present in stratiform systems was related to the strength of the orographic component of the airflow. (4) The majority of the cloud liquid water was concentrated over the windward slopes of the mountain range. (5) The temporal variation of the cloud water field is significant, even in cloud systems that appeared steady-state on the

mesoscale. (6) The conversion from shallow cloud systems to deep cloud systems was accompanied by a reduction in the concentration of supercooled cloud water and a conversion in the characteristics of the precipitation from predominantly single rimed crystals to unrimed aggregates.

The results of this analysis indicate that shallow, stable wintertime cloud systems over the northern Colorado Rockies have the highest potential for weather modification. These observations are significantly different from previously reported aircraft observations of supercooled water distributions over other mountain ranges of the western United States. These differences may be due to climatological differences between the areas, but are most likely due to the method of observation. Radiometric techniques are shown to be extremely advantageous because they allow observation of a large volume of cloud in a short amount of time. These techniques also permit monitoring of the temporal evolution of the cloud water field and allow observations of regions of cloud unapproachable by aircraft in complex terrain. For these reasons, the scanning dual-channel radiometer can be used as a powerful tool to re-examine the cloud physical properties and weather modification potential of wintertime cloud systems over mountainous regions.

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1. INTRODUCTION

One requirement for successful precipitation augmentation from wintertime mountain cloud systems is the presence of supercooled cloud liquid water. In addition to this requirement, natural ice particle formation and growth processes must be sufficiently slow that the supercooled water present in the cloud is not removed naturally during the time in which air parcels move toward and over the mountain barrier. Factors such as cloud depth and horizontal extent, cloud temperature, droplet size distributions and concentrations, ice particle concentrations and others constitute additional vital controls on the potential for weather modification. Knowledge of the presence, amount, and location of supercooled water can, however, provide a necessary initial basis for considering the precipitation augmentation potential of wintertime mountain cloud systems.

The major motivation of the present research has been related to potential for weather modification. However, knowledge of the distribution of cloud liquid water can also be used for planning aircraft operations in interior mountainous areas. Additionally, the presence and distribution of cloud liquid water has been shown to be strongly related to the chemistry of the mountain snowpack. Borys et al. (1982) have shown that most of the deposition of the atmospheric aerosol to the mountain snowpack is associated with accretion of cloud droplets either directly on mountain surfaces or on crystals that impact on the mountain.

A primary objective of several weather modification research programs conducted in the western United States in recent years has been to determine the spatial and temporal distribution of supercooled liquid water in wintertime cloud systems over mountainous regions. Aircraft observations of the distribution of liquid water in various storm types have been reported for the Cascade Mountains of Washington (Hobbs,1975), the Wasatch and Uinta Mountains of Utah (Marwitz and Stewart, 1978), the San Juan Mountains of Colorado (Cooper and Saunders, 1980) and the Sierra Nevada of California (Marwitz et al.,1978, 1979), Stewart and Marwitz, 1980; Heggli et al., 1983). Surface observations of liquid water content collected at high altitude sites have been reported for Elk Mountain in Wyoming (Rogers et al. 1983), Colorado's Park Range (Hindman et al. 1983), and the Sierras (Henderson and Solak, 1983). Measurements of cloud supercooled liquid water have also been collected with balloon-borne instruments such as the observations described by Hill and Woffinden (1980). Each of these techniques used to determine the cloud water content has specific advantages and drawbacks.

With the development of the dual-channel scanning microwave radiometer (Hogg et al., 1983), a new observational technique became available to determine supercooled cloud liquid water distributions. Unlike aircraft or surface observations, radiometric measurements have the distinct advantage of covering large volumes of the cloud system in a short amount of time. In addition, the radiometer can view regions of the cloud that are unapproachable by aircraft and it can operate continuously in marginal weather conditions.

This radiometric system was used as one part of a cloud physics field program conducted by Colorado State University (CSU) in the Park Range Region of northwest Colorado during December and January of 1981-82. The purpose of the field effort was to determine the natural physical structure and the modification potential of wintertime cloud systems over the northern Colorado River Basin. For this reason, no seeding was done prior to or during any of the storm systems reported in this paper. One objective of the field program was to document the presence, spatial distribution, and temporal variation of cloud supercooled liquid water occurring in storms affecting the region.

This paper examines the evolution of the supercooled water field during nine wintertime storm systems occurring over the Northern Colorado Rockies. The storms include pre-frontal convective bands, pre-frontal stratiform cloud systems, orographic clouds, and post-frontal stratiform and convective systems. The radiometric measurements are supported by simultaneous measurements of liquid water at mountaintop, ice crystal rime measurements at high and low altitude sites, radar measurements of cloud top height and cloud maximum reflectivity, rawinsonde measurements of cloud stability and cloud temperature structure, and specially collected precipitation intensity measurements.

2. INSTRUMENTATION AND DATA COLLECTION PROCEDURES

The major topographic features of the area and the locations of instruments used in this analysis are shown in Fig. 1. This section presents a discussion of the instrumentation and the data collection procedures used during the experiment.

a. Dual-channel microwave radiometer

Details and references concerning the operation, theory, and accuracy of measurements of cloud liquid and vapor water content obtained by the dual-channel microwave radiometer are given in Part I of this series (Rauber and Snider, 1985). The instrument and scanning techniques used to obtain the spatial and temporal distribution of supercooled liquid water are briefly described here.

The dual-channel microwave radiometer simultaneously measures the

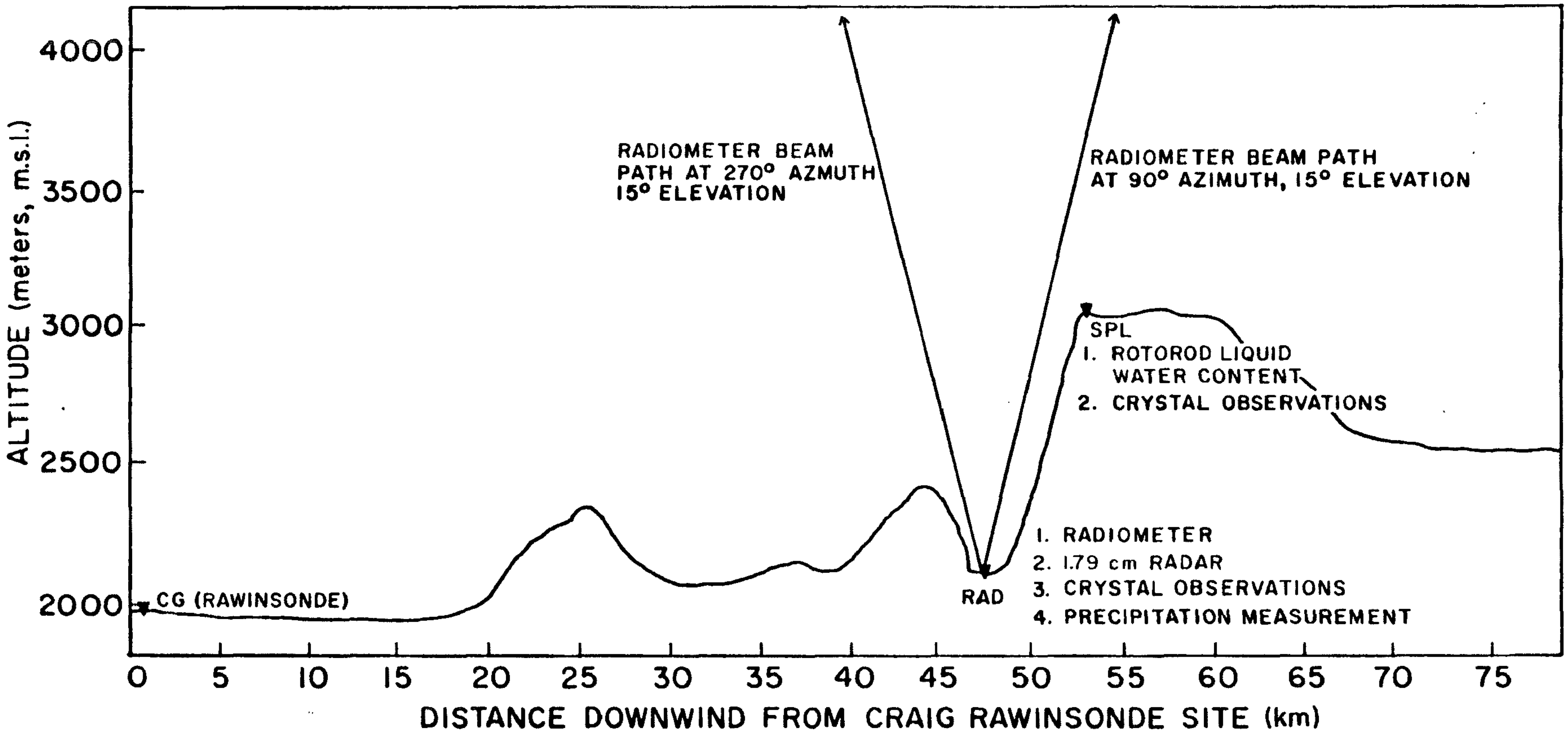


Fig. 1. Topographic profile of the COSE study area showing the location of instrumentation used in the study.

total amount of liquid water and water vapor contained along the atmospheric path being observed by the system's antenna. In this analysis, only data from the liquid water channel are used. Because liquid water at any temperature emits and absorbs radiation at the wavelength used, the radiometer can measure supercooled liquid. However, since absorption of microwaves by ice is some two orders of magnitude less than that by liquid water, ice produces essentially zero response from the system (see Part I).

The radiometer incorporated a steerable antenna so that the spatial and temporal variability of the liquid water and vapor field could be studied. A standard scanning technique was adopted to observe the evolution of these fields. The antenna was set at a 15° elevation angle and rotated continuously through 360° azimuth sweeps approximately every 15 minutes. By using this technique, it was possible to observe the changes in integrated liquid water content in all directions. The data were then analyzed on azimuth/time diagrams, which allowed for easy interpretation of the lifting mechanisms responsible for the production of cloud water. Radiometric integrated liquid water contents are reported in millimeters.

The radiometer was located near Steamboat Springs, Colorado, at an elevation of 2050 m (all heights reported in this paper are mean sea level), approximately 6 km west of the crest of the Park Range (3100 m). The Park Range is oriented north-south. An azimuth angle of 0° in the radiometric data presented in the following sections would correspond to the antenna's pointing north, or parallel to the range. At 90°, the beam points over the range, directly through the region of maximum orographic lift. At 180°, the beam is pointed southward, parallel to the range. At 270^{o}, the beam is directed away from the region of primary lift, over the western valley of the Yampa River.

b. 1.79 cm radar

The CSU constructed, vertically pointing 1.79 cm wavelenght radar was specifically designed for operation during orographic cold cloud storm events. Built in 1978, the system uses the receiver-transmitter designed for the B-58 aircraft. Coupled to the original duplexer is a double balanced mixer, followed by a radio frequency pre-amplifier and 30 MHz intermediate frequency amplifier. Reflected echoes are digitized by an eight-bit analog-to-digital converter and thereafter loaded into the memory of a minicomputer. Non-averaged data are written onto 9-track magnetic tape once every 30 seconds or multiples thereof. Storage of data in an array of 46 pulses by 200 range bins affords access to individual pulse values for statistical calculations such as signal variance and bias. The computer also produces a real time display of reflected power, calculated in dBZ, based on averages of 46 consecutive pulses. The real-time display is formatted as a horizontal intensity profile with 80 positions, each corresponding to 100 meters vertical distance. The overall effect is to establish a time-height history of the cloud vertical structure from 0.4 to 8.0 km height. Since water droplets are nearly always smaller than precipitation size in the cloud systems observed in winter over the Park Range, the radar return is virtually always due to ice particles in the cloud system.

During the COSE program, this radar was colocated with the dual-channel radiometer near Steamboat Springs, Colorado. In this paper, the radar data are used to continuously monitor cloud top height, cloud depth, variations in the observed maximum reflectivity and cloud top temperature (with special rawinsonde data).

On 16 January 1982, a transmit-receive (TR) tube in the radar failed and had to be replaced. The tube in place prior to the failure had higher general attenuation characteristics than the new tube. This resulted in all data prior to 16 January, 1982 having lower reflectivity values than those data collected after this date. Two parameters from the radar, cloud top height and cloud maximum reflectivity, are reported in this paper. Radar cloud top height was checked during several research flights, before and after tube replacement, and found to be within 100-200 m of visual cloud top. The maximum reflectivity during the two storms occurring after 17 January 1982 will be higher due to the reduced attenuation.

c. Precipitation intensity, crystal habit and rime

Visual observations of snow crystals and special measurements of precipitation were made continuously during storm periods at the radiometer site (RAD). Visual observations of snow crystals were normally conducted at 15-20 min intervals. The crystals were collected on a piece of framed black felt (250 cm^2). The length of exposure to snowfall ranged from 3 to 30 seconds depending on the snowfall intensity. In each observation, snow crystal habits were identified and classified according to the scheme of Magono and Lee (1966). The crystals were also examined for accretion and aggregation. The number flux and number of single crystals composing aggregates were determined by counting the number of crystals collected. Shadow photography (Higuchi, 1956) was also used to record the characteristics of the crystals.

Special precipitation intensity measurements were collected at RAD.

A plastic recepticle with a 160 cm^2 opening was used to measure snowfall intensity. Samples 10 to 15 minutes in duration were taken consecutively and weighed manually to determine the average snowfall intensity during the collection period.

In this paper, the Magono and Lee (1966) classification is simplified. All unrimed single crystals and unrimed aggregates are classified as crystals with no rime (NR). Crystals classified by Magono and Lee as R_{1a}, R_{1b}, R_{1c}, and R_{1d} are all classified as R1. Similarly, the crystal habits R_{2a}, R_{2b}, R_{2c} are classified as R2; R_{3a}, R_{3b}, R_{3c} as R3; and R_{4a}, R_{4b}, and R_{4c} as R4. Two additional classifications are added for aggregates. Lightly rimed aggregates are classified as LA and moderately rimed aggregates as MA. If no precipitation was falling, the category NS (No Snow) was used.

D. Storm Peak Laboratory measurements

A mountaintop laboratory was operated at the summit of Storm Peak (3100 m) on the Park Range directly east of the radiometer site during the 1981-82 field program. The laboratory was equipped with numerous instruments to measure the characteristics of aerosol and cloud particles in the vicinity of mountaintop. In-cloud liquid water content measurements were made using a Rotorod (registered trademark of Metronics, Inc., Palo Alto, California). This instrument is described in detail by Rogers et al. (1983). Hindman et al. (1983) describe its use in the COSE program. Rime characteristics of crystals at Storm Peak were also recorded approximately every 15 min during most storm periods. Ice crystals were characterized in one of four rime categories. The categories were no rime (NR, no visible accretion of droplets), lightly rimed (LR, accretion of droplets apparent, crystal habit easily identified), moderately rimed (MR, accretion of droplets sufficient to make the crystal habit difficult to distinguish), and heavily rimed (HR, snow pellets or graupel). If no precipitation was falling, the category NS was used. Many other measurements were collected routinely at Storm Peak Laboratory (SPL), but the ice crystal rime and Rotorod liquid water content measurements are the only SPL measurements used here.

e. Supporting data sets

Surface temperature, pressure, wind velocity and precipitation were measured continuously at RAD and at other sites with Portable Remote Observations of the Enviornment (PROBE) surface weather stations provided by the Bureau of Reclamation. These data were used to monitor surface temperature at RAD to estimate the effects of melting ice particles (see Part I) and to provide additional information in synoptic and mesoscale analyses of storm evolution.

Special rawinsondes were launched approximately every 3 h near Craig, Colorado, 48 km upwind of RAD. Data obtained were used with the radar data to determine cloud top temperature. Synoptic and supporting data were obtained from standard National Weather Service products, from special analyses made available through the Bureau of Reclamation Environmental Data Network and from satellite data provided by the National Weather Service office in Cheyenne, Wyoming.

f. Data presentation

The various data collection platforms described above were operated simultaneously during each of the storm events. To facilitate easy interpretation of these data, a standard diagram was developed which consists of eight independant data sets all plotted as a function of time for easy comparison.

III. CASE STUDIES

During the COSE program, nine storm systems occurred for which scanning radiometer and other supporting data sets were available. These storms occurred in pre-frontal and post-frontal environments and involved cloud systems that included convective bands, embedded cellular convection, widespread stratiform cloud systems and clouds formed by orographic lifting. For presentation as case studies, these storms are divided into three broad categories: storms occurring in the pre-frontal environment or during frontal passage, storms occurring in the post-frontal environment, and orographic storm systems. The first case documents the passage of a strong convective band. The second case involves a cloud system which developed in the warm sector and involved the passage of two predominantly stable deep cloud bands. The third case occurs during a cold frontal passage. Sec. b includes storms which occurred in a post-frontal environment. In the first case, the storm consisted of widespread clouds with weak mid-level embedded convection. The second case study occurred during the decaying stages of a storm system. During the period a cap cloud with numerous embedded convective cells was present along the Park Range. The third case also involves a cap cloud, but with much greater stability. In Section C, the three case studies presented are clouds formed primarily by orographic lifting. These clouds occur when a strong cross-barrier pressure gradient is present and middle and low level moist air simultaneously advects into the Park Range region from the west.

a. Pre-frontal and frontal cloud systems

1. Case study: 22 January 1982

Synoptic scale and local weather conditions

The evolution of the large scale weather features at the surface and at 50 kPa for the period 0000 to 1200 on 22 January 1982 is shown on Fig. 2. The radiometer operated in the scan mode from 0030-0330 GMT during the storm.

At 0000 GMT on 22 January 1982, a large trough system was present over the western United States; the axis of the trough was located along the Utah-Nevada border. At the surface, ahead of the trough axis, a developing low pressure system continued to deepen and move southeastward from eastern Utah into Colorado. Ahead of this low, four bands of moderate to heavy precipitation developed and advected eastward into the Park Range region. The first band arrived at RAD at 0200 GMT. The intensity of each successive band decreased. Very light snowfall occurred between bands. The last band crossed the study area at 0720 GMT. By 0800 GMT, the low pressure center had moved east of the Park Range region. This case study focuses on the passage of the first convective band at 0200 GMT.

Storm evolution and supercooled water distribution

Before the passage of the first convective band at 0200 GMT on 22 January, southwesterly flow prevailed over the Park Range region. A mid-level stratiform cloud deck covered the Park Range and the Yampa River Valley to the west. The base of this deck was approximately 4000 m. Breaks in the overcast were frequently observed and no precipitaton fell at any of the sampling sites.

At 0100 GMT, the first band arrived at the Craig, Colorado, rawinsonde site (CG), 48 km upwind of RAD. The equivalent potential temperature profile obtained from a sounding launched after the first band passed CG (Fig. 3) indicated that a potentially unstable layer

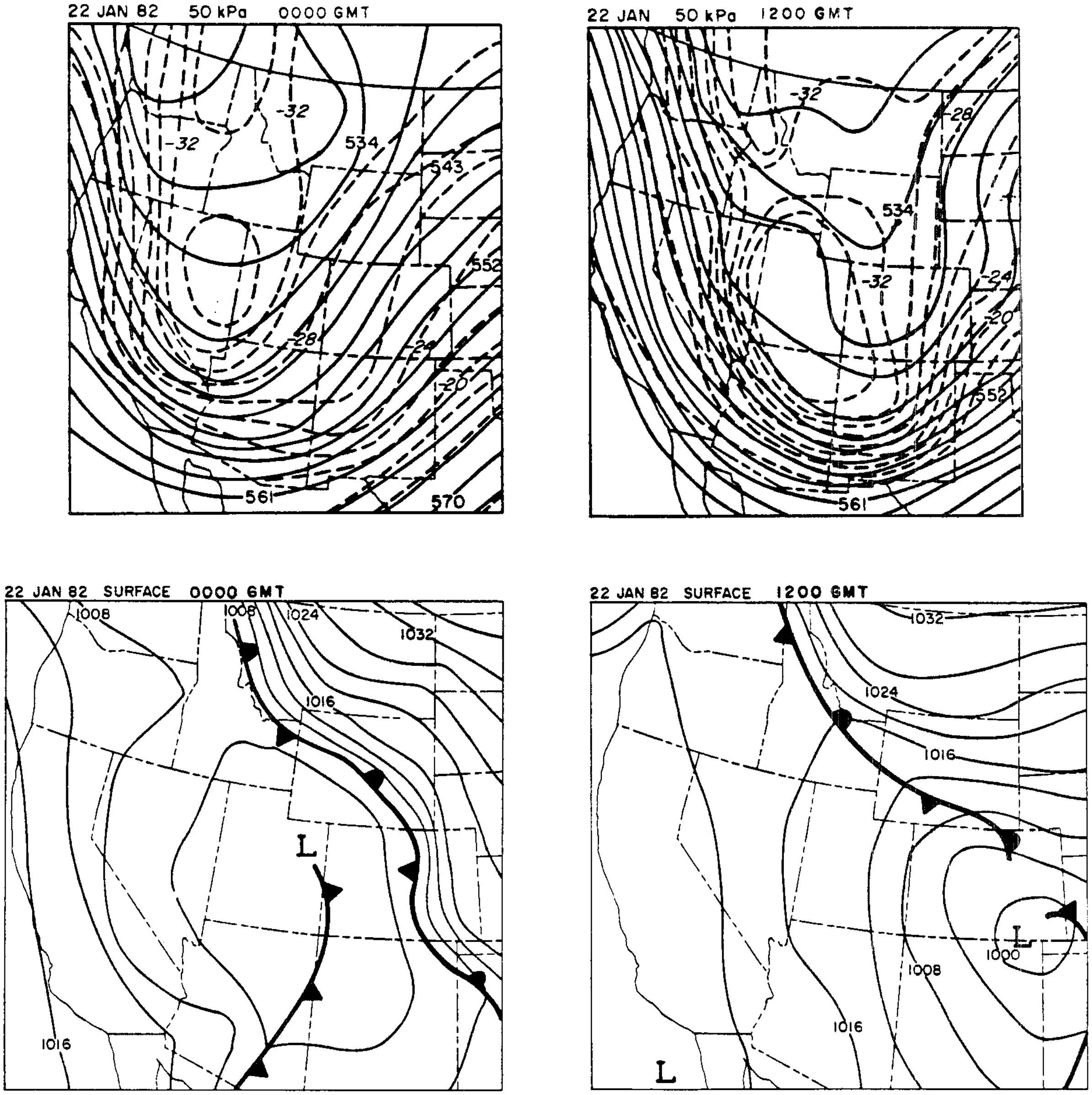


Fig. 2. Synoptic scale weather features for the 22 January 1982 storm system.

