Measurements of Liquid Water Content in Winter Cloud Systems over the Sierra Nevada

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ABSTRACT

Investigations of the structure and organization of synoptic-scale storms over the Sierra Nevada Mountain Range during two successive winters (1971–73) were made with a modified B-26 aircraft. Measurements of liquid water content, temperature and dew point were made along horizontal traverses in a vertical plane oriented roughly perpendicular to the main crest and extending from Lake Tahoe to Sacramento, Calif. It is shown that the spatial distribution of liquid water is linked to the gross terrain features, as is the surface distribution of precipitation. The main centers of cloud liquid water content tend to form 40–75 km upwind of the main crest in highly convective cells.

1. Introduction

The effects that mountain ranges have on synoptic-scale storms are diverse and complicated. The significance of the influence is seen in the relatively large amounts of precipitation that fall at the higher terrain elevations of isolated peaks and on the windward sides of extensive ridges. Very often the distribution of surface precipitation is as complicated as the terrain itself. Surveys of precipitation patterns in the Sierra Nevada Mountains of California and Nevada are given by Lee (1911) and in two U. S. Weather Bureau Reports (1961, 1962).

Important to any investigation of the physical mechanisms resulting in the association of atmospheric processes with terrain is a mapping of the spatial distribution of cloud liquid water content. Such a representation is also valuable in gaining an overview of the structure and organization of synoptic storms modified naturally by major mountain ranges. From a more practical point of view, any attempt to modify the cloud systems artificially in order to alter the spatial distribution of fallout to the sheltered lee slopes would require knowledge of the distribution of liquid water aloft. For these reasons cloud liquid water was chosen as the primary variable to be measured in the aircraft studies conducted during the winter seasons of 1971–72 and 1972–73 over the Sierra Nevada of California. The observations are presented here.

2. Data acquisition and reduction

The data used in this study were for the most part acquired with the instrumented B-26 aircraft of the Desert Research Institute. The primary variables measured were liquid water content (Johnson-Williams), temperature (Rosemount), dew point (Cambridge) and the common aircraft parameters. Position of the aircraft was measured relative to Squaw Peak, Calif., site of the Lake Tahoe radio-navigation beacon (LTA), by resolution of standard VOR and DME signals.

During the first year of operations, data were recorded in analog form on strip charts and reduced by hand. During the second season the analog outputs of all variables were multiplexed, digitized and recorded onto magnetic tape aboard the aircraft. Post-analysis procedures included the reduction of the stored data by digital computer, from which tabulations of all variables as functions of time and plots of selected variables as functions of the spatial position of the aircraft were obtained[1].

The flight pattern used during the investigation of the winter storms was so designed that a vertical cross section of the pertinent meteorological variables would be obtained. Thus, the aircraft flew between Lake Tahoe and Sacramento along horizontal traverses in a vertical plane oriented perpendicular to the main crest of the Sierra. Such an orientation, being also roughly parallel to the mean wind, allows the maximum effect of the mountain barrier on the meteorological variables to be assessed. Whenever possible each traverse was both begun and terminated in clear air to the east or west of the main cloud mass, thus affording good views of the system and an accurate estimate of its limits.

In addition to the information acquired onboard the aircraft, data were also obtained from the network of

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[1] Further details of the aircraft systems and the data reduction procedures are given in the Project Skywater Supplementary Final Report, Desert Research Institute (1 July 1972–30 September 1973).

precipitation gages in this region of the Sierra Nevada and from an X-band radar atop Squaw Peak (LTA; 2705 m MSL). The locations of these stations with respect to the mean flight track are shown in Fig. 1.