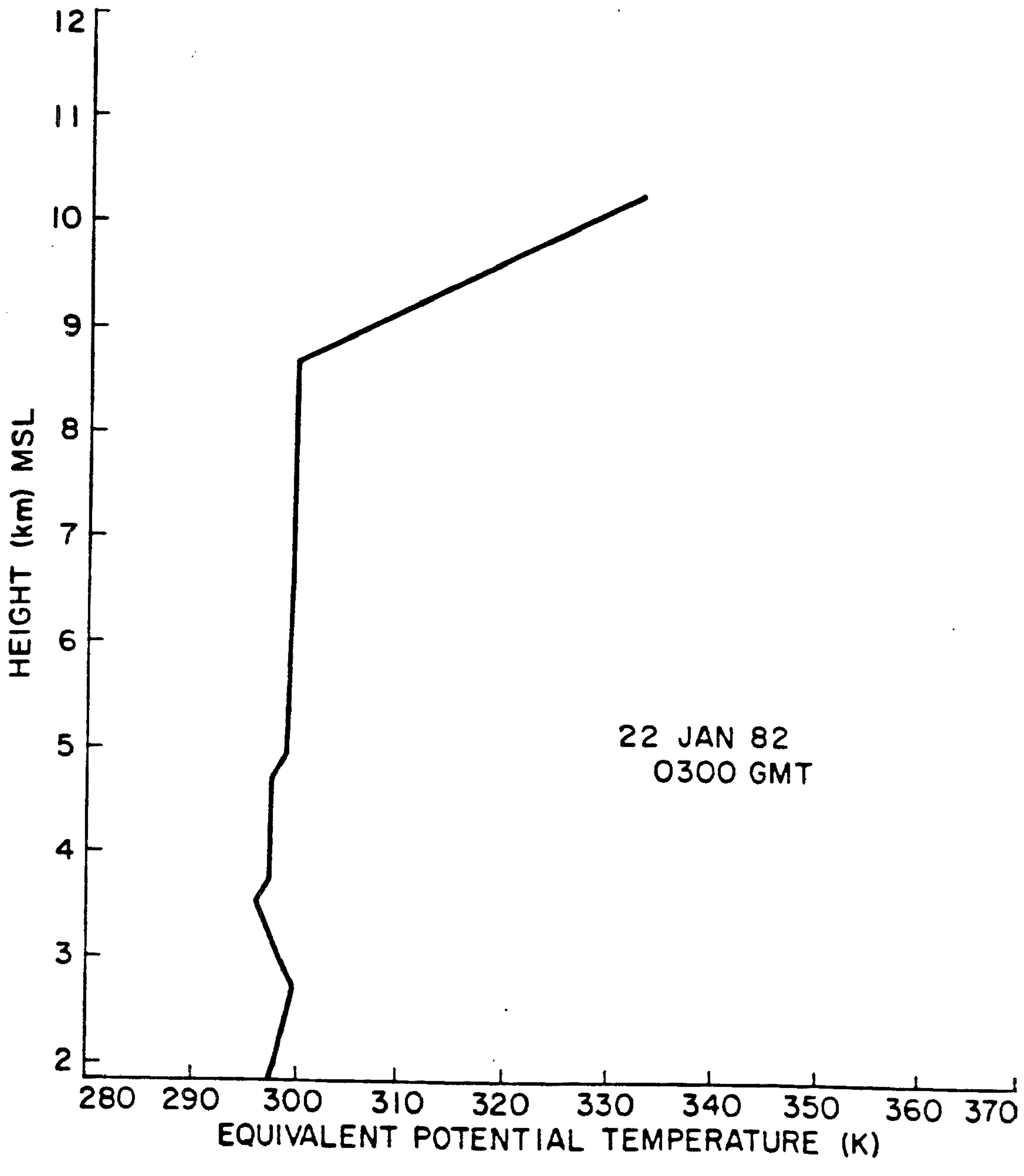


Fig. 3. Vertical profile of Equivalent Potential Temperature at 0300 GMT on 22 January 1982.

existed between 2739 and 3551 m. The equilibrium level for a convectively unstable parcel originating at 2739 m was near 6940 m and corresponds well to the cloud top height observed by the radar during band passage. The band propagated eastward at 15 m/s, arriving at RAD at 0155 GMT. Shortly after this time, winds at SPL shifted from southerly to west-southwesterly. Snow began falling at RAD and SPL at 0225 GMT.

The time evolution of the supercooled water field, precipitation intensity, and rime characteristics of crystals collected at RAD, rime characteristics of crystals at SPL, radar cloud top and maximum reflectivity, and surface temperature at RAD during the passage of the first convective band are shown in Fig. 4.

Radiometric data collected during the period prior to the passage of the band indicated that the mid-level stratiform cloud system preceding the band contained almost no supercooled cloud water. Weak radar reflectivities during this time indicated that the cloud was composed of ice crystals that were too small to precipitate. No significant orographic enhancement of the cloud water field was evident in the radiometric data with the possible exception of the period between 0030 and 0045 GMT. The lack of orographic enhancement is consistent with observations of boundary layer and mid-level winds, which had weak cross-barrier components in the vicinity of the range.

The approaching convective band was observed initially by the radiometer west of RAD. At this time, the cells within the beam path contained small but significant quantities of supercooled water. As the band approached the barrier, strong orographic enhancement of the vertical motion within the cells resulted in significant increases in

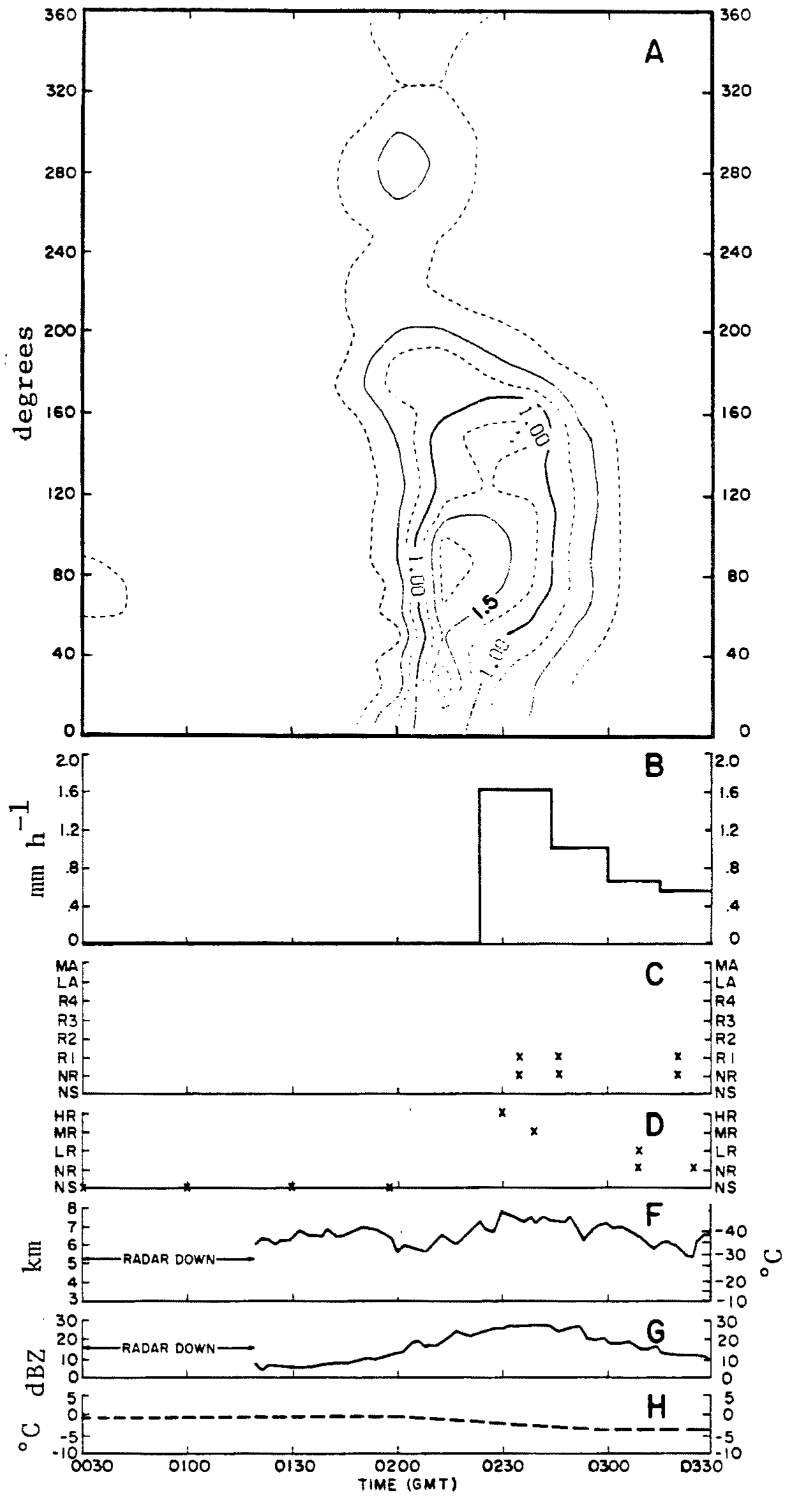


Fig. 4. 22 January 1982 (0030-0330 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

observed cloud water contents along and over the barrier. Twenty minutes elapsed between the arrival of the leading edge of the band and the onset of precipitation at SPL and RAD. These observations suggest that the developing convective towers in the vicinity of the ridge were initially composed predominantly of supercooled water.

As cells within the band moved toward the barrier and developed, a continuous conversion of cloud water to the ice phase ensued. This is most evident from the radar reflectivity return, which continually increased between the arrival of the band and the onset of precipitation. Once the ice phase was established, rapid depletion of the cloud liquid water occurred, primarily through accretion processes, as shown by the rime characteristics of the ice crystals at SPL and the rapid disappearance of the liquid water throughout the cloud as measured by the radiometer.

Crystals observed at RAD during the passage of the band were unrimed or lightly rimed. Simple trajectory considerations show that these crystals would have originated well upwind of the major concentration of supercooled cloud water indicated by the radiometer. Radiometric observations showed that only small amounts of cloud water were present west of RAD, upwind of the barrier, and that most of the cloud water was present in cells along and over the barrier slopes. For these reasons, crystals arriving at RAD would be expected to interact only minimally in accretion processes.

The radiometric distribution of liquid water during band passage reached a maximum at an azimuth angle of 85°, almost directly over the windward slopes of the range. At 0230 GMT at SPL, heavy precipitation began to fall consisting of snow pellets and graupel. As the convective cells evolved, the observed radiometric liquid water content in the cloud system decreased substantially in the clouds over the barrier. Corresponding decreases in the amount of rime visible on collected crystals were also observed at SPL, although moderate snowfall continued throughout the period. By 0330 GMT no riming was apparent on the crystals collected at SPL. Radiometric observations at this time indicated that the supercooled cloud water within the cloud system had been largely depleted.

The convective band was very efficient at converting liquid water initially produced in its development stages to the ice phase. Ice particles initially produced in this system rapidly removed the liquid water present through accretion processes and later depleted available condensate by sustained diffusional growth.

2. Case study: 15 December 1981

Synoptic scale and local weather conditions

Major synoptic scale weather features at the surface and 50 kPa for the storm system occurring on 15 December 1981 are shown in Fig. 5. The radiometer operated in the scan mode from 1320 to 1920 GMT during the storm.

At 0600 GMT on 15 December 1981, a low pressure center was located in west-central Nebraska. A weak high pressure system was centered near the Four Corners area of southwest Colorado. A stationary front extended from the low in Nebraska across southern Wyoming and into Utah where it became a warm front associated with an intense storm system still off the coast. By 1200 GMT, this intense storm system had moved rapidly inland. Ahead of the system, a strong, moist, mid-level jet developed. The axis of this jet was located along the warm frontal

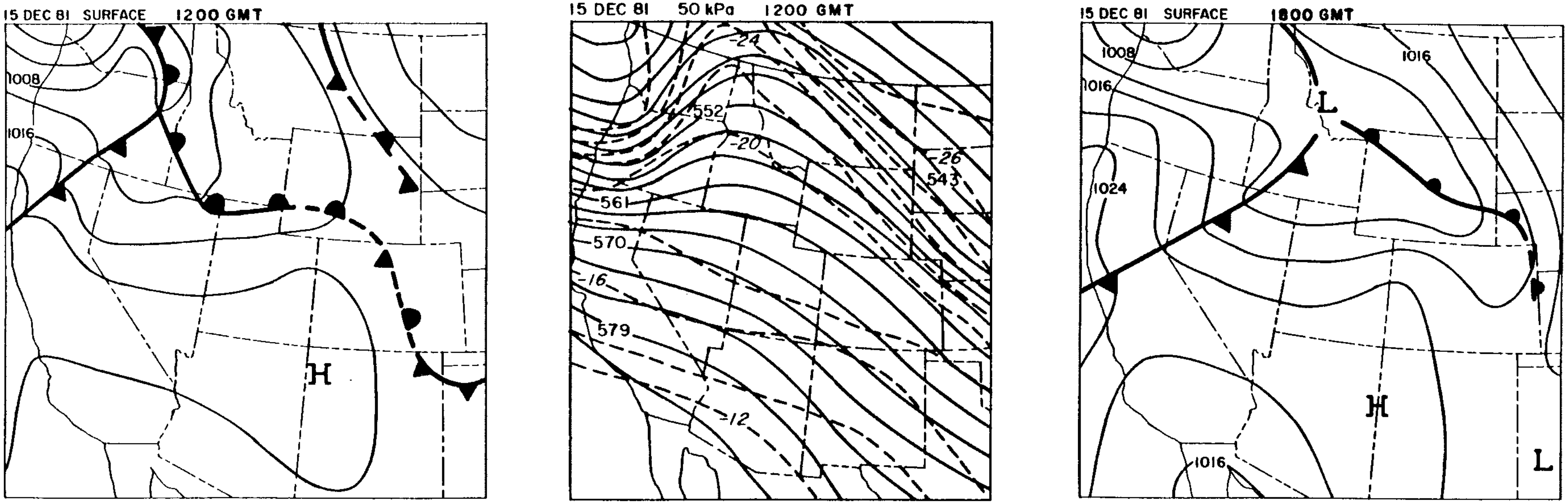


Fig. 5. Synoptic scale weather features for the 15 December 1981 storm system.

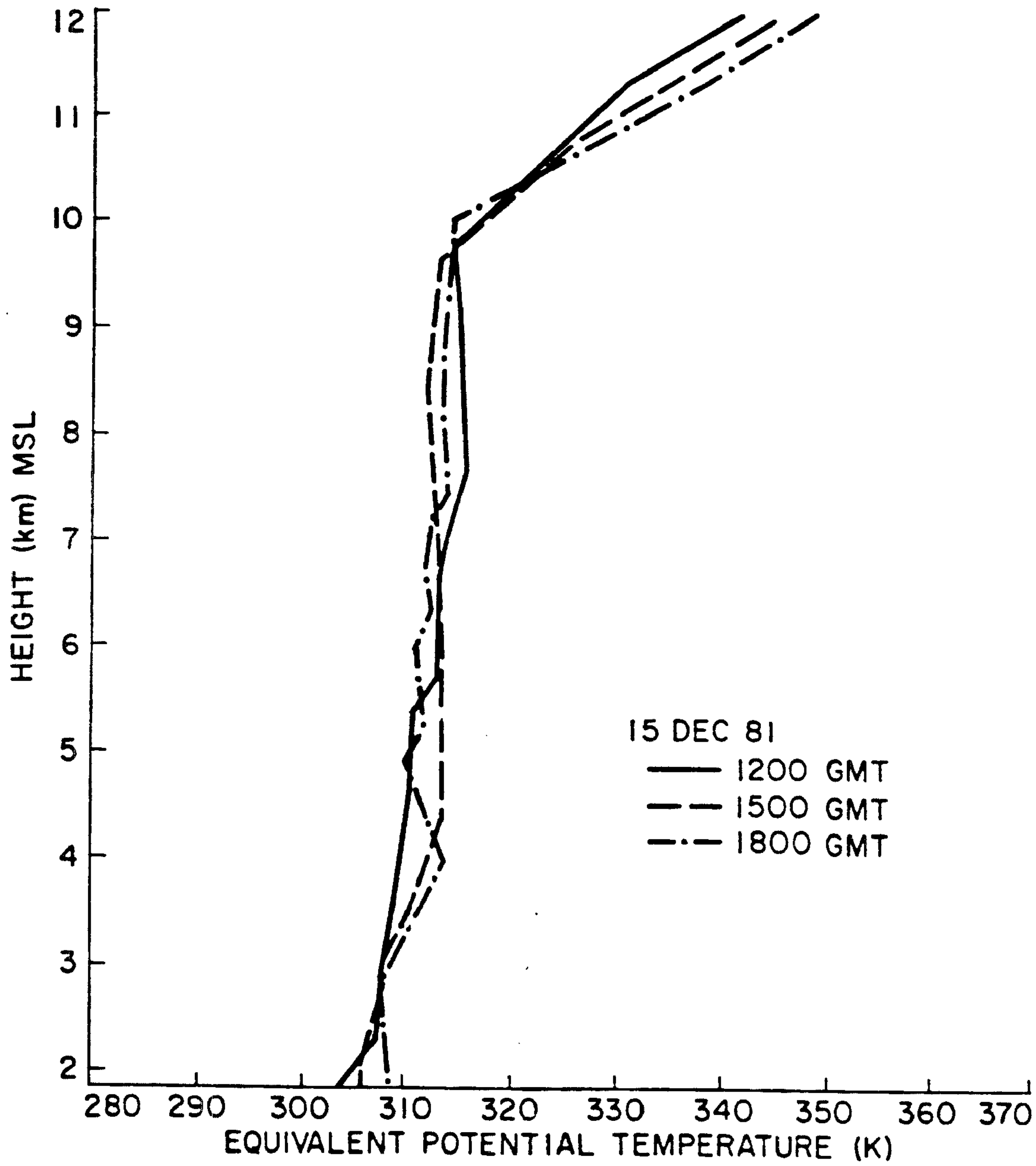


Fig. 6. Vertical profiles of Equivalent Potential Temperature at 1200 GMT, 1500 GMT and 1800 GMT on 15 December 1981.

boundary. These winds strongly enhanced the development of clouds along the Wasatch Range of Utah and in the mountains of Colorado. Winds of 18 m/s were observed at 70 kPa during this period. During the next hours, through 1800 GMT, the warm frontal boundary slowly moved northward and a secondary low pressure center developed in southwest Montana along the cold front. During this period, a primarily orographic induced stratiform cloud system was present within the warm sector of the storm, including the experimental area in the northern Colorado Rockies. Several bands of heavier precipitation were periodically superimposed on this orographic cloud system. The storm system slowly weakened in intensity as the mid-level jet weakened, the warm frontal boundary moved slowly northward, and the strong cold front continued to approach the study area from the west.

Storm evolution and supercooled liquid water distribution

The cloud system of 15 December 1981 evolved through several distinct stages, each exhibiting significant variations in the cloud liquid water distribution. These variations were associated with the passage of two wide area bands of heavy precipitation. The bands were embedded in a large scale shallow stratiform cloud system which extended over much of the northern Colorado Rockies. Passage of the bands was marked by significant increases in cloud depth and precipitation intensity. The first band arrived at RAD at 1450 GMT, passing over the site in approximately 1 hr. The second band, which also moved over the site in approximately 1 hr, arrived at RAD at 1700 GMT. Vertical profiles of equivalent potential temperature derived from special rawinsondes launched at 1200, 1500, and 1800 GMT from CG are displayed in Fig. 6. At 1200 GMT, weak potential instability was present only in the upper atmosphere above 7650 m, well above the stratiform cloud layer in the lower troposphere. By 1500 GMT, this layer of potential instability extended down to 6400 m. Below this potentially unstable layer, a neutral layer extended as low as 4415 m, well within the stratiform cloud layer. By 1800 GMT, a much stronger potentially unstable layer had developed between 4800 and 4920 m. A second layer was also present between 5560 and 6012 m.

These soundings indicate that the atmosphere in the warm sector became progressively less stable as the cold frontal system approached from the west. However, during the period of interest, the atmosphere was near neutral throughout its depth. The banded structure evident on the radar analysis (Figs. 7 and 8) was not associated with the passage of deep convective elements as in the previous case, but rather with organized regions of deep moisture and clouds embedded in the near-neutral middle and upper troposphere.

The time evolution of the supercooled liquid water distribution, precipitation characteristics at SPL and RAD, liquid water contents at SPL, radar characteristics and temperature at RAD are shown on Figs. 7 and 8. During the early stage of this storm, from 1310 to 1450 GMT, a stratiform cloud system with tops at 5000 m (-16°C) was present over the Park Range region. Precipitation from this storm fell steadily at a rate of 1 mm/hr at RAD. During this period, radiometric measurements of the cloud water field indicated that cloud liquid water was present throughout the cloud system, but was concentrated over the Park Range, particularly over the mountains southeast of RAD. Simultaneous measurements of rime intensity at SPL and RAD supported the radiometric measurements. At RAD, crystals were observed primarily in the R3, R2,

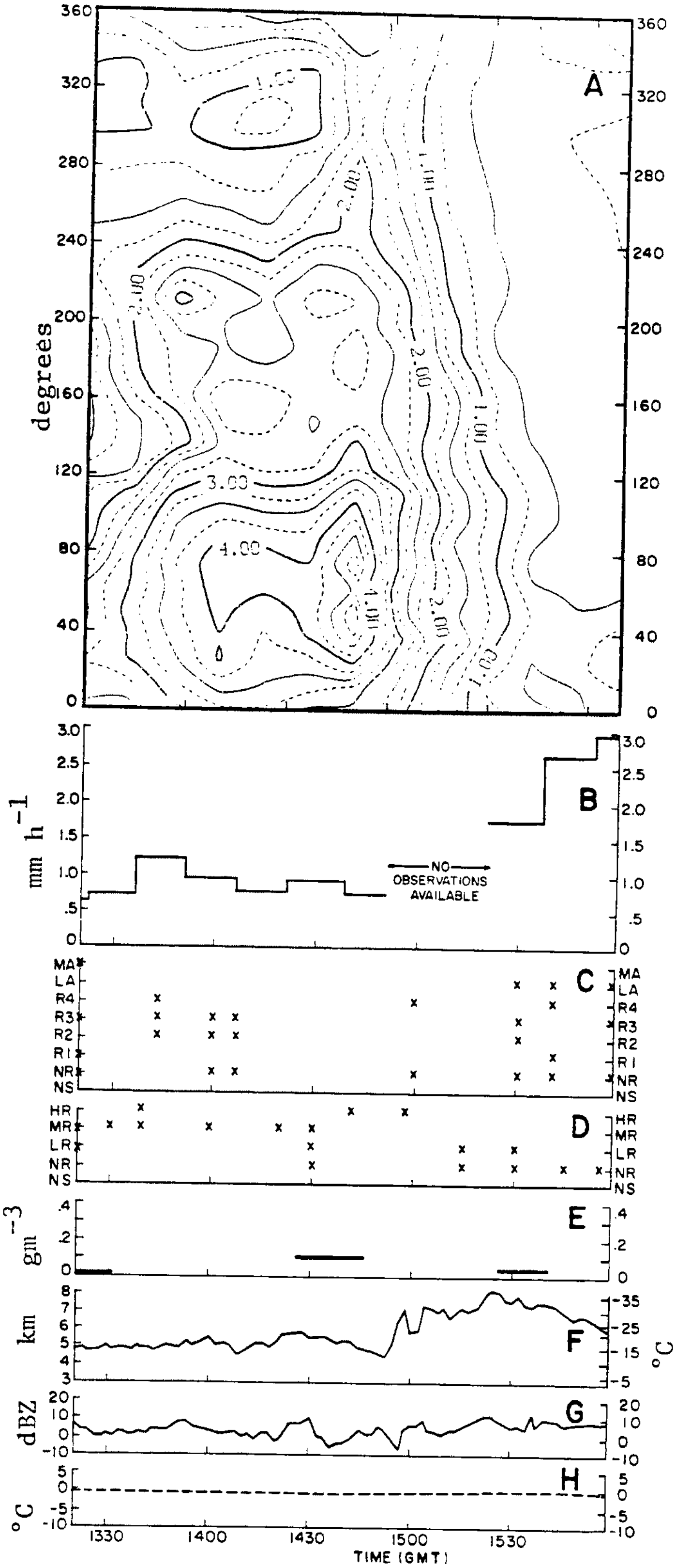


Fig. 7. 15 December 1981 (1320-1600 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

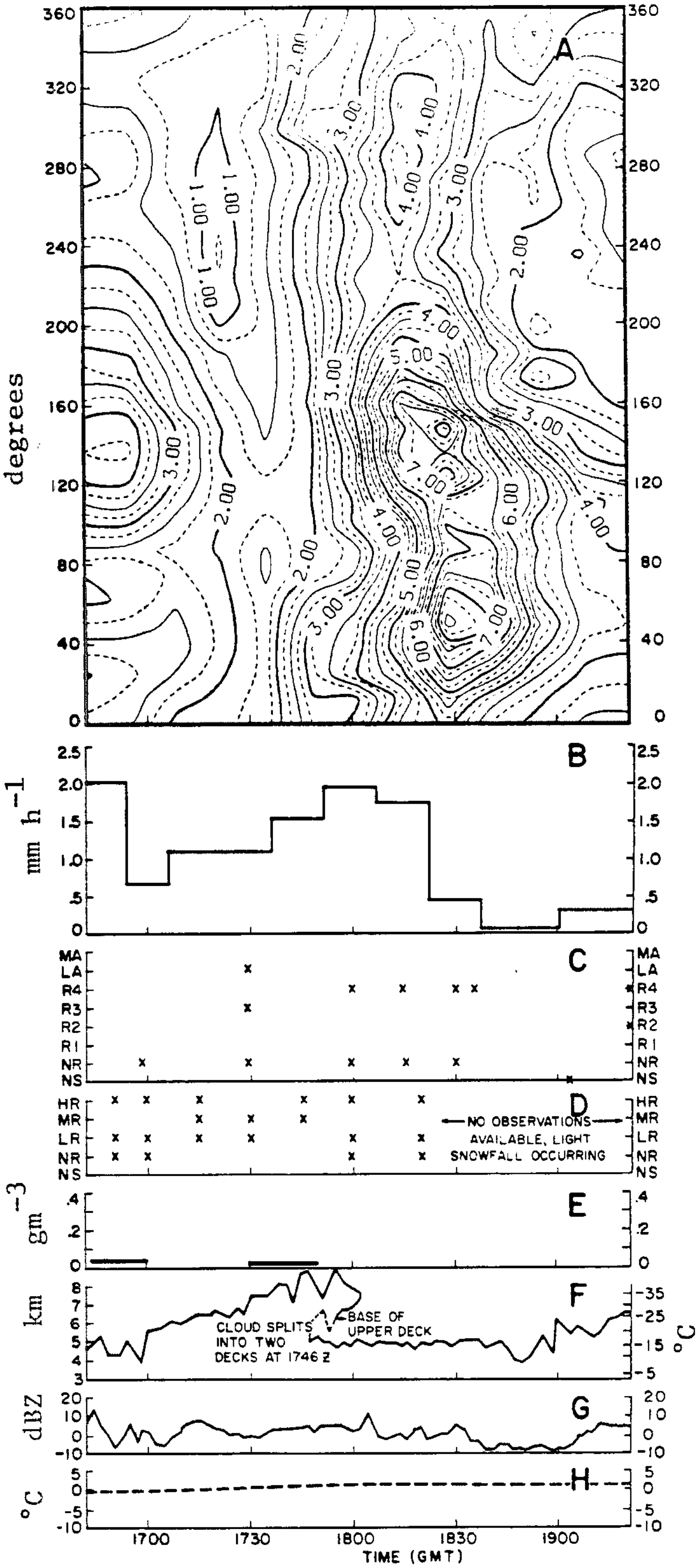


Fig. 8. 15 December 1981 (1640-1920 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

and NR categories, indicating that significant accretion of supercooled cloud droplets occurred in clouds upstream of RAD. Nearly all crystals collected at SPL during the period were moderately rimed. The absence of unrimed crystals at this site provides strong support for the radiometric measurements of increased liquid water content over the Park Range. During the early stage of this storm, mountaintop observations of supercooled water gradually increased from 0.02 gm^{-3} to 0.10gm^{-3}, paralleling the observed increases in supercooled water observed by the radiometer in the vicinity of the barrier.

With the onset of the first deep cloud band, cloud tops rapidly increased to 7000-8000 m (-30^{o} to -35^{o}C). Radiometric liquid water content rapidly decreased throughout the cloud system during this stage of the storm. Prior to the onset of the band, crystals observed at SPL were all heavily rimed, but as the band progressed across the area, the amount of rime decreased substantially. During the passage of the band, precipitation rates increased considerably at RAD and SPL.

Within 40 minutes after the onset of the band, all crystals observed at SPL were unrimed. Crystals collected at RAD showed a marked degree of aggregation. Many of the aggregates continued to be lightly rimed, although a few crystals continued to be rimed more heavily. Liquid water contents at the surface at SPL during the passage of the band reduced to 0.05 gm^{-3}.

These observations all suggest that the liquid water remaining in the cloud during band passage was largely confined to the lower levels of the cloud system below SPL and was distributed uniformly in the horizontal throughout the cloud system. The rapid decrease in liquid water throughout the cloud system and the rapid increase in precipitation intensity and depth of the cloud all suggest that additional nucleation of significant numbers of ice crystals and/or ice crystal production through ice multiplication processes was occurring. The additional nucleation could have occurred in the colder regions of the cloud, or could have been associated with localized regions of enhanced supersaturations. In any case, significant numbers of ice crystals were produced which effectively removed the liquid water remaining in the cloud system by diffusional growth and accretion processes.

Data collection with the radiometer was interrupted at 1558 GMT and resumed at 1633 GMT. During this period, cloud tops gradually returned to 5000 m. When the radiometer was reactivated, the liquid water distribution resumed a pattern similar to that observed prior to band passage. The highest liquid water contents were observed over the mountains just northeast of the radiometer. Heavily rimed crystals were again consistently observed at SPL; unrimed crystals were observed at RAD.

The second cloud band moved over the radiometer site at 1700 GMT. From this time until 1740 GMT, cloud tops gradually increased, reaching 8000 m. At 1746 GMT, the cloud deck split, and the portion above 5000 m dissipated. Prior to the split, liquid water contents throughout the cloud system again decreased. Crystals and aggregates at RAD were mostly lightly rimed during this period. At SPL some crystals continued to be heavily rimed, but the intensity of the rime decreased with time. Liquid water contents observed at SPL were quite low during this period. These observations again suggest that enhancement of accretion processes by aggregate and single collectors was significant in the lower regions of the cloud during the development stages of the band.

When the cloud deck split and the upper deck dissipated, an immediate increase in the liquid water field occurred in all quadrants, particularly over the barrier. Precipitation during this period at RAD consisted of snow pellets and unrimed needles. At SPL, precipitation was similar in character with snow pellets and needles predominating. The liquid water field reached a maximum at 1840 GMT, then began to decrease in all directions as a third precipitation band moved into the region.

The radiometric liquid water contents measured during the period after the upper cloud deck dissipated were the highest measured during the field experiment and probably were complicated by melting occurring as the crystals fell through the boundary layer. The surface temperature during this period was between 1° and $2^{\circ}C$, so at least initial melting of some ice crystal surfaces was likely. However, rime observations at both sites indicate that a substantial amount of this water existed in the supercooled state.

The evolution of the cloud liquid water in this cloud system was such that the shallow portions of the cloud system with warm cloud top temperatures consistently had the highest liquid water contents. The deep cloud bands with cold cloud tops had lower liquid water contents. The decrease in liquid water during passage of the deep cloud bands was accompanied by an increase in the precipitation rate, indicating that the production of cloud ice particles was significantly enhanced during these periods.

3. Case study: 30 December 1981

Synoptic scale and local weather conditions

Major synoptic scale weather features at the surface and 50 kPa for 30 December 1981 are shown on Fig. 9. The radiometer operated in the scan mode from 2200 GMT on 30 December 1981 to 0100 GMT on 31 December 1981.

At 1200 GMT on 30 December 1981, a low pressure system was centered in eastern Wyoming. From this low, a cold front extended westward into southern Idaho, then southwest into central California. In the warm sector of this storm ahead of the cold front, strong mid-level winds, in association with the moderately moist airmass, produced a widespread stratiform cloud system over the northern Colorado Rockies. 70 kPa wind speeds were 15-18 m/s.

During the early portion of the study period between 1900 and 2210 GMT, the study area was in the warm sector of the storm. Light and sporadic precipitation occurred until 2100 GMT in the lower elevations associated with weak embedded convective elements in the cloud system. Light to moderate snow fell at higher elevations. By 2100 GMT, all snowfall had stopped at both low and high elevation observation stations although cloud cover remained over the region. At and behind the surface frontal boundary, a wide band of convective precipitation developed. Heavy precipitation continued through the remainder of the study period.

Storm evolution and supercooled liquid water distribution

The cloud systems occurring near frontal passage during the 30 December 1981 storm system were predominantly convective and were characterized by considerably greater cellular structure than in the previous two cases. These cells were emergent from a stratiform layer having a top around 4500 m (-15^{o}C).

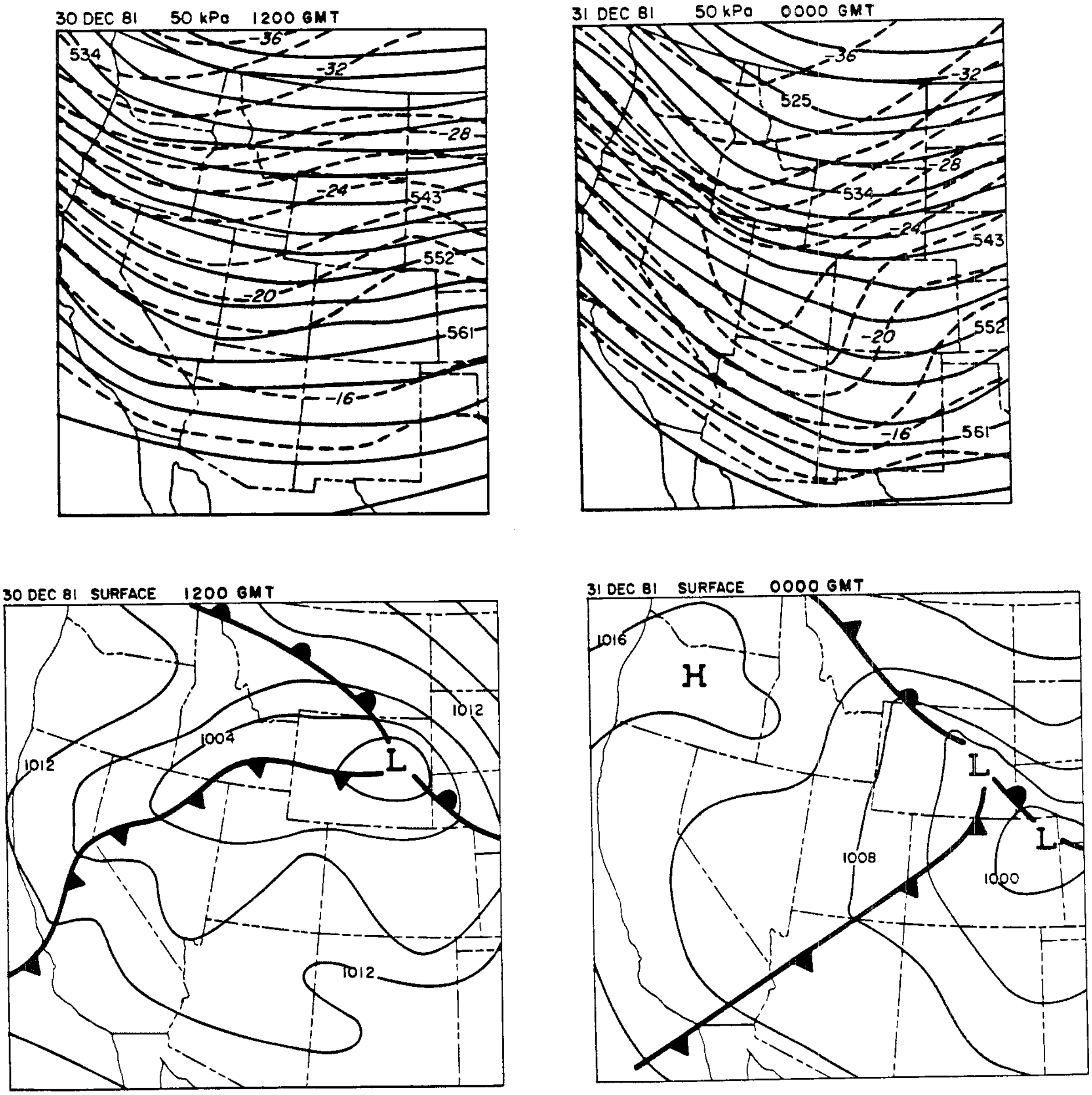


Fig. 9. Synoptic scale weather features for the 30-31 December 1981 storm system.

For an hour before frontal passage, snow fell in showers at higher elevations from cells that developed upwind of the range near RAD and moved over the ridge. No precipitation was observed at lower elevations during this period. At the time of frontal passage, considerable convective activity developed throughout the region, heavy precipitation began falling at all observation sites, and winds increased substantially at all elevations.

The storm system was organized into two bands of heavy precipitation. Each band took about 1.5 hr to pass through the Park Range region. Between bands, a low level stratiform cloud continued to produce precipitation at significantly lower rates. Vertical profiles of equivalent potential temperature from rawinsondes launched at CG at 2100 GMT, just prior to frontal passage, and 0000 GMT (31 December), after the front had passed, are shown on Fig. 10.

Before frontal passage, two potentially unstable layers were present, the first extending from the surface (1886 m) to 2355 m and the second from 4418 m to 6418 m. At 0000 GMT, potentially unstable layers were present between the surface and 2430 m and between 4127 and 6569 m. The primary difference between these soundings was the presence of the stable layer at 0000 GMT between 3040 and 4127 m associated with the cold frontal surface. The potential instability of the later sounding was also somewhat greater because of cold air advection aloft. The two wide area bands present after frontal passage developed in response to lifting along the cold frontal surface and subsequent release of the potential instability in the middle troposphere.

The time evolution of the supercooled liquid water field prior to, during and following frontal passage is shown on Fig. 11. Data sets

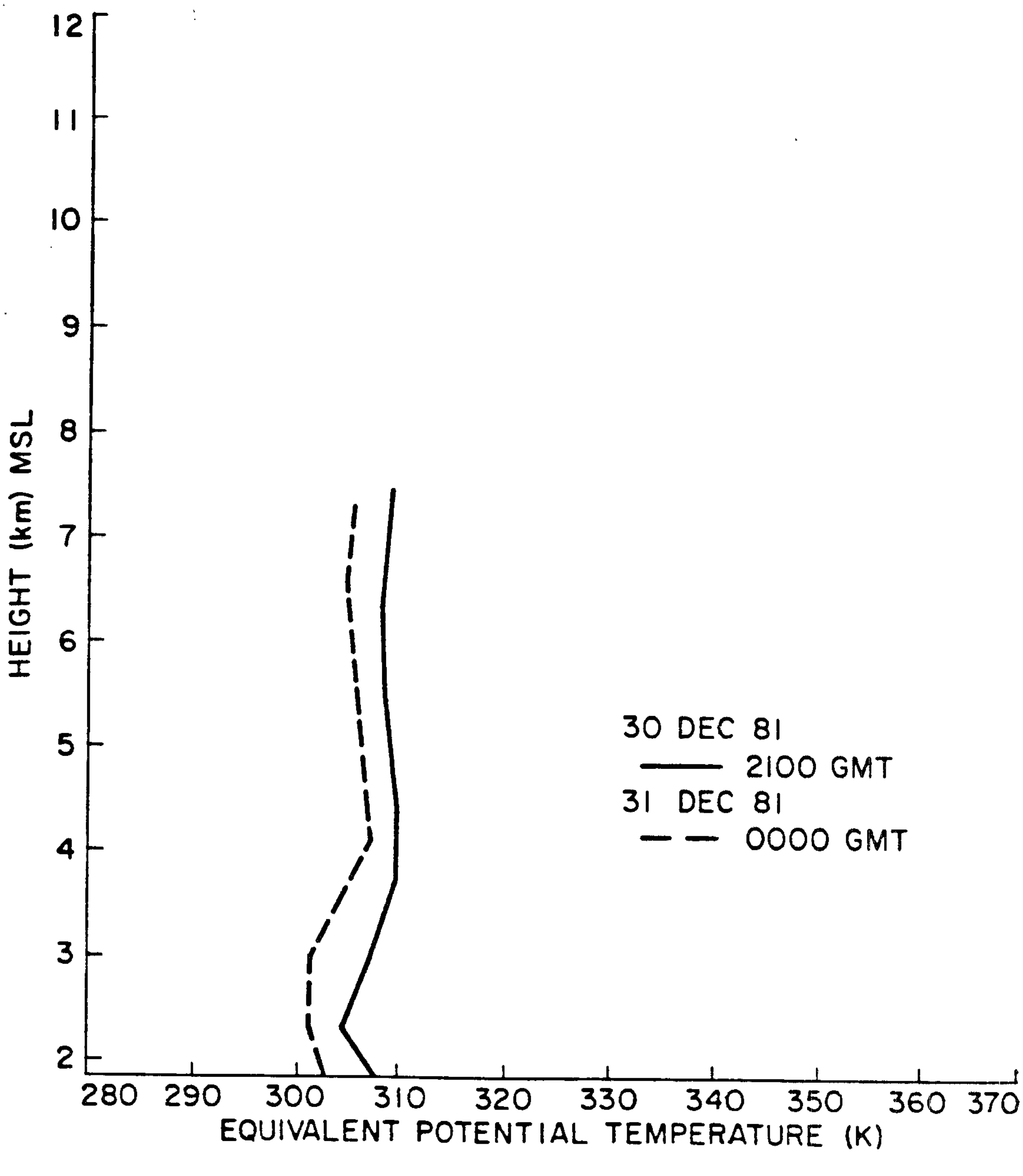


Fig. 10. Vertical profiles of Equivalent Potential Temperature at 2100 GMT, 30 December 1981 and 0000 GMT, 31 December 1981.