3. Results

Of the more than 30 synoptic-scale storms in which research flights were made over the two-year period, 1971–1973, six were selected for detailed study. The basis for this selection involved the following considerations: 1) a selected storm should have yielded at least moderate amounts of precipitation, 2) a major portion of the storm should have passed through the mesoscale operations area and 3) most of the airborne instrumentation should have been operational during the storm penetrations. Despite the subjectiveness of these cri-

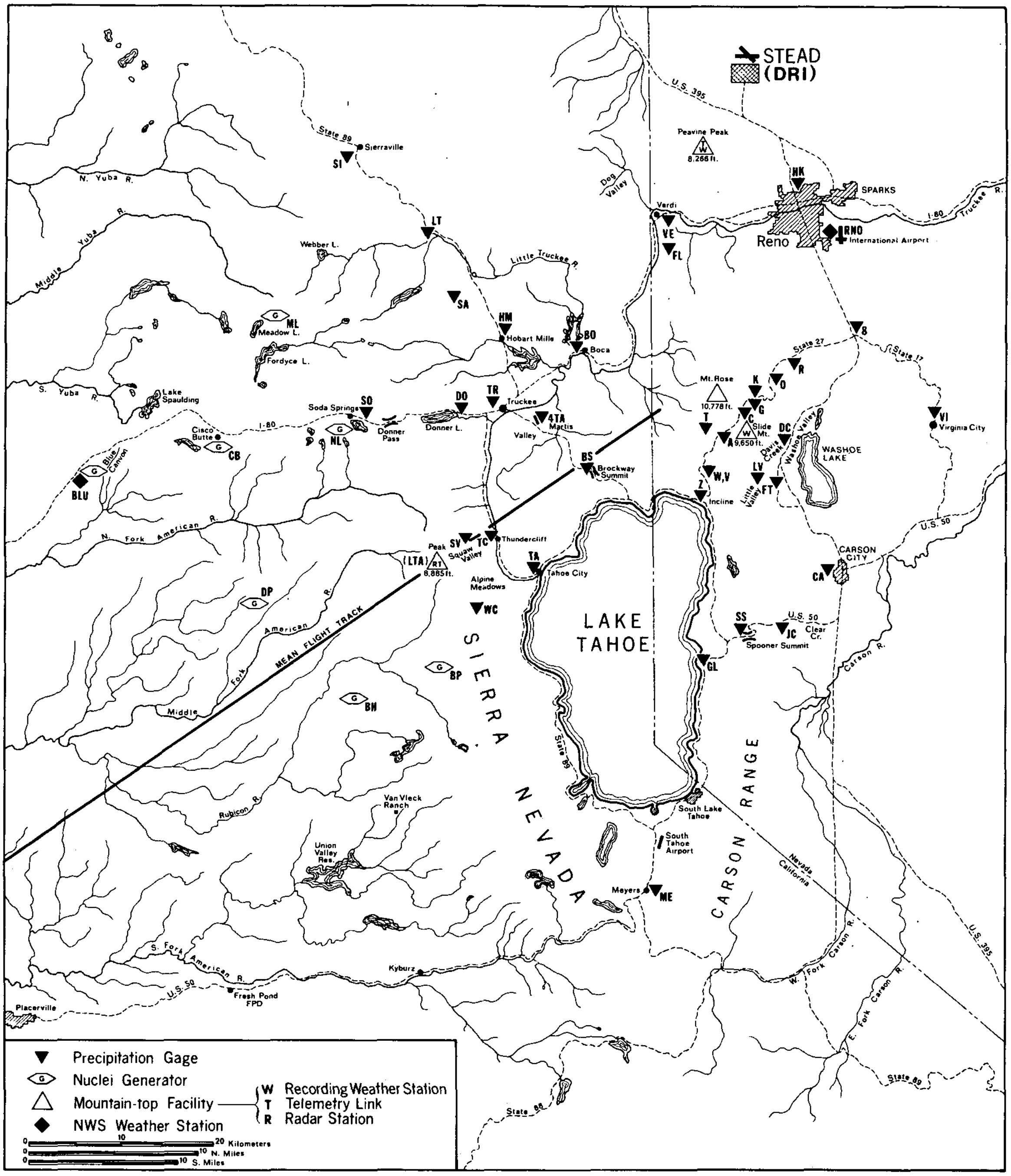

FIG. 1. Locations of precipitation gages and mountain stations in relation to the mean flight track.