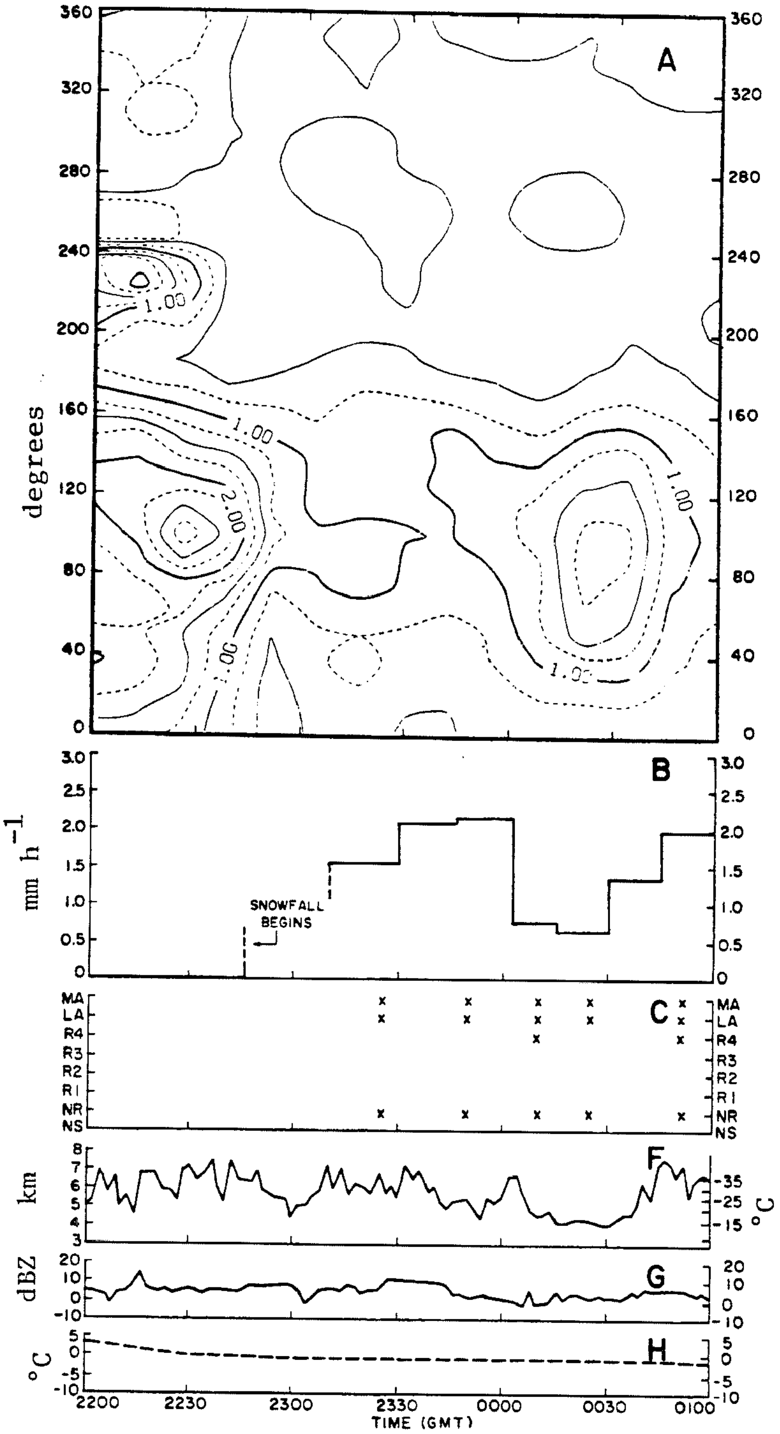


Fig. 11. 30-31 December 1981 (2200-0100 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

available for the period are included on the figure. SPL did not operate during this storm period. During the time prior to frontal passage, a stratiform cloud deck with considerable cellular convection was present over the area. No precipitation fell in the valley. Occasional snow pellet showers were reported by an observer near SPL. During this time, considerable liquid water was concentrated primarily over the ridge. The majority of the liquid water was concentrated over the windward slopes with concentrations decreasing to the west away from the primary lift zone. An exception was a strong concentration of water southwest of the site. This localized zone of liquid water to the southwest was probably associated with a region of developing convection. The large concentration of liquid water over the slopes was most likely associated with a stratiform deck over the Park Range that was produced by more uniform lifting as air was forced over the barrier.

The arrival of the frontal zone and the onset of the first wide area band of convective precipitation at about 2300 GMT was marked by a rapid increase in the snowfall rate at RAD and a simultaneous decrease in the liquid water content of the cloud system, particularly in the vicinity of the barrier. Although substantial decreases were observed, liquid water was present throughout the cloud system during band passage. Values of integrated liquid water were generally about 0.4 mm upstream of RAD throughout the period. Snowfall during band passage consisted primarily of aggregates. These flakes were composed mostly of rimed crystals. Often the rime was of moderate intensity. Some snow pellets were observed at the time of band passage. These observations indicate that the passage of the band of convective precipitation resulted in a substantial decrease in the total liquid water present in the system associated with the orographic component of the vertical motion, although some liquid water remained in the system associated with the wide area lifting above the frontal surface and with developing cellular convection. Water removal in this system was primarily through accretion processes.

The passage of the first band occurred at 0000 GMT. The cloud system following band passage was largely stratiform with a top around 4200 m (-15^{o}C). During this period, the cloud system returned to a liquid water configuration similar to that observed prior to the arrival of the first band; high liquid water concentrations were centered over the barrier. Liquid water continued to be present in the cloud system upstream of RAD, but in much smaller quantities than were observed over the ridge. Snowfall continued to be aggregated with considerable rime.

The second band arrived at 0030 GMT. As precipitation rates increased, a simultaneous decrease in liquid water content over the barrier occurred, similar to what was observed with the first band. Precipitation again consisted largely of aggregates with varying degrees of rime accumulation. Some snow pellets were occasionally observed, but precipitation was predominantly aggregated crystals. These observations support the earlier conclusion that the ice phase processes associated with a well developed cloud system supported by convective activity substantially reduce the total liquid water content of the cloud system.

b. Post-frontal cloud systems

1. Case study: 21 December 1981

Synoptic scale and local weather conditions

Large scale weather features for the period from 1200 GMT, 21 December 1981 to 0000 GMT on 22 December 1981 at the surface and 50 kPa are shown on Fig. 12. Radiometer scans were performed during the period from 1320 to 1620 GMT.

At 0600 GMT on 21 December 1981, a strong cold front moved southward from Wyoming into the northern Colorado study area. Heavy precipitation began to fall throughout the region at the time of boundary extended westward from a weak low in western Nebraska, through central Colorado and into central Utah. Heavy precipitation continued throughout the mountainous regions north of the front. Aloft at 1200 GMT, strong cold air advection was evident throughout much of the troposphere associated with a short wave trough over western Utah.

During the period from 1200 to 0000 GMT on 21 December, the surface cold front moved southward out of Colorado and reorganized about a deepening low pressure system in the Texas Panhandle. Aloft, the trough deepened rapidly throughout the period in response to strong cold air advection. The trough axis at 50 kPa remained west of the study area at 0000 GMT with the coldest air located over northern Nevada.

During the period of the radiometric scans, the precipitation was light to moderate at valley sites and heavy on the barrier. The precipitation occurred entirely in the post-frontal airmass. During the same period, mid-level wind speeds continuously decreased. At 70 kPa wind speeds were measured at 19 m/s at 1200 GMT decreasing to 11 m/s at 1500 GMT.

<u>Storm Evolution and Supercooled Liquid Water Distribution</u>

The period of the storm system for which liquid water observations were available was characterized by predominantly orographically driven vertical motions with potential embedded low level convection, particularly in the vicinity of the ridge. During the early stages of

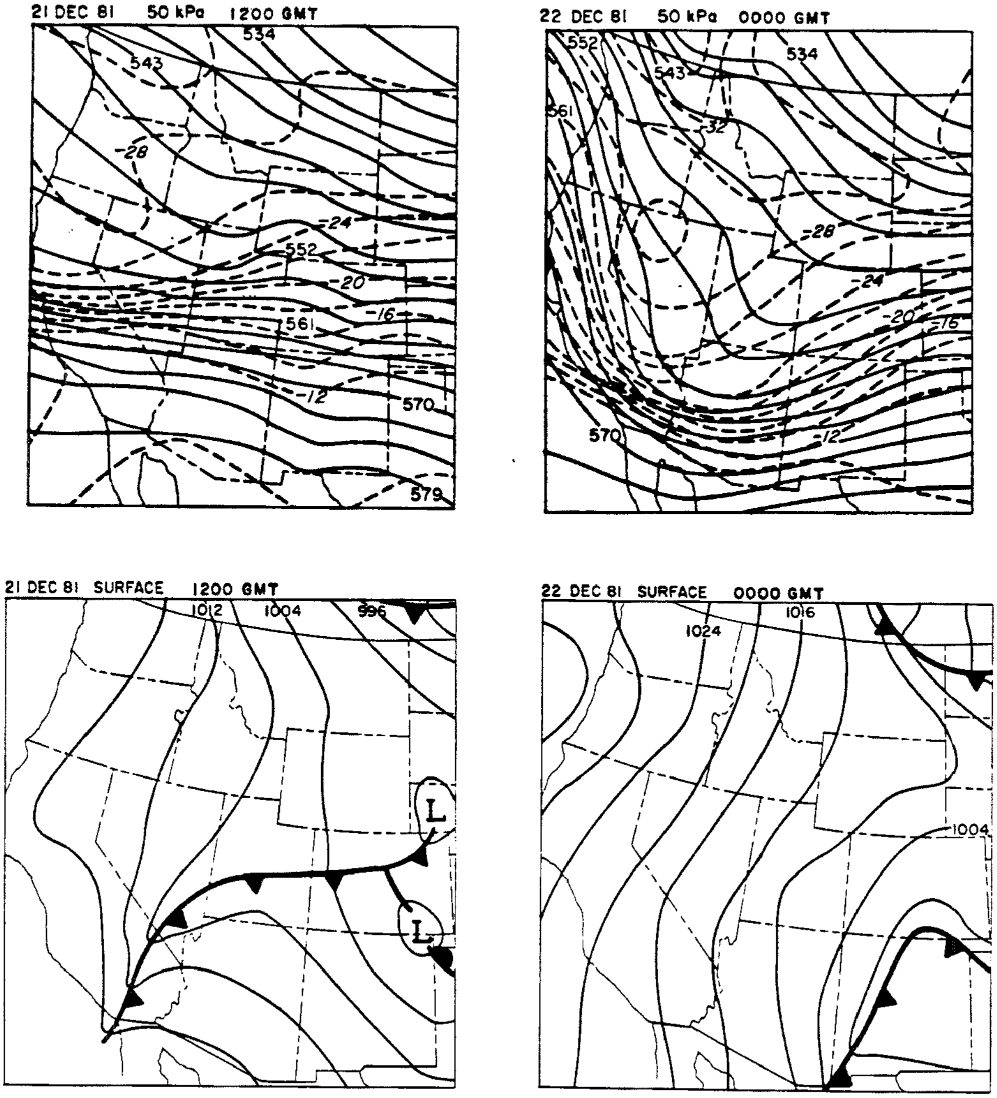


Fig. 12. Synoptic scale weather features for the 21 December 1981 storm system.

the storm system before 1345 GMT, heavy precipitation fell at both mountain and valley sites. At 1345 GMT, just after the initiation of the radiometer scans, a sharp transition in the character and the intensity of the precipitation occurred. The cloud system after this transition had characteristic tops between 5000 and 6000 m (-20° to $-25^{\circ}C$), and low precipitation rates at RAD, but produced continuous heavy precipitation at SPL near the barrier crest.

The vertical profile of equivalent potential temperature from the 1500 GMT sounding launched at CG is shown in Fig. 13. A potentially unstable layer was present during the period between 2319 and 3283 m, with a neutral layer extending to 4052 m. The equilibrium level for convection originating at the lower levels of the cloud system was near 4600 m, well below the observed cloud top during the observation period. For this reason, convective cells developing within the cloud system were embedded rather than emergent.

Precipitation intensity at RAD during the period (Fig. 14) indicated that any cellular embedded convection within the cloud upstream of the site was weak, since no significant increases were apparent in the precipitation rate associated with convective activity. The lack of significant changes in the low level reflectivities of the vertically pointing radar provides additional evidence that cellular convection was not the dominant mechanism in the production of precipitation in the valley.

Along the windward ridges, the potential for release of convective instability, coupled with the enhanced vertical motions associated with the orographic component of the airflow, led to considerably greater precipitation rates at the mountaintop observation site. Heavy

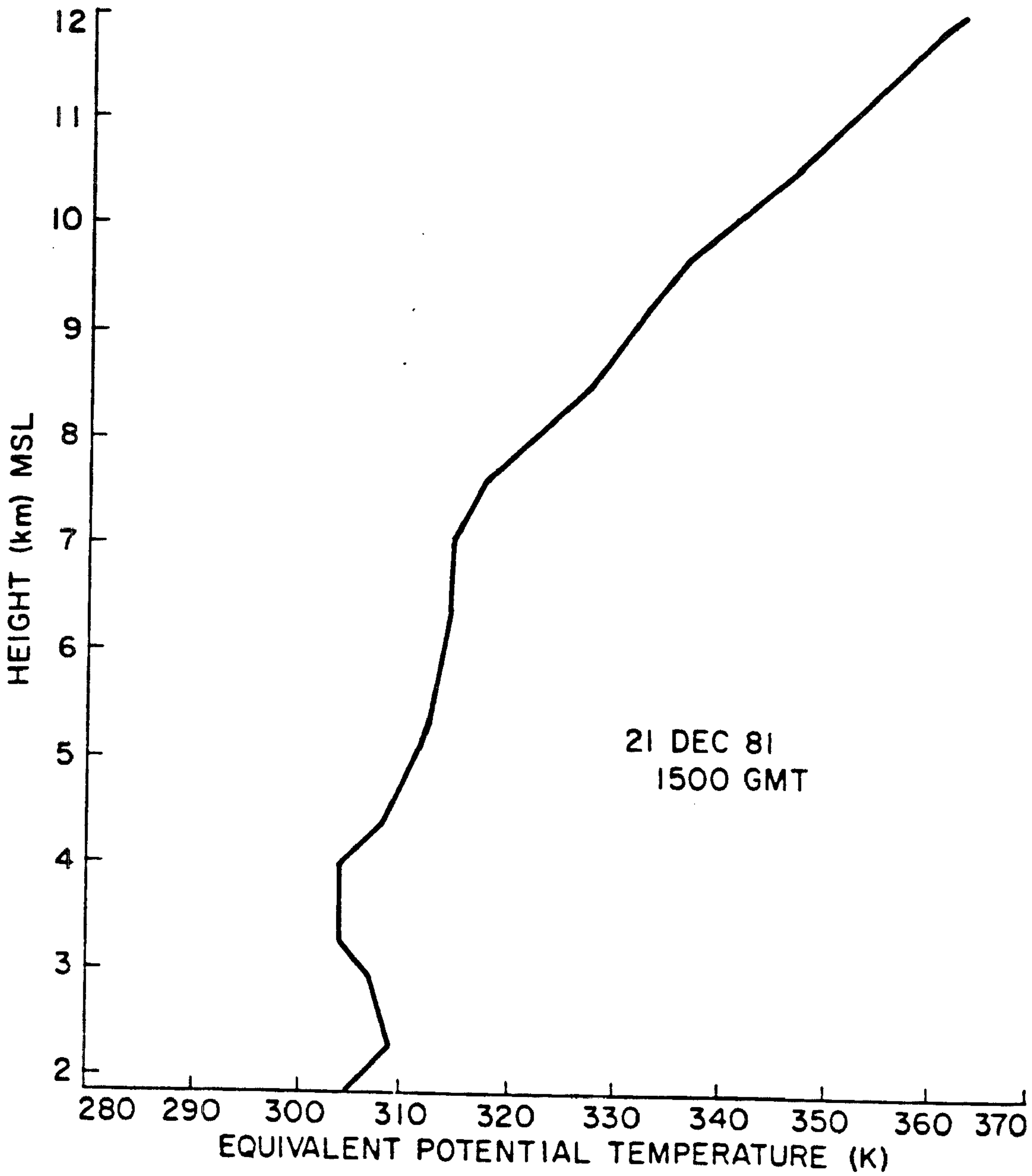


Fig. 13. Vertical profile of Equivalent Potential Temperature at 1500 GMT on 21 December 1981.

precipitation persisted at this location throughout the observation period from 1345 to 1620 GMT.

The time evolution of the supercooled water field and all associated parameters are shown in Fig. 14. Throughout the observation period, liquid water was present throughout the cloud system, but concentrated over the barrier. Maximum values of liquid water were consistently at an azimuth angle of approximately 90^{o}, directly over the windward slopes. Before the decrease in precipitation rate, crystals fell primarily as aggregates at RAD and were generally lightly rimed. Simultaneous observations of crystals at SPL indicated considerably more accretion; some crystals were rimed so heavily that the original crystal habits could not be recognized. These observations support the radiometric measurements of high liquid water contents in the vicinity of the barrier.

After the decrease in precipitation rate at RAD, liquid water contents increased in the vicinity of the barrier, accompanied by an increase in the amount of accreted water drops on crystals collected at SPL. During this period, the laboratory was enveloped in a liquid cloud with liquid water content of 0.10 gm^{-3}. At RAD, crystals continued to be lightly rimed.

From 1430 GMT to 1630 GMT, the character of the precipitation at SPL and at RAD was similar. Observations at both locations consisted primarily of heavily rimed crystals and unrimed needles. The needles were mostly observed at SPL, which was located at the $-7^{o}C$ isotherm, but were also occasionally observed at the low altitude RAD site. These observations suggest that the precipitation in this system was growing by accretion primarily in the low level, embedded convective cells

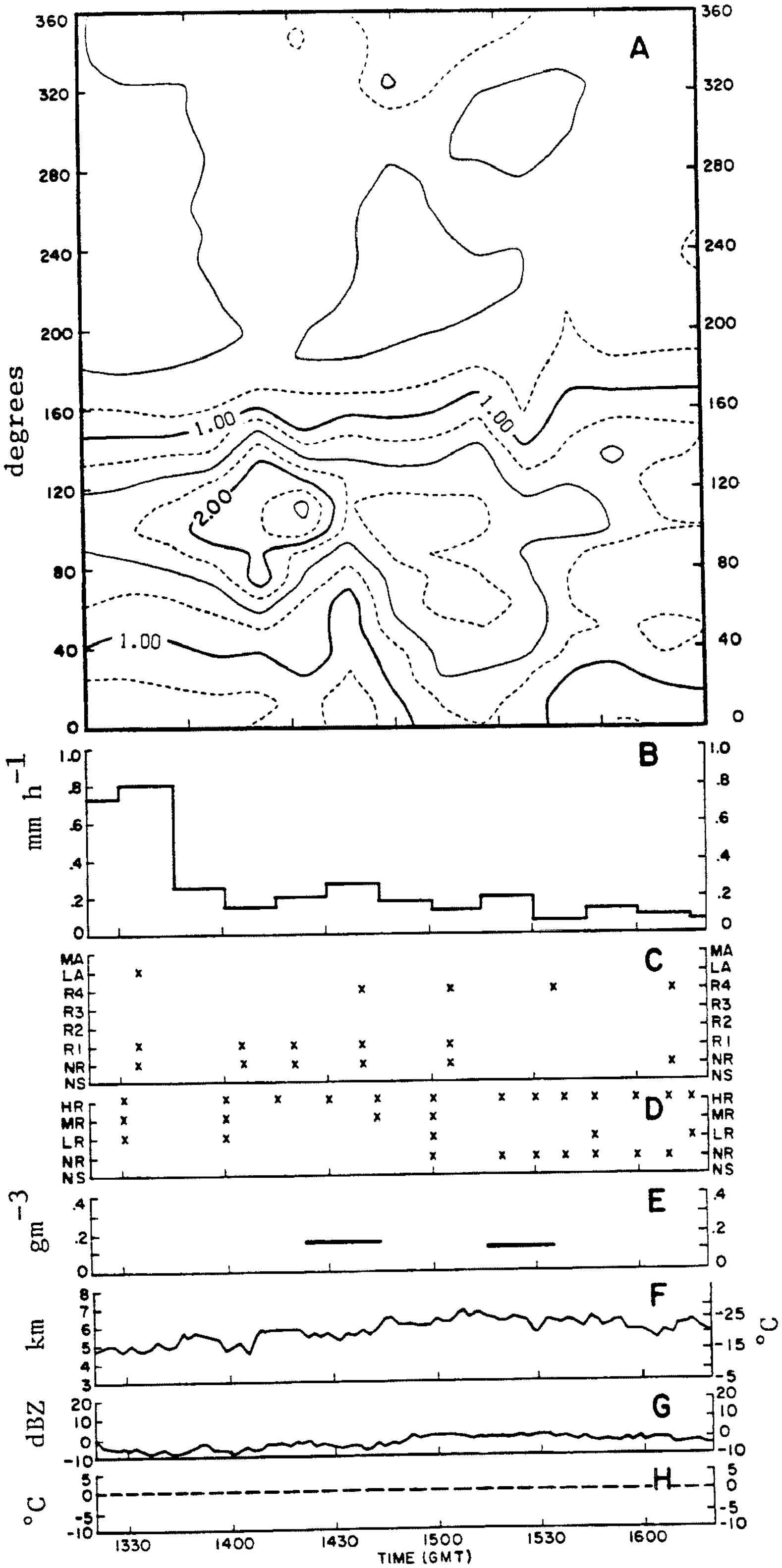


Fig. 14. 21 December 1981 (1320-1620 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

forming in the vicinity of the ridge. The needles observed possibly resulted from secondary ice multiplication production (Hallet and Mossop, 1974) occurring in the cloud just upstream of SPL. The appropriate conditions specified by recent experiments (e.g. Mossop, 1978) were all present in this region. These needles, forming near SPL, had little time to grow by accretion before impacting on the barrier. For this reason, these crystals were generally observed to be unrimed. During the entire period, SPL continued to be enveloped in a liquid cloud.

2. Case study: 13 December 1981

Synoptic scale and local weather conditions

Fig. 15 shows the evolution of the large scale weather features at the surface and at 50 kPa on 13 December 1981. The radiometer operated in the scan mode between the hours of 1700 GMT and 2000 GMT during the storm.

At 0000 GMT on 13 December 1981 a stationary front extended from a low near Laramie, Wyoming, west to northern California where it intersected an approaching Pacific frontal system. By 0600 GMT, a low centered in eastern Nevada had developed along the Pacific front. The stationary front extended between this low and the low in eastern Wyoming. As the western front and the associated low progressed southeast across Utah, the stationary front became a cold front and began to move across northwest Colorado. A band of stratiform clouds about 200 km wide developed ahead of this front. Between 1300 and 1500 GMT, this band of clouds passed through the study area and produced heavy precipitation. The frontal passage occurred at 1430 GMT. Aloft at 1200 GMT, a fast-moving short wave with significant cold core

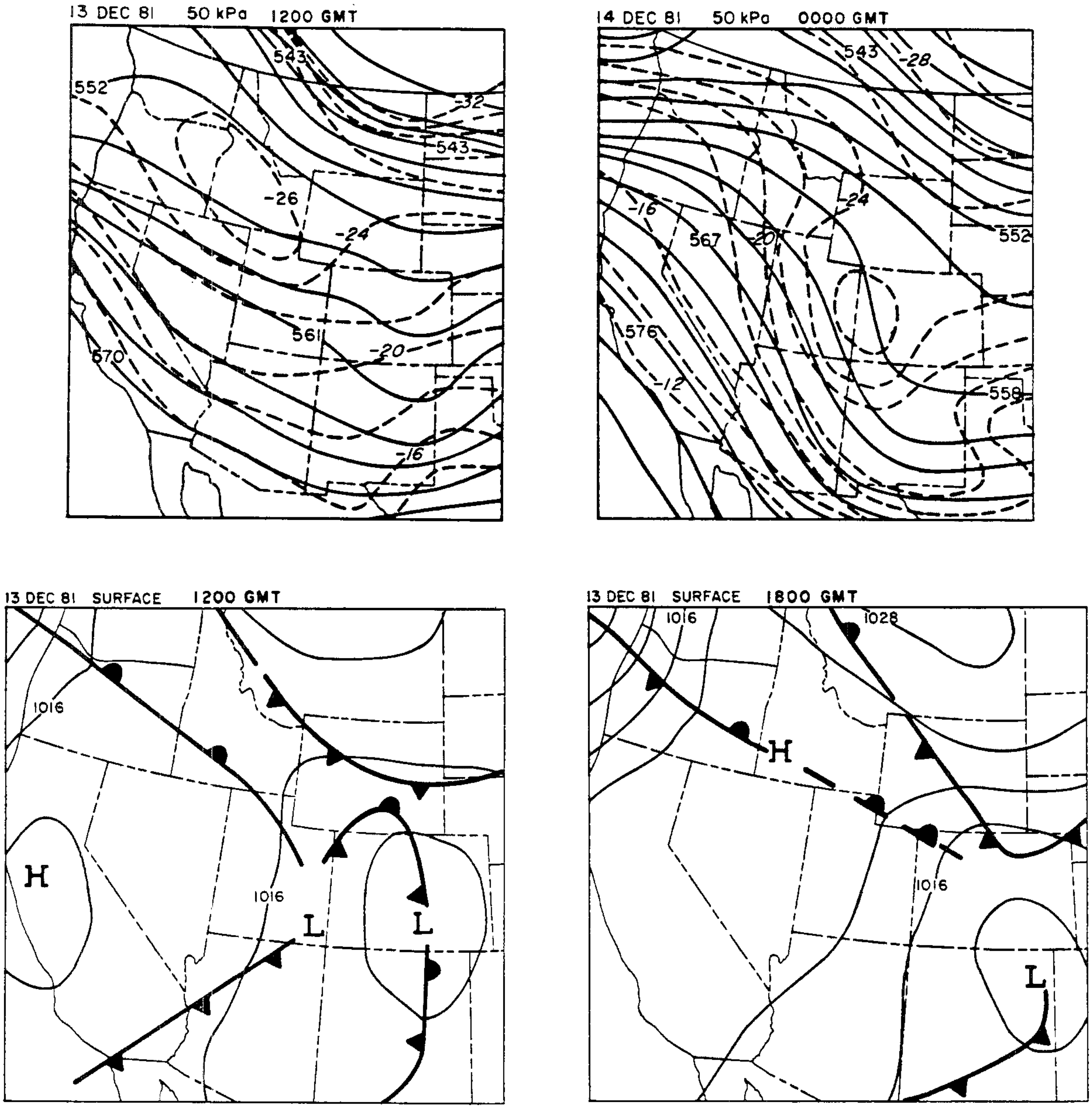


Fig. 15. Synoptic scale weather features for the 13 December 1981 storm system.

temperatures approached the study area from the northwest. As the short wave passed, the temperature at the 50 kPa level dropped 6^{o}C over northern Colorado. This short wave, combined with predominantly westerly, moist mid-level flow behind the front, led to the development of isolated convective cells along the ridges. These cells were mostly embedded in a cap cloud which extended west of the ridge about 10-15 km. The average top of this cloud in the vicinity of the vertically pointing radar was 6000 m. The radiometer scans were conducted during the period when the cap cloud was present and initial cellular convection was beginning to develop.

Storm evolution and supercooled liquid water distribution

The storm system of 13 December 1981 evolved through three distinct stages, each characterized by different regimes of cloud development. During the initial stage, precipitation was produced from a stratiform cloud band which developed ahead of and parallel to the approaching cold front. This cloud system developed in mid-level southwest flow, had a width of about 200 km, and produced steady, moderate to heavy precipitation. Frontal passage marked the transition to the second stage of development. With frontal passage, mid-level winds shifted to westerly and increased in speed. The cloud system from this time onward was maintained primarily by orographic forcing. The clouds during this period were stably stratified. Between 1430 and 1800 GMT, the moisture flux from the west steadily decreased; the decrease was accompanied by a decrease in the extent of the cloud system and in the precipitation rate at RAD. Precipitation continued to be heavy at SPL due to strong orographic lifting of the airstream near the ridge. During this period, the atmosphere continually destabilized because of cold air advection aloft. By 1800 GMT, convective cells began to develop along the ridges. Precipitation during this latter stage of storm development was primarily produced by orographic forcing, but enhanced in the vicinity of localized convection. The period of radiometric observations covers the latter part of the second stage of storm development and 2 hr during the convective period. Fig. 16, the vertical profile of equivalent potential temperature from rawinsondes launched at 1500 and 1800 GMT at CG, shows the rapid decrease in atmospheric stability associated with the approach of the cold core of the short wave trough. At 1500 GMT, no potentially unstable layers were present on the sounding. A neutral layer extended from 5537 m to 6884 m. By 1800 GMT, the entire troposphere over the study area had cooled considerably. A potentially unstable layer extended from the surface (1886 m) to 3064 m. Above this layer, a neutral layer extended to 4483 m. Cloud tops were observed to extend to approximately 6000 m.

The time evolution of the supercooled cloud water field and associated parameters are displayed on Fig. 17. Observations of the rime characteristics of crystals at SPL were not made during this storm period. During the latter part of the second stage of this storm, prior to the development of cellular convection, precipitation rates at RAD were approximately 4.0 mm/hr and no rime was observed on any of the crystals. During this period, liquid water was distributed throughout the cloud system with only slight increases in the vicinity of the barrier. With the decline in precipitation intensity, liquid water contents in the vicinity of the Park Range began to increase substantially. At the beginning of this period, Rotorod measurements of liquid water at SPL confirmed the presence of a liquid cloud in the

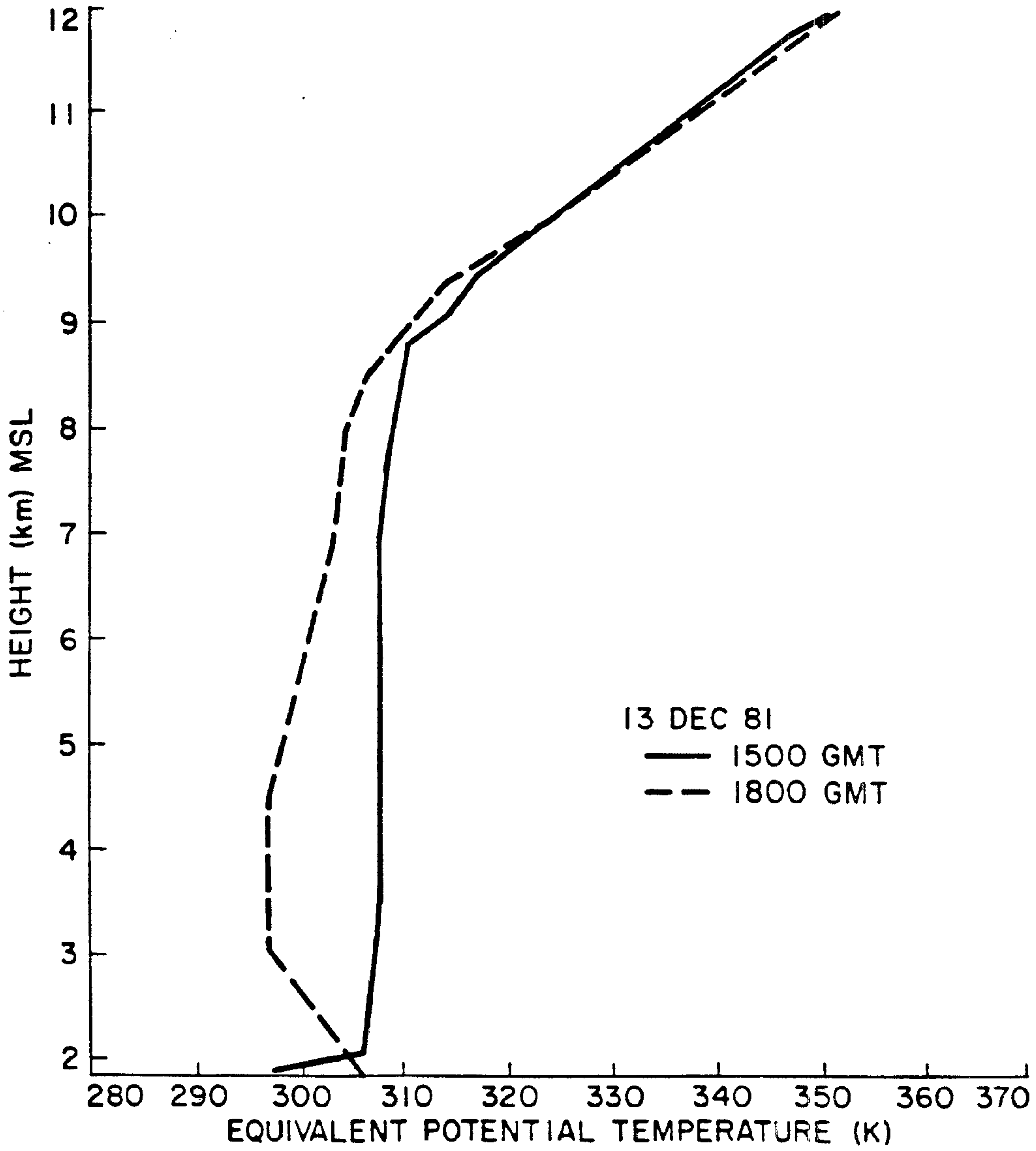


Fig. 16. Vertical profiles of Equivalent Potential Temperature at 1500 GMT and 1800 GMT for the 13 December 1981 storm system.

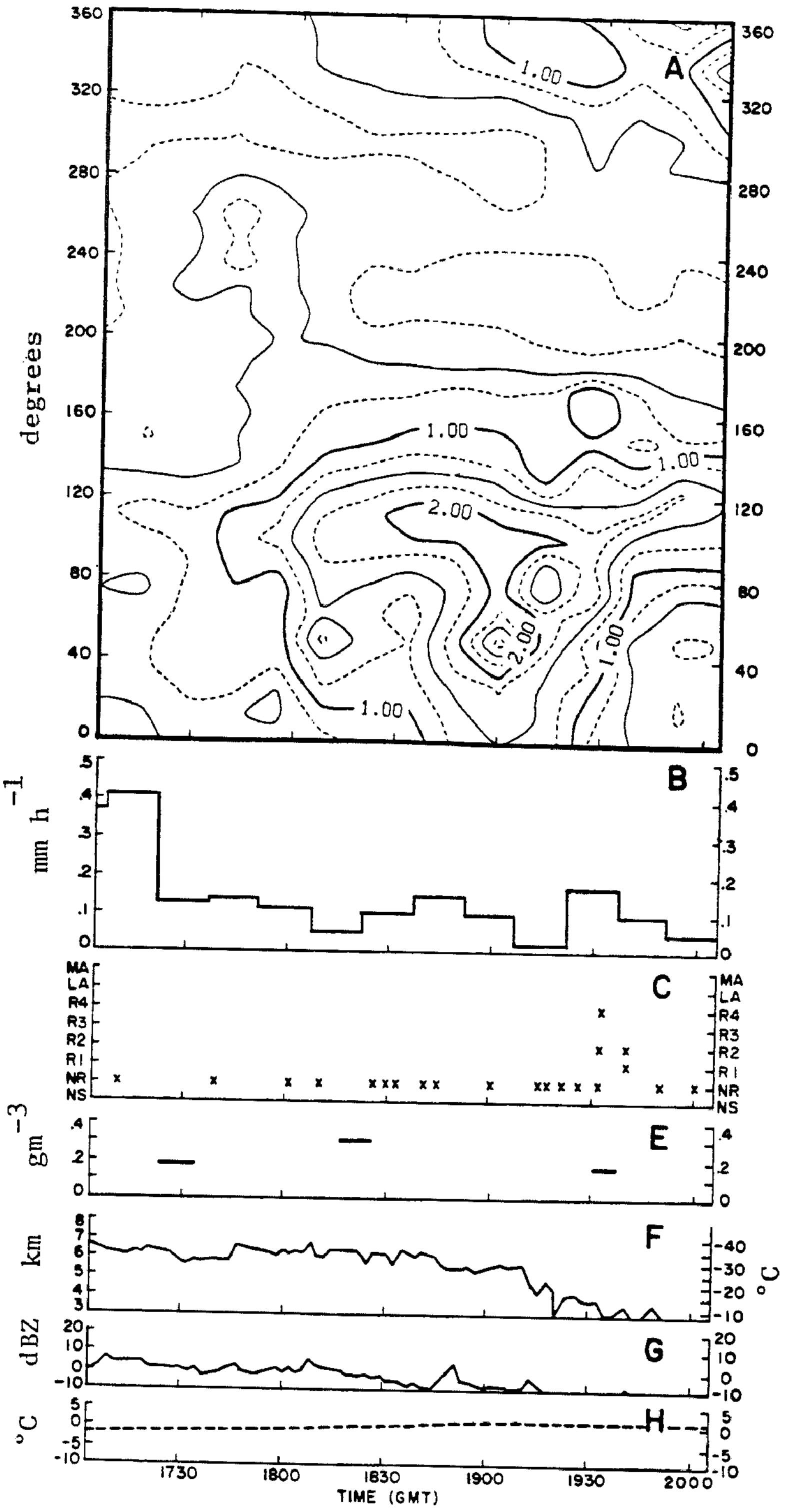


Fig. 17. 13 December 1981 (1700-2003 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

vicinity of the barrier; the liquid water content was about 0.20 gm^{-3}. Within an hour, this value increased to 0.40 gm^{-3}. Simultaneous measurements with the radiometer indicated that these increases were localized over the ridge, but did not extend far upstream. This was also evident from the crystals that fell at RAD. These crystals originated well upstream of the mountain and were unrimed throughout the period. It is likely that during the latter stage of storm development, part of the enhanced liquid water field over the barrier was due to liquid water production in convective cells. However, the persistence of the liquid water over the barrier for such a long period suggests that orographic forcing was the dominant mechanism sustaining the liquid water field.

The local effect of convective cells is evident in the crystal observations at 1935 GMT at RAD. Crystals originating in localized convection in the vicinity of RAD fell at the site for 15 min. During this period, precipitation initially contained snow pellets. Unrimed crystals, presumably originating near the upwind locations of the stratiform cap cloud, also fell at RAD during this same period. Although precipitation from the cell fell at RAD, the cell did not move directly over the vertically pointing radar.

The concentration of liquid water in the cloud system reached a maximum just before 1900 GMT and then began dissipating. Rotorod measurements of liquid water also decreased during the period to 0.16 gm^{-3}. During this period, the extent of the cap cloud decreased, mid-level wind speeds declined and the system continued to slowly dissipate. Light snowfall continued until 2125 GMT at RAD, occasionally containing snow pellets associated with cellular convection.

3. Case study: 27 January 1982

Synoptic scale and local weather conditions

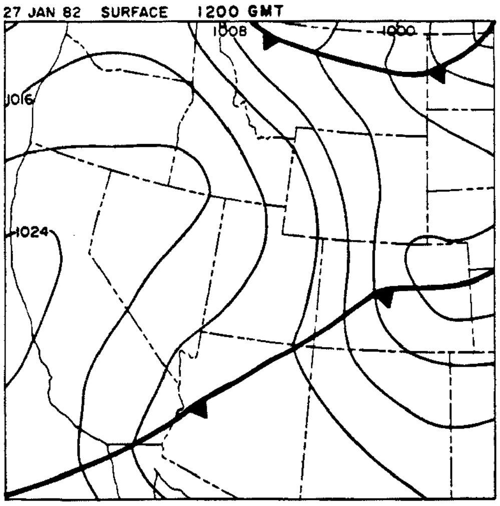
Large scale weather features over the western United States at the surface and at the 70 kPa level are shown on Fig. 18. The radiometer performed azimuth scans between 1500 and 1800 GMT.

AT 1000 GMT on 27 January 1982, a strong cold front moved through the study area in northwest Colorado. From the time of surface frontal passage until 1530 GMT, precipitation fell continuously throughout the Park Range region. This precipitation was associated with an area of cloudiness which extended approximately 300 km northwest of the surface front. At 1530 GMT, the western edge of this cloud mass passed over the region and the clouds over the valleys rapidly dissipated. After 1530 GMT, strong mid-level winds maintained cap clouds over the higher elevations. The cap clouds persisted until well after 1900 GMT and frequently contained shallow convective elements. The extent of the cap cloud cover decreased during the afternoon and skies were clear by 2100 GMT.

Storm evolution and supercooled liquid water distribution

The 27 January 1982 storm system moved rapidly through the Park Range area, producing about 7 hr of snowfall. Radiometric scans were performed during the latter dissipating stages of this system. During this period, a shallow cap cloud was present over the Park Range. The edge of this cloud extended west of RAD, but the cloud produced no precipitation at RAD or at other valley observation sites. The cap cloud contained embedded shallow convective elements which were primarily along the ridge line.

Fig. 19 shows the vertical profile of equivalent potential



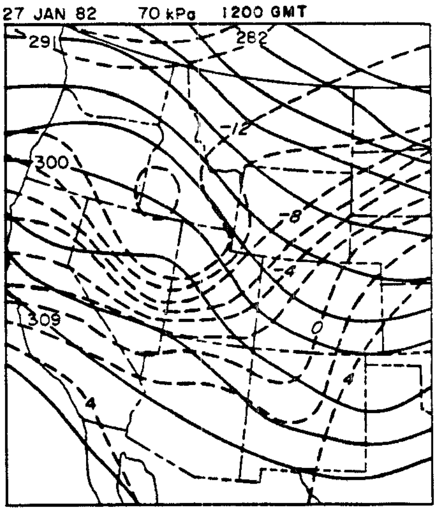


Fig. 18. Synoptic scale weather features for the 27 January 1982 storm system.