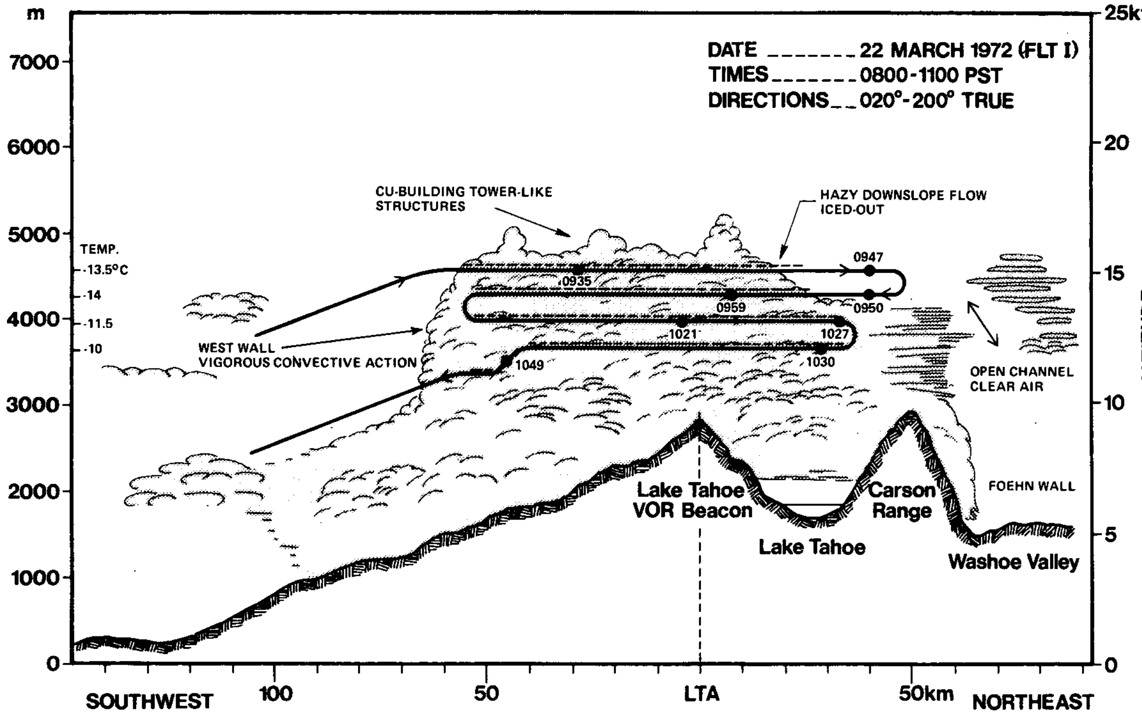

Fig. 2a. Flight profile and storm cross section obtained during Flight I of the storm of 22 March 1972.

teria, we feel that the storms selected are typical of winter synoptic storms in the central Sierra Nevada. The four most intense storms are presented here. Because even "typical" storms exhibit large variabilities in their internal structure and intensity, we have chosen to present the data on a case study basis. In the concluding section a few generalizations are made from the composite of our observations.

a. Storm of 22 March 1972

On this day a shallow and fast-moving surface front passed over the Sierra Nevada late in the morning,