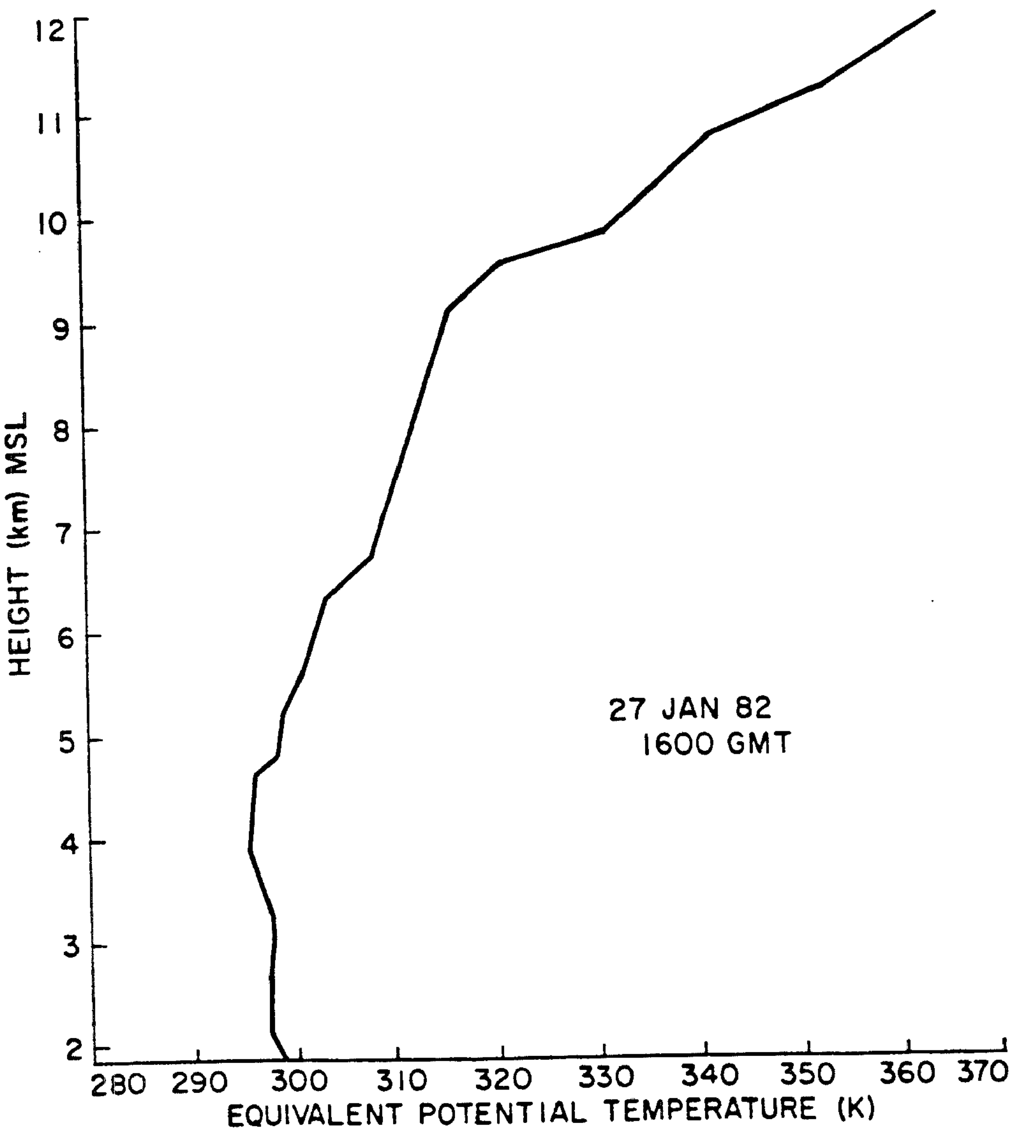


Fig. 19. Vertical profile of Equivalent Potential Temperature at 1600 GMT on 27 January 1982.

temperature from a sounding taken at CG at 1600 GMT. Two potentially unstable layers were present on the sounding, the lowest between the surface and 2124 m and a second layer between 3208 and 3891 m. The weak convective instability observed within the cap cloud resulted from instability release in the mid-level potentially unstable layer. More important to the production of liquid water in this cloud was the strong orographic forcing of the airflow due to exceptionally strong mid-level winds. The 70 kPa wind speed normal to the barrier from the 1600 GMT CG sounding was 21.7 m/s. Between 1600 GMT and 1900 GMT, the 70 kPa normal wind speed reduced substantially to 8.5 m/s. During this period, the extent of the cap cloud over the Park Range decreased. Precipitation at SPL was light in intensity between 1500 and 1800 GMT, gradually decreasing as the mid-level wind speed declined.

The time evolution of the supercooled water field is shown in Fig. 20 along with associated parameters. Except for a brief time during the initial part of the scan period, no precipitation occurred at RAD. From the radiometric scans, it is evident that virtually all the liquid water in this cloud system was concentrated over the windward slopes of the barrier. The liquid water content slowly decreased with time, indicating that the production of liquid water was primarily due to the orographic component of the vertical motion. Some contribution to the liquid water field was probably associated with enhanced liquid water production in individual convective elements, but the strong association between the strength of the mid-level winds and the quantity of supercooled water present in the system indicates that the convective component of the liquid water production in the cloud was a secondary effect.

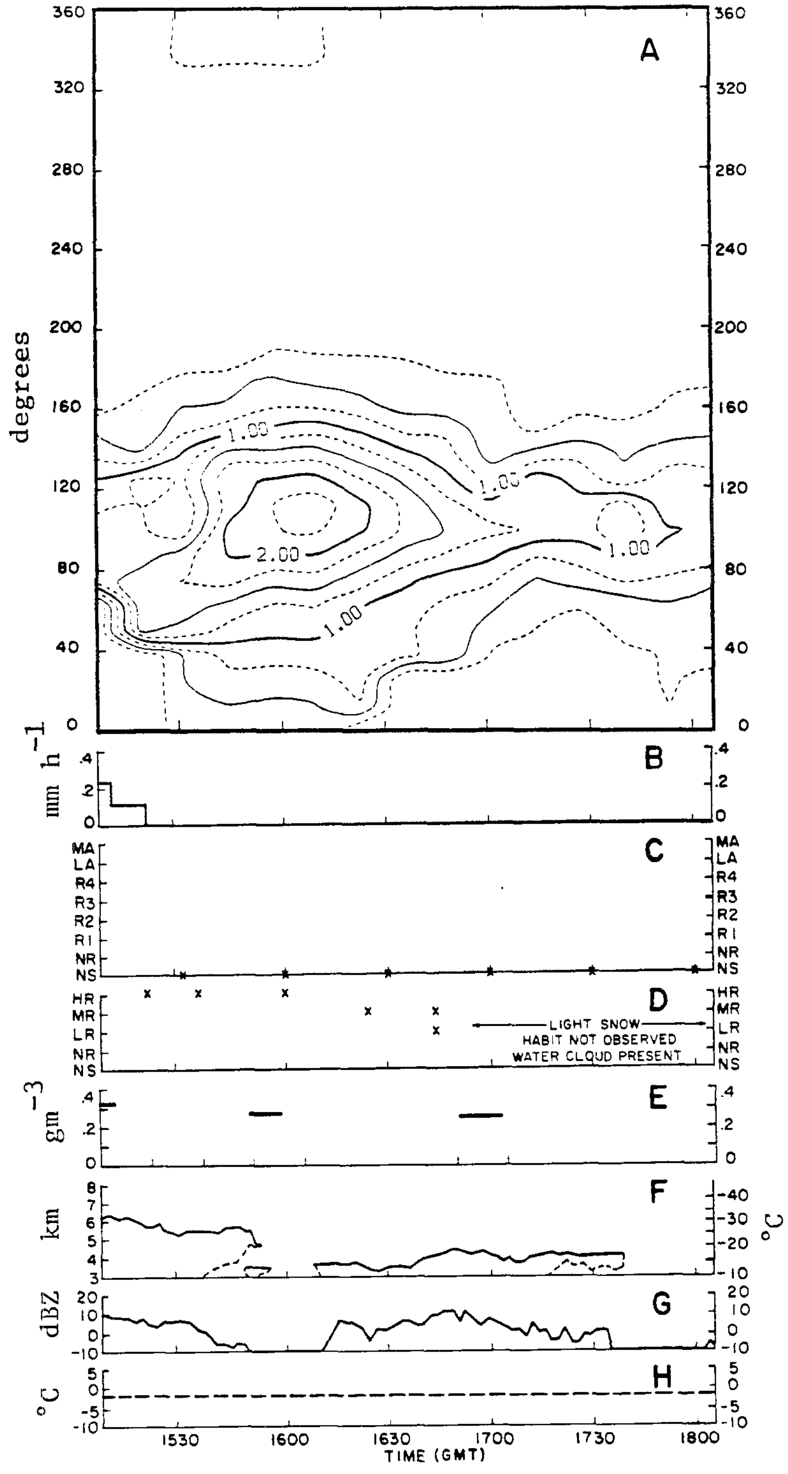


Fig. 20. 27 January 1982 (1500–1805 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C).

The presence of liquid water in the zone over the windward slopes was confirmed both by observations of crystals at SPL and by the Rotorod measurements. During the observation period, the cloud enveloping Storm Peak had liquid water contents near the surface ranging from 0.25 to 0.32 gm^{-3}. Although only light precipitation fell at SPL, all of the precipitating crystals were rimed. During the first hour of radiometric scans, crystals were heavily rimed. The amount of rime reduced with time as the cloud system slowly dissipated, but the laboratory remained in a liquid cloud throughout the period.

c. Orographic systems

1. Case study: 14 December 1981

Synoptic scale and local weather conditions

The evolution of the large scale weather pattern over the western United States on 14 and 15 December 1981 at the surface and at 70 kPa is shown on Fig. 21. Radiometric scans were performed during the period 1800-2100 GMT.

At 1200 GMT, a low pressure center was located in central Montana with a front extending southeast through Salt Lake City, Utah, across Nevada and into central California. This front separated a warm, moist Pacific airmass to the west from colder continental air to the east and south. Well ahead of the front at mid-levels, in a basically anticyclonic upper level flow pattern, an area of moist air and clouds approached the study area. At the same time, a lee side trough was present east of the Continental Divide. During the 12 hr period between 1200 and 0000 GMT, the lee side trough deepened significantly in response to the southeasterly movement of the surface low from Montana to western Nebraska, causing an intensification of the pressure gradient

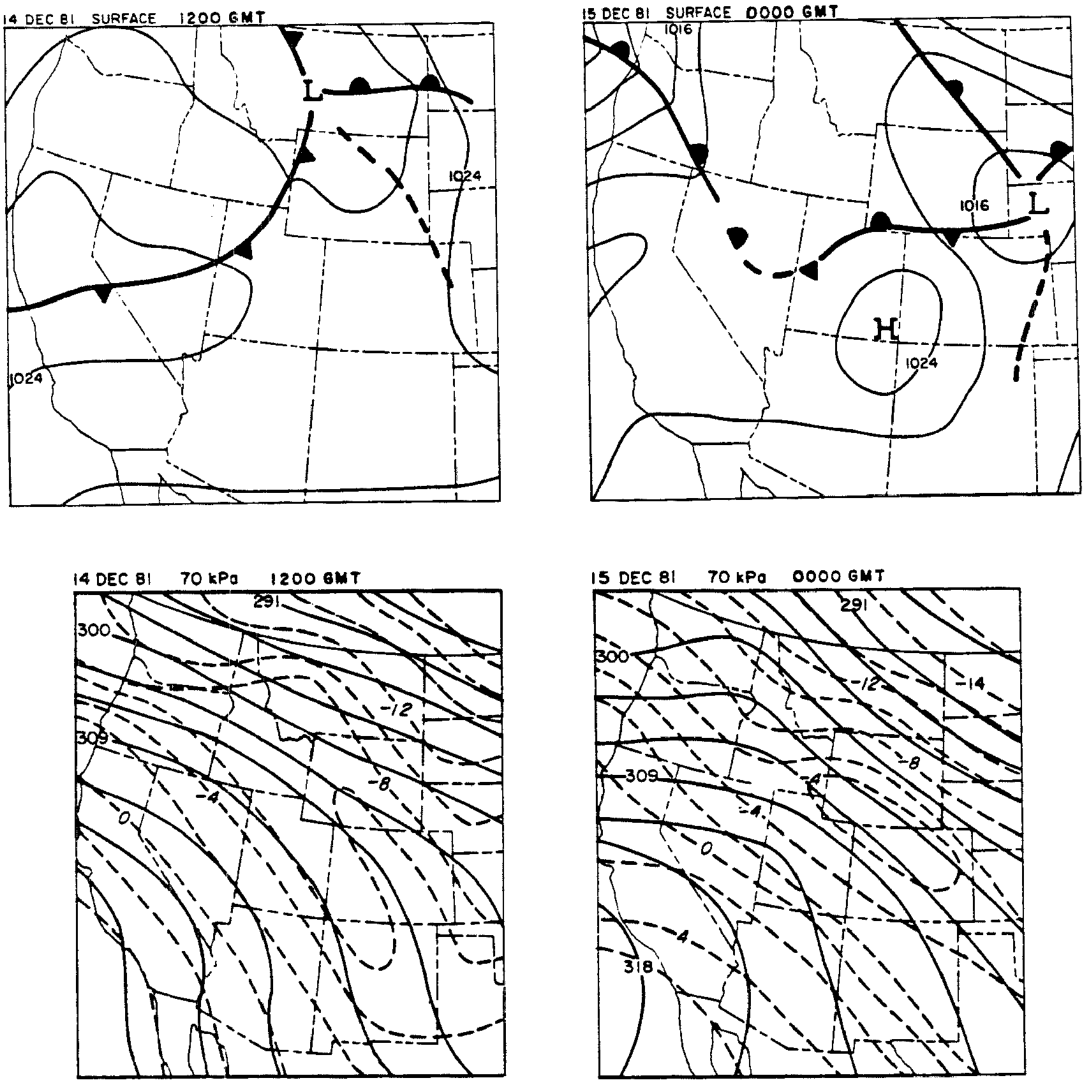


Fig. 21. Synoptic scale weather features for the 14 December 1981 storm system.

across the mountains and an enhancement of the mid-level cross-barrier wind velocity. The storm on 14 December developed in response to an intensification of the cross-barrier pressure gradient and a simultaneous influx of mid-level moisture from the west. The presence of a foehn wall visible from the lee side of the Park Range and the shallow nature of the cloud system indicated that the storm during the study period was primarily orographically forced. Warm air advection occurred during the study period.

Storm evolution and supercooled liquid water distribution

The cloud system occurring on 14 December 1981 was shallow, with tops around 4000 m (-15°C). Despite these warm temperatures, considerable precipitation fell from the cloud system, predominantly as aggregated crystals. The storm was stably stratified during the observation period. Fig. 22, the vertical profile of equivalent potential temperature from an 1800 GMT sounding at CG, indicated that one potentially unstable layer existed between 4097 and 4766 m. For the greater part of this storm, this layer was located above cloud top and did not contribute to cloud destabilization. The intensity of the mid-level winds increased during the period when radiometric scans were conducted. 70 kPa winds normal to the barrier measured at CG increased from 7.2 m/s at 1800 GMT to 15.7 m/s at 2100 GMT. This increase was partly responsible for changes observed in the cloud liquid water distribution.

The time evolution of the supercooled liquid water distribution is shown in Fig. 23, along with associated measurements from SPL and RAD. Between 1800 and 2000 GMT, liquid water was present throughout the cloud system, but was concentrated over the mountain crest, particularly to

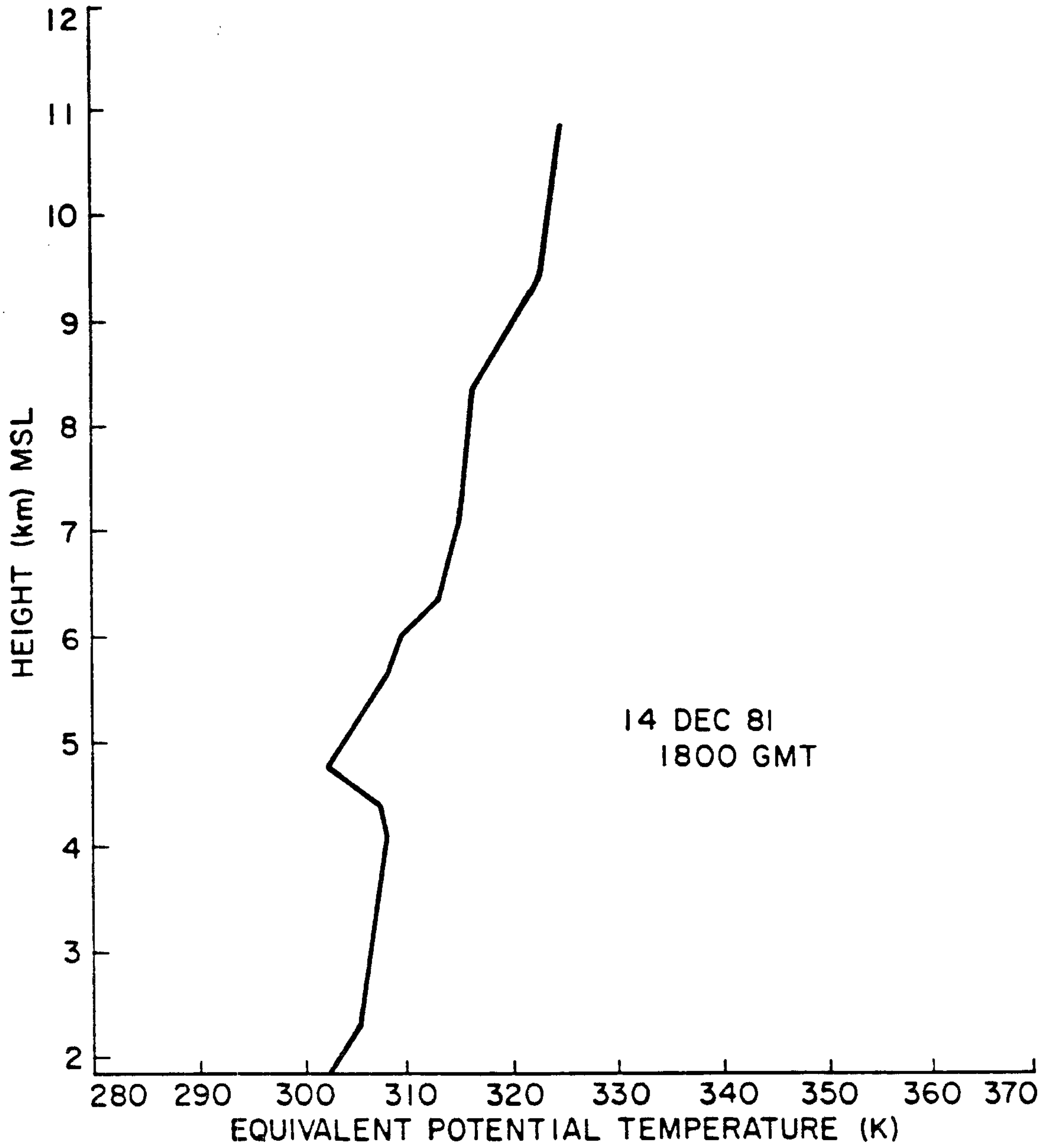


Fig. 22. Vertical profile of Equivalent Potential Temperature at 1800 GMT on 14 December 1981.

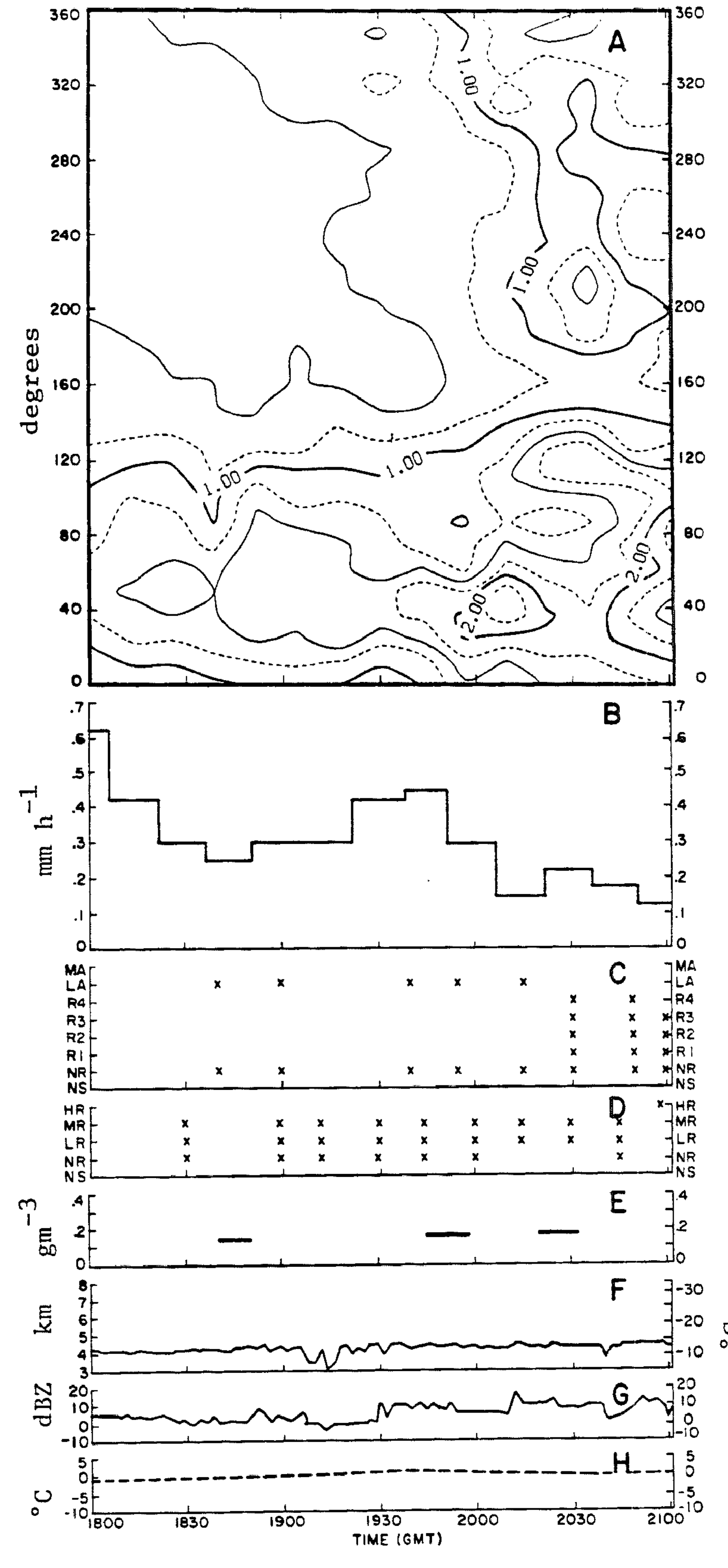


Fig. 23. 14 December 1981 (1800-2100 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (E) Rotorod liquid water content at SPL (gm^{-3}); (F) Radar determined cloud top height (km) and cloud top temperature (^oC); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (^oC).

the southeast. Precipitation, primarily aggregates, fell at moderate intensity at RAD. During this time, single crystals collected at RAD had no observable rime accumulation, but some of the crystals clustered in aggregates were lightly rimed. At SPL, the mountain crest was enveloped in cloud with liquid water contents ranging from 0.16 to 0.24 gm^{-3}. Aggregated snowfall was also predominant at this location, but approximately half of both the single and aggregated crystals observed at this site were lightly to moderately rimed.