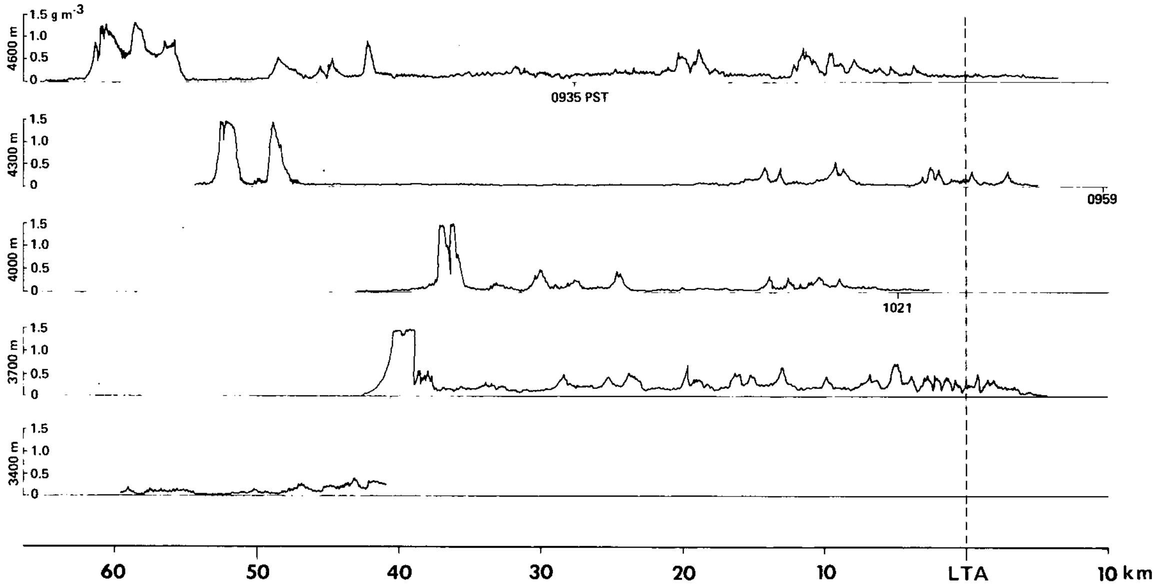

Fig. 2b. Measured cloud liquid water content from Flight I of the storm of 22 March 1972 as a function of aircraft position along the flight track relative to Squaw Peak (LTA) and of flight altitude.

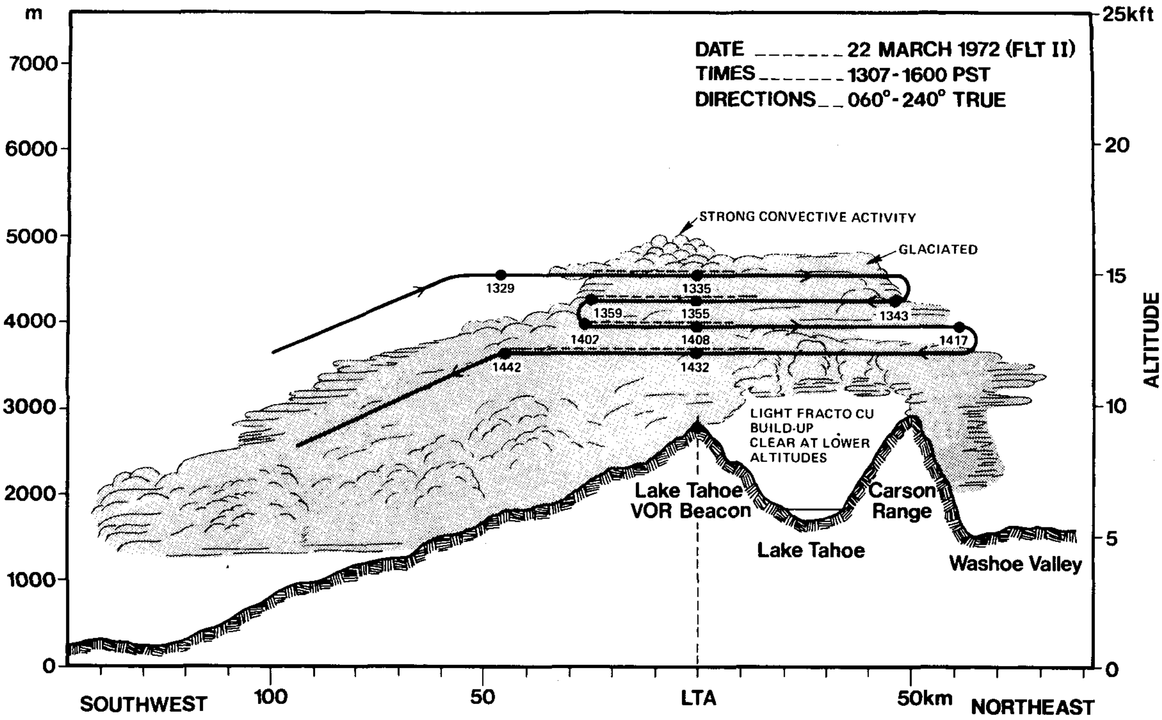

FIG. 3a. As in Fig. 2a except for Flight II of the storm of 22 March.

followed by a cold upper-level trough. It was primarily the effects of the short-wave trough that gave rise to the observed cloud and weather development.