A change in the character of the precipitation at RAD occurred at 2030 GMT. Just before this time, liquid water contents increased significantly upstream of RAD. This increase in liquid water was accompanied by a decrease in snowfall intensity. By 2030 GMT, the predominant precipitation growth mechanism for crystals arriving at RAD had changed from aggregation to accretion, although many of the crystals were only lightly rimed. Liquid water contents also increased in the vicinity of the barrier during this period. Crystals continued to be lightly to moderately rimed and mostly aggregated at SPL until 2100 GMT. AT 2100 GMT, as liquid water contents continued to increase, a reduction in aggregation occurred and all crystals became heavily rimed. No significant change in the character of cloud top occurred during this period. The observed increase in mid-level wind speed during this time may have accounted for the increased liquid water content throughout the cloud. By changing the total growth time available for cloud particles, the increase in wind speed may also have at least partially affected the microphysical growth mechanisms in the cloud; this may partially account for the observed changes in the intensity and character of the precipitation.

2. Case study: 16 December 1981

Synoptic scale and local weather conditions

Major synoptic scale weather features at the surface and at 70 kPa for 16 and 17 December 1981 are shown in Fig. 24. The radiometer operated in the scan mode from 1200 to 1500 GMT during this storm. At 0600 GMT on 16 December 1981, a strong low pressure system was centered over the plains of northeast Colorado. Extending north and west from this system, a wide area of cloud cover associated with a large occlusion produced widespread precipitation through Wyoming and Montana. As this low pressure system moved southeast during the day, the southern boundary of the moisture associated with the occlusion progressed southward into the Park Range area. Prior to this moisture intrusion, strong mid-level northwesterly winds produced a small orographic cloud system over the Park Range. At 1300 GMT, the southern end of the moist occluded airmass entered the area. Until 1400 GMT, precipitation from the system fell only on the mountain. From 1400 through 0000 GMT on 17 December, light to moderate snowfall occurred throughout the Park Range region. The orographic storm system prior to 1400 GMT was forced largely by the strong pressure gradient present across the mountains. After 1400 GMT, precipitation processes were significantly enhanced by the advection of deeper clouds and moisture associated with the occluded region into the area. During the study period, winds progressively weakened.

Storm evolution and supercooled liquid water distribution

Before the onset of the deeper clouds associated with the occlusion, the cloud system present over the Park Range region was orographic in nature. Cloud tops during this period were approximately

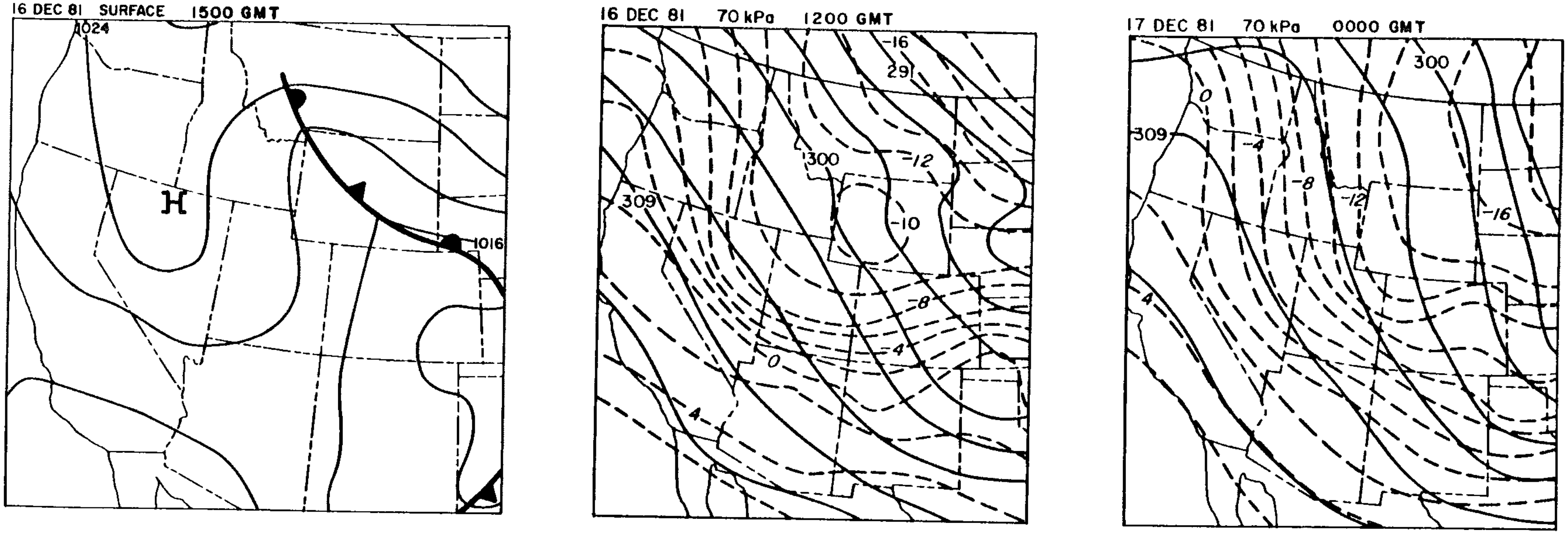


Fig. 24. Synoptic scale weather features for the 16 December 1981 storm system.

3800 m (-14^{o}C), and precipitation fell only at higher elevations. After the occluded airmass entered the area, cloud tops increased to 5400 m (-23^{o}C). Within the hour, light precipitation began to fall throughout the valley.

Unfortunately, local soundings were not available during the observation period to assess the potential for instability in these clouds. Qualitative evidence from the vertically pointing radar indicated that at least the early portion of this storm was stably stratified.

The time evolution of the supercooled water distribution is shown in Fig. 25. Except for one observation near the end of the storm period at SPL, no microphysical observations were available at the SPL or RAD sites. Radar characteristics and RAD surface temperature are included in the figure. During the orographic portion of the storm, liquid water was distributed throughout the cloud, but strongly concentrated over the slopes of the barrier. As the cloud from the occluded region advected into the area, liquid water concentrations throughout the cloud system dropped substantially. This was first evident upstream of RAD and later over the mountain. The reduction in liquid water content throughout the cloud system was most likely associated with more efficient ice crystal production in the cloud system due to nucleation at colder cloud temperatures and subsequent removal of the crystals by diffusional growth and accretion processes. Unfortunately, observations of crystal rime characteristics were not available for this storm.

3. <u>Case study: 13 January 1982</u>

<u>Synoptic scale and local weather conditions</u>

Large scale weather features over the western United States at the

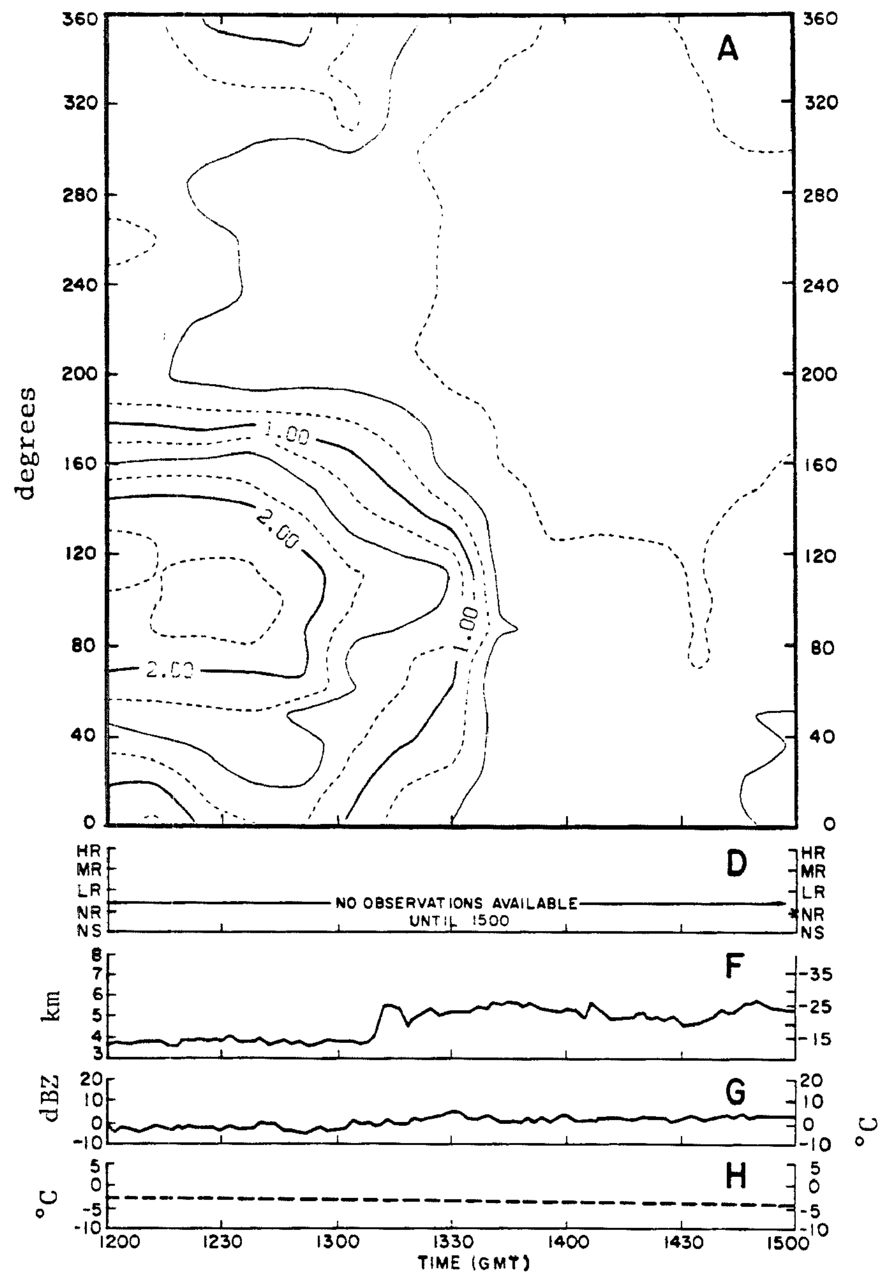


Fig. 25. 16 December 1981 (1200-1500 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer (D) Rime Characteristics of crystals collected at SPL (see Sec.2D); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C)

surface and at 70 kPa for the period 1200 GMT, 13 January 1982 to 0000 GMT, 14 January 1982 are shown on Fig. 26. The radiometer operated in the scan mode from 2000 to 2300 GMT. On 13 January at 1200 GMT, a rapidly moving trough system had passed through Colorado and had propagated eastward into Texas. To the west of the trough, a strong high pressure system and associated upper level ridge continued to build over the western United States. Along the east side of this ridge system, west of the Continental Divide, a shallow mid-level layer of moisture produced shallow orographic cloud systems over the mountains of Utah and northern Colorado. During the period from 1200 to 0000 GMT, the ridge system continued to build eastward with warm advection occurring throughout the depth of the troposphere. Moist air continued to advect into the Park Range region from the northwest during this period. During the entire period, a widespread shallow cloud system was present over the western mountains. Radar cloud tops seldom exceeded 1 km above ridgetop level, although light to moderate snow fell continuously at both mountain and valley sites throughout the day.

b. Storm Evolution and Supercooled Liquid Water Distribution

The mechanism of formation of the 13 January 1982 cloud system was typical of many purely orographic cloud systems occurring over the northern Colorado Rockies. This type of cloud system often occurs when a strong high pressure system develops over the Great Basin, a trough of low pressure is present over the western Great Plains, and the lower atmosphere north and west of the Colorado Rockies is near saturation. The combination of the strong cross-barrier pressure gradient and sufficient low level moisture lead to a quasi-steady state cloud system that exists for many hours. Despite the generally low precipitation

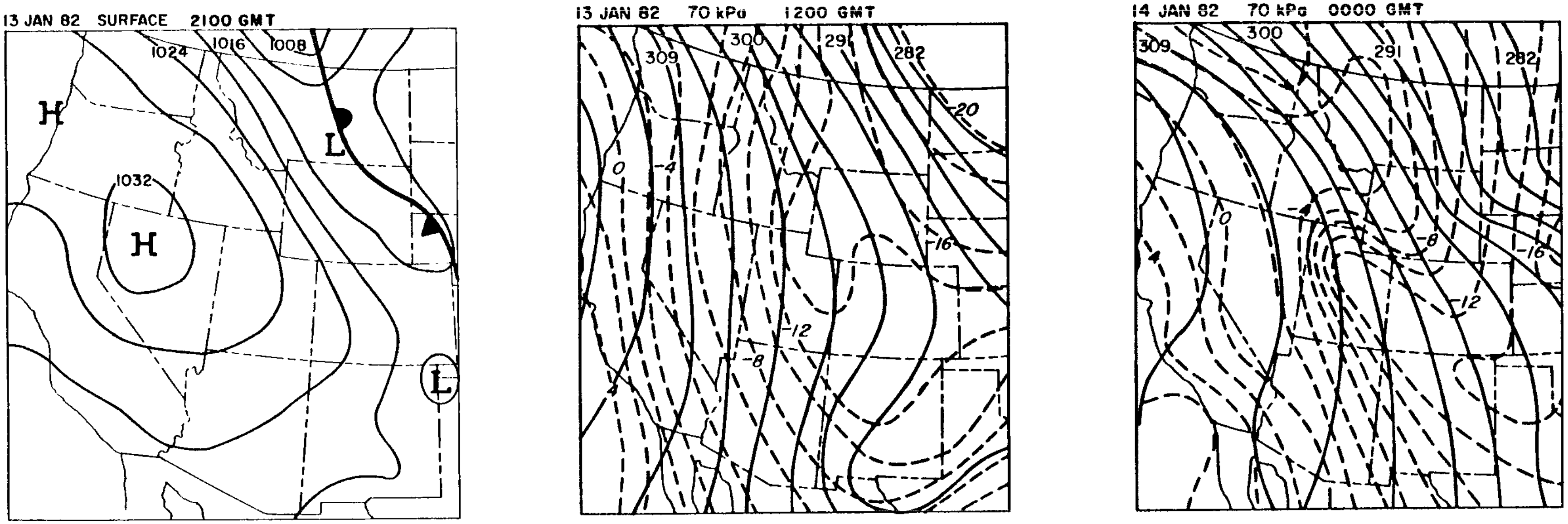


Fig. 26. Synoptic scale weather features for the 13 January 1982 storm system.

rates associated with this type of cloud system, the system often produces a substantial amount of precipitation because of its duration.

The cloud system present over the Park Range region on 13 January was extremely shallow, but produced precipitation at rates varying from 0.1 to 0.8 mm/hr. Cloud tops never exceeded 4000 m (-20^{o}C). Fig. 27 shows the equivalent potential temperature profile for a sounding taken at CG at 2100 GMT. Except for a shallow, potentially unstable layer at the surface, the entire atmosphere was stably stratified. The cloud system during the study period extended at least 60 km west of the crest of the Park Range, and produced light precipitation as far west as CG, the rawinsonde site.

The time evolution of the supercooled liquid water distribution is shown in Fig. 28. Associated parameters from the RAD site are also shown. SPL operated on a limited basis during this storm. Only one observation of crystal rime characteristics was available during the scan period. Despite the steady-state nature of the mesoscale cloud characteristics during this storm system, the microphysical characteristics of the cloud system varied considerably with time. Precipitation rates during the storm varied slowly. Corresponding variations were observed in the liquid water distribution; more liquid water appeared in the cloud as the efficiency of the precipitation process decreased. The predominant characteristic of the precipitation observed at RAD was light aggregation. At the beginning of the period for which scanning radiometer data are displayed in Fig. 28, precipitation rates at RAD were moderate (0.7 mm/hr), and very little liquid water was present anywhere in the system. The rate of ice crystal growth during this period was in near equilibrium with the rate

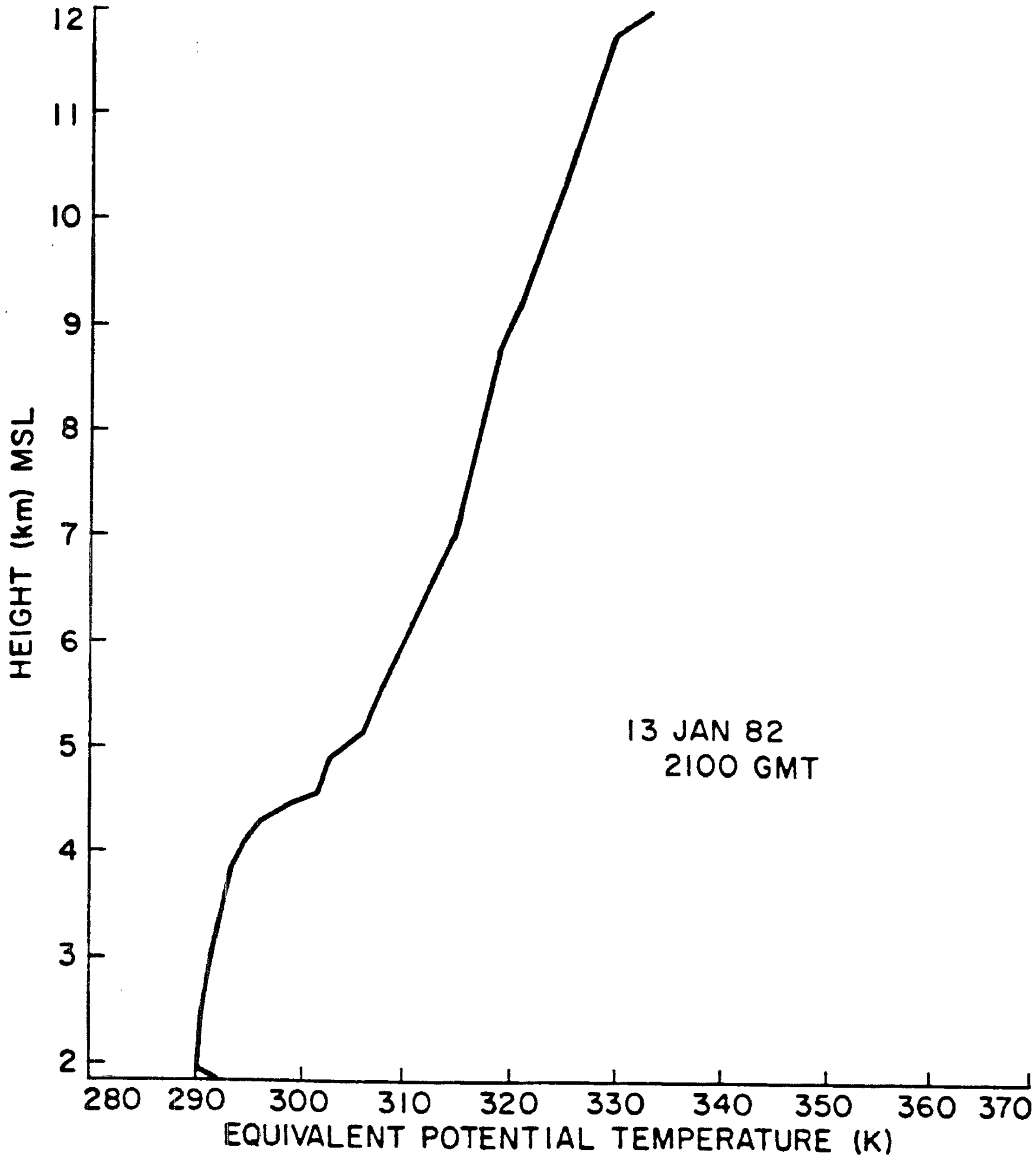


Fig. 27. Vertical profile of Equivalent Potential Temperature at 2100 GMT on 13 January 1982.

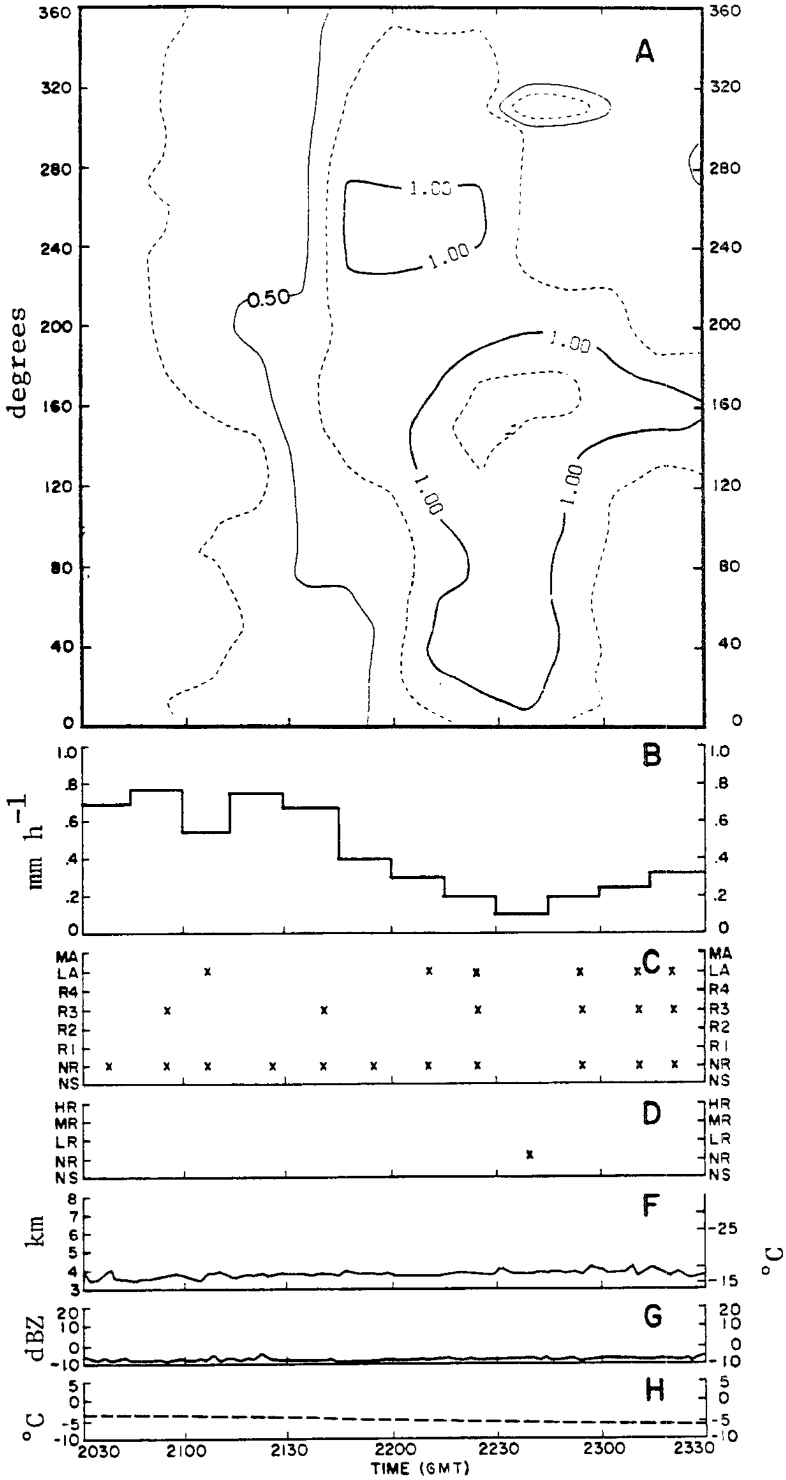


Fig. 28. 13 January 1982 (2030-2330 GMT): (A) Radiometric integrated liquid water content (mm) as a function of azimuth angle from the radiometer; (B) Precipitation intensity at RAD (mm/hr); (C) Rime characteristics of crystals collected at RAD (see Sec. 2C); (D) Rime Characteristics of crystals collected at SPL (see Sec. 2D); (F) Radar determined cloud top height (km) and cloud top temperature (°C); (G) Radar observed maximum reflectivity (dBZ); (H) Surface temperature at RAD (°C)

of condensate production in the cloud due to forced orographic lifting. Nearly all the precipitation was unrimed, although a few R_{3c} crystals were occasionally observed. Extremely light rime was also occasionally observed on crystals collected in aggregates. As precipitation rates decreased, a substantial increase in the cloud liquid water content throughout the cloud system occurred. Slightly greater water contents were observed in the vicinity of the barrier. From 2213 GMT onward, the frequency of rime on the aggregates increased considerably. Both R_{3b} and R_{3c} crystals were also observed at the RAD site after this time. The maximum liquid water contents occurred at 2235 GMT, the time of the lowest precipitation rates. From this time onward, precipitation rates started to increase and liquid water contents throughout the cloud system began to decrease slowly.

The single observation at SPL at 2240 GMT occurred at the time of the maximum liquid water contents. The observation was taken at a temperature of $-10^{o}C$. Precipitation at this location was moderate to heavy and consisted of aggregates of unrimed planar crystals. This limited observation suggests that the bulk of the liquid water detected by the radiometer was located in the low levels of the cloud system between cloud base and ridgetop.

The inverse relationship between liquid water content and snowfall rate indicates that variations in the cloud ice crystal concentrations in this type of cloud system strongly modify the liquid water production, primarily through the enhancement of the diffusional growth process. Once crystal concentrations were reduced (i.e. precipitation rates were reduced), the accretion process became an important mechanism for the removal of cloud water. The source of variations in crystal concentrations in this system is uncertain but may be related to variations in the moisture supply, ice nucleation activity, or to some ice multiplication mechanism.

4. DISCUSSION

A. Pre-frontal and Frontal Cloud Systems

Pre-frontal cloud systems in the northern Colorado Rockies are generally characterized by wide area stratiform cloud regions formed primarily by lifting associated with the Rocky Mountain massif. Bands of deeper clouds and heavier precipitation are frequently superimposed on this stratiform cloud system. Most of these bands are observed to be convective, but some occur in a stably stratified or neutral atmosphere.

The mesoscale characteristics of the stratiform component of the pre-frontal cloud system are strongly controlled by the depth of the moisture in the pre-frontal environment and the strength of the component of the wind normal to the barrier. In the northern Colorado Rocky Mountain region, these parameters are closely associated. Because the mountains in this region are oriented north-south, winds with a strong southerly component undergo weak orographic forcing. In addition, the source of air is much more continental, generally originating over the southwest desert regions and often crossing several mountain ranges before arriving in the area. Pre-frontal mid-level winds with a strong westerly component undergo stronger orographic forcing and generally have higher moisture content. The predominant direction of the flow is closely associated with the orientation of the approaching front. The southwesterly flow situation applies to the case of 22 January 1982. The 15 December 1981 case is an example of more predominant westerly flow. The pre-frontal environment of the 30

December 1981 case was more similar to 22 January, but not as extreme. The stratiform clouds in the pre-frontal environment for the three cases discussed had tops around 4000-5000 m and weak reflectivities. With the exception of the 22 January, which had a strong southerly mid-level wind component prior to the passage of the convective band, precipitation rates were low in the valley and moderate at high elevations. On 22 January, the cloud was non-precipitating prior to band passage.

The convective regions of the pre-frontal environment are often organized into a banded structure. The duration of these convective bands is generally about an hour. Two or three of these bands are frequently observed prior to frontal passage. In one case, 30 December, the convective activity was less organized. The convective components of the pre-frontal cloud systems have higher precipitation rates at all elevations and stronger radar reflectivities.

The distribution of supercooled water in the stratiform regions of cloud systems in the pre-frontal environment is closely related to the strength of the orographic component of the airflow. In the case of 22 January, where this component was extremely weak, the shallow stratiform cloud system contained virtually no supercooled water. In the more developed cases of 15 December and 30 December, supercooled water was present throughout the cloud system. Highest values were located over the windward slopes of the range in the zone of strong orographically forced vertical motions.

The concentration of liquid water in convective regions in the pre-frontal environment was observed to be much lower than in the stratiform cloud regions. Maximum liquid water contents in the bands were observed during the initial stages of development, but the concentration of liquid water was rapidly depleted by extremely efficient precipitation growth processes. In general, within 15-20 minutes after the onset of these bands, liquid water concentrations reached a minimum. Evidence from rime observations at SPL and RAD indicated that any supercooled water present in these cloud systems after the initial period was confined to the lower cloud levels.

The microphysical characteristics of precipitation observed at SPL and RAD during stratiform and convective storm periods provided important information concerning the evolution of the precipitation process during these events. During stratiform periods, cloud particles arriving at RAD were generally single crystals and often lightly rimed. At SPL, the concentration of rime on the particles was considerably greater. Precipitation rates were generally low at RAD and moderate at SPL. With the onset of convective activity, the amount of rime observed on crystals sometimes increased initially, but rapidly reduced in intensity and often was completely eliminated. Precipitation observed during convective periods was heavy at both sites and consisted of mostly unrimed, highly aggregated particles.

These observations imply that mid-level stratiform cloud systems have ice crystal concentrations that are low enough that the condensate supply rate in the cloud frequently exceeds the bulk diffusional growth rate of the ice phase, particularly in the vicinity of the barrier. In general, the production and growth of water droplets in this environment is sufficient that accretion processes become important. In the case of mountaintop precipitation, accretion often becomes the dominant growth process. Significant amounts of liquid water are frequently present at the barrier crest.

With the onset of convective bands, liquid water production is initially enhanced, particularly in the vicinity of the barrier, but rapid production of ice crystals in the cloud system leads to effective removal of the water initially by accretion and later by diffusional growth processes. Indications that cloud ice crystal concentrations are generally large are the high precipitation rates associated with these bands and the tendency for aggregation of the falling crystals. After band passage, the liquid water distribution was generally observed to return to a configuration similar to that in the stratiform cloud system prior to band passage.

B. Post-Frontal Cloud Systems

Post-frontal cloud systems are also characterized by wide area stratiform cloud regions. These stratiform systems generally have a much stronger orographic wind component because of considerably greater mid-level wind speeds normal to the barrier. Two regions of convective instability were observed in these systems, the first occurring just after frontal passage and the second during trough passage as the storm is decaying. The first region of convection was observed to be organized into banded structure. This situation was discussed in the 30 December 1981 case. The discussions in Sec. 4a all apply to this type of band. The second convective period occurred late in the storm. Convective cells during this period were disorganized, shallow, and occurred primarily over higher topography.

In general, the stratiform component of the post-frontal cloud system produced significant amounts of precipitation at high elevations. Three factors contributed to this large amount of precipitation: (1) winds in the post-frontal airmass had a strong orographic component forcing additional condensate production in the vicinity of the mountain; (2) the post-frontal airmass typically has its origins over the northeast Pacific Ocean and often contains considerable middle and low level moisture;(3) Probably most important, these cloud systems often exist for long durations. The horizontal extent of the cloud varies with the moisture supply, generally decreasing with time, but a cap cloud extending 15-20 km upstream can often survive for 24-36 hr. This cloud makes little contribution to the total snowfall at low elevations, but contributes substantially to the total winter snowpack at higher elevations.

The distribution of the supercooled liquid water in the stratiform regions of the post-frontal cloud system is generally well defined and strongly associated with the orographic component of the vertical air motion. High liquid water concentrations were found to develop about 10-15 km upwind of the barrier crest and reach a maximum over the windward slopes. This is expected since condensate supply rates are generally highest in this region. The presence of this zone of high liquid water content was most evident on 27 January 1982, but also evident on the other post-frontal cases. In these cases, lesser amounts of liquid water were also present upstream.

The initial convective bands associated with frontal passage generally move through the region within an hour or two. These bands produce moderate to heavy precipitation at both valley and mountain sites. Radar evidence from the 30 December case described in Sec. 3a indicates that these bands may be less organized, possessing more cellular structure. Precipitation intensity and cloud depth during these periods are similar to the pre-frontal bands described in Section

3a. The late post-frontal period is characterized by weak cells extending to about 6000 m. These cells usually occur in the latest part of the storm. Because of their limited duration and spatial extent, they probably make a minor contribution to the total snowpack.

The concentration of the cloud water in the convective bands in the post-frontal regions is complicated somewhat by the interaction of the convective and orographic components of the airflow. The convective activity generally produced deep clouds capable of producing effective numbers of ice crystals to accrete any water droplets produced in the convective vertical motions. However, steady orographic production of additional cloud water in the low levels of the cloud may have occurred on some occasions. This may be the explanation for the observed rime collected on aggregates observed at RAD on 30 December 1981. In general, however, total cloud water concentrations decreased substantially during periods of organized convection.

The distribution of supercooled water in the late post-frontal convective cells is difficult to ascertain because these cells generally develop over the ridges in regions of strong orographic lift. With radiometric data, it is difficult to separate the contribution of the convective and the orographic components of the motion. In general, the steady nature of the cloud liquid water field in the vicinity of the barrier during these periods indicates that the predominant mechanism producing the liquid water in these clouds is vertical motion due to orographic lifting.

The microphysical characteristics of the precipitation observed at SPL and RAD were consistent with the liquid water measurements. During stratiform events, generally light rime, no rime or no precipitation was observed at RAD, while nearly all precipitation observed at SPL was moderately to heavily rimed. During organized convective activity, aggregation became the dominant growth mode. Some rime was observed at RAD during band passage.

C. Orographic Systems

Orographic systems, as discussed in this paper, are cloud systems that occur over mountainous regions during periods when no major synoptic scale disturbance is directly influencing the region. These cloud systems typically form when a strong cross-barrier pressure gradient is present and sufficiently moist air is simultaneously advected into the region from the west. The clouds are generally shallow, stable, and persist for many hours. Despite their shallow nature, they can produce significant amounts of precipitation at both low and high elevations because of continuous production of cloud condensate for a long period of time.

The distribution of liquid water in these cloud systems was found to vary considerably from storm to storm. The highest liquid water contents were generally found over the slopes of the barrier. However, liquid water was observed to increase uniformly throughout the cloud system on 13 January 1982 and 14 December 1981 without any significant changes in the mesoscale characteristics of the storm systems, except for a reduction in precipitation rate.

These observations indicate that variations in ice crystal concentrations in these clouds strongly affect the liquid water production in the clouds. The causes of these variations are poorly understood. Recent evidence presented by Demott et al. (1982) indicates that enhanced nucleation of ice particles occurs in localized zones of high supersaturations associated with vertical motions generated by variations in topography upwind of the primary barrier, but this does not account for the temporal variations. Ice multiplication by means of the mechanism described by Hallet and Mossop (1974) is not likely because virtually all precipitation particles are dendritic and form at temperatures well below those specified by their and other experiments. Fracturing of dendritic crystals (Vardiman, 1978) may occur, but again, this does not account for the temporal variations observed. Research is being conducted to address this question.

5. Comparison with other results

These results have important implications concerning weather modification in the northern Colorado Rockies. On the basis of their aircraft observations over the San Juan mountains of southwest Colorado, Cooper and Marwitz (1980) concluded that the best opportunity for successful weather modification in that area should be associated with convective clouds because of their observed high liquid contents. Their observations of convective clouds showed that liquid water was often significant in convective regions. Recently, Heggli et al. (1983), from aircraft observations of clouds over the California Sierras, have also concluded from climatological treatment of aircraft data that a weather modification program to enhance snowfall should concentrate primarily on convective clouds. Both of these groups of investigators reported little liquid water present in the shallow, stable cloud systems.

Data presented here show that, although liquid water may attain a high value in developing convection, precipitation processes that remove liquid water are extremely effective in these convective elements.

Large concentrations of ice crystals, as evidenced by high precipitation rates, are rapidly produced. These crystals efficiently remove the liquid condensate from the convective clouds. In all cases studied, cloud water reduced rapidly throughout the cloud system a short time after the onset of the band. Most of the time when convective systems effected the area, liquid water contents were minimal, crystals were unrimed, and precipitation rates were high. Based on these observations, it appears that the convective bands provide only a limited time period when supercooled water is present. Because of their high efficiency in producing precipitation naturally, they provide only a limited opportunity for snowfall augmentation.

It is likely that the differences between our findings and those of Cooper and Marwitz (1980) and Heggli et al. (1983) are related to climatological differences among the study areas, but even more so to the observational method. Aircraft data collection in convective regions is, by nature, selective. By sampling individual convective cells in their development stages when liquid water is present, it could be concluded that these clouds have high weather modification potential. This conclusion could be justified only by following that individual cell or groups of cells through their life cycle to observe if the cloud produces precipitation size ice particles naturally or if the liquid water drops evaporate before converting to the ice phase. Radiometric data and supporting measurements in the Park Range area have indicated that although these clouds may initially contain high liquid water contents, this liquid water is efficiently converted to the ice phase in a very short time period.

Both Cooper and Marwitz (1980) and Heggli et al.(1983) present climatological summaries of the average liquid water content present in the cloud system during unstable storm periods. This climatological treatment of the distribution of liquid water based on aircraft observations of discreet cells does not take into account the temporal variability of the individual cells within the storm. The implication from these climatological distributions is that liquid water is present in large quantities over broad regions during unstable storm events. In fact, the data which were averaged were collected at a specific time during the lifetime of individual cells. Radiometric observations and surface measurements indicate that the precipitation processes in these cloud systems are very effective naturally when observed over the lifetime of the storm event.

Aircraft observations such as those of Cooper and Saunders (1980) and Heggli et al. (1983) have generally not been able to document significant amounts of liquid water in stable cloud systems. Such aircraft observations, however, have been constrained by the necessity to maintain a substantial minimum flight altitude that is at least 1 km above the highest point on the mountain barrier in the vicinity of the study area and often as much as 2 km above cloud base. Rauber and Snider (1985) have shown in Part I that more tham 75% of the total condensate available to this type of cloud system is located below the altitudes which can safely be observed by aircraft.

This large portion of the condensate is located in the warmest portion of the cloud system and has the greatest likelihood of occurring in the liquid phase. This portion of the cloud is observed by the radiometer. Such radiometric measurements and supporting data show that shallow, stable cloud systems with warm cloud tops (> $-20^{\circ}C$) over

Colorado's Park Range frequently have significant amounts of liquid water both upwind and over the range, particularly in the vicinity of strong orographic lift. Due to their long duration and the rapid replacement of condensate, these clouds have the potential for production of highly significant amounts of mountain snowfall. The presence of supercooled water in most of these cloud systems meets at least one criterion for weather modification potential.

6. SUMMARY

This paper has examined the temporal and spatial evolution of the supercooled cloud water field during nine wintertime storm systems occurring over the northern Colorado Rockies. These storms occurred in pre-frontal, post-frontal and orographic environments and included cloud systems with convective bands, cellular convection, stable wide area clouds and clouds formed primarily by orographic lifting. The following are the main conclusions based on these case studies:

1) During individual storm events, the amount of liquid water present in the cloud system was inversely related to storm intensity. Liquid water contents in storms decreased whenever cloud top temperatures decreased, precipitation rates increased and radar reflectivity increased. It is important to emphasize that this relationship applied to individual storms. The relationship between one parameter, such as precipitation rate, and liquid water content is modified throughout the winter season by variations in the condensate supply rate, cloud vertical temperature structure, ice nuclei and cloud condensation nuclei concentrations, low level blocking, horizontal wind speed and wind direction.

2) Liquid water presence in convective bands was generally limited to

a short period during the developing stages of the band. In nearly all cases of band passage, cloud water present initially in the system was quickly depleted by rapid growth of crystals by diffusion and accretion. During the majority of the time that the convective band affected the region, the entire cloud system had minimal liquid water contents.

3) The distribution of supercooled water in the stratiform regions of the cloud system was closely related to the strength of the orographic component of the airflow. In the prefrontal environment, the cross-barrier component of the wind was found to vary significantly depending on the orientation of the approaching frontal system. Liquid water concentrations were highest in the stratiform pre-frontal cloud when this component was large. In the post-frontal environment, this component was generally large and liquid water was commonly observed.

4) In virtually all stratiform cloud systems, the majority of the liquid water is concentrated over the windward slopes of the mountain range. Substantial riming was consistently observed at the mountaintop laboratory when these cloud systems were present. In most of these cloud systems, quantities of cloud water upsteam of the range were sufficient to at least cause minimal riming on crystals falling in the valley. In some cases, values of liquid water upstream were much higher and riming was extensive.

5) The temporal variation of the supercooled liquid water distribution is significant, even in cloud systems which appear to be quasi-steady on the mesoscale.

6) The conversion from shallow systems with high liquid water contents and low precipitation rates to deep systems with low liquid water contents and high precipitation rates is accompanied by a systematic

evolution in the microphysical characteristics of the precipitation. Prior to the onset of the deep storm system, precipitating crystals are usually single, and are rimed. The degree of rime is a strong function of elevation, since crystals falling near the top of the mountain have to pass through the zone of high water content over the windward slopes. During the initial stages after the onset of the deep system, the intensity of the accretion increases as large numbers of crystals sweep out the cloud droplets remaining in the system. Within thirty minutes, all of these particles have precipitated or were carried over the barrier. From this point onward until the system returns to a more shallow structure, the precipitation is predominantly composed of aggregates of unrimed crystals.

This paper has shown that the scanning microwave radiometer can be used as a powerful tool to reexamine the cloud physical properties and weather modification potential of wintertime cloud systems in the semi-arid western United States. With continued expansion and development of water needs in this region, it is essential that this and other newly developed sensors be used to reassess the role of weather modification in the development of future water resources.

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