A schematic representation of the storm cross section as it appeared during the first of the two research flights is shown in Fig. 2a. The cloud system was penetrated at four levels beginning at an altitude of 4600 m, near the top of the storm, after which the flight was forced to terminate due to the large accumulation of ice on the aircraft. Mean temperatures recorded along each traverse are indicated along the left-hand edge of Fig. 2a. A record of the measured liquid water content

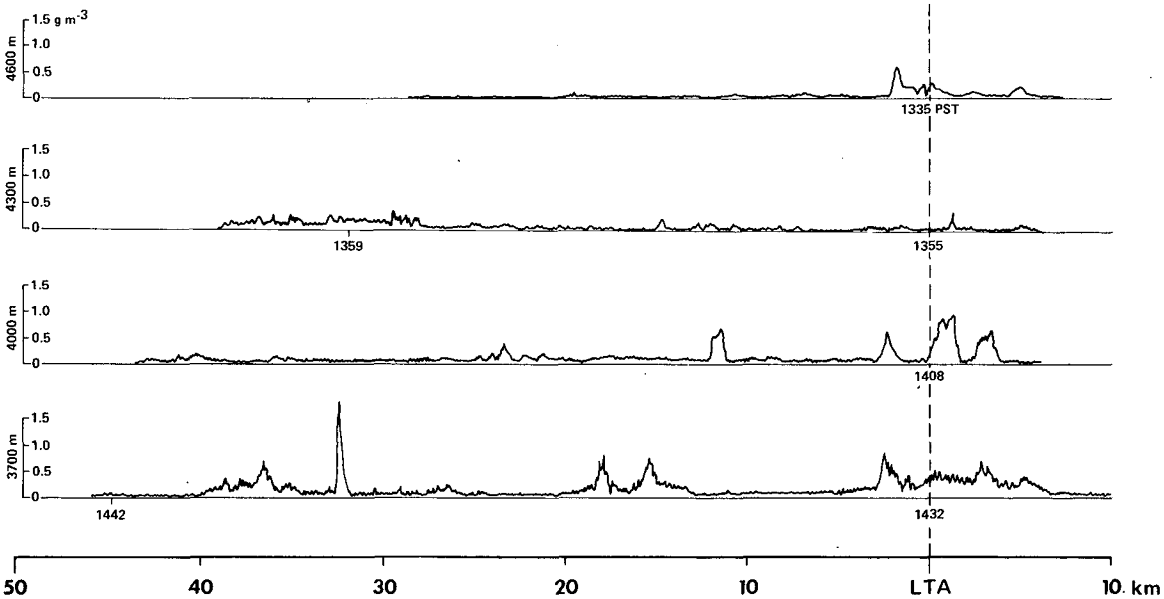

FIG. 3b. As in Fig. 2b except for Flight II of the storm of 22 March.

is presented in Fig. 2b for those portions of the flight indicated in Fig. 2a by a superimposed dashed line.

The storm system during this flight was characterized by embedded pockets of vigorous convective activity which were felt as strong turbulence aboard the aircraft. The inhomogeneity of the system is also evidenced in Fig. 2b. Large convective cells were particularly prevalent along the western boundary of the storm where the system was seen to have the highest liquid water contents and to be the most active, in contrast to the eastern parts which were highly glaciated and generally less turbulent.

Flight II originated early in the afternoon after aircraft servicing in Sacramento. The flight details and storm cross section are presented in Fig. 3a, the corresponding measurements of liquid water content in Fig. 3b. It can be seen that the western convective activity had by this time diminished considerably in intensity as the main storm center moved eastward. Most of the liquid water and turbulence were by now found over the Sierra crest, but had considerably lower values. Again, glaciated conditions predominated along the eastern edge over the Carson Range.

It is interesting to relate conditions found in the atmosphere with those on the surface during the storm period. An isohyetal analysis of the total storm precipitation over northern California is presented in Fig. 4. Effects of the mountainous terrain are immediately apparent, the storm totals being greatest over the Coast and the Sierra Ranges. A more detailed analysis of the distribution of surface precipitation in the flight operations area is shown in Fig. 5, corresponding to the region within the dashed rectangle of Fig. 4. The maximum in precipitation is found just west of the main Sierra crest in association with the airborne measurements of high liquid water content aloft. A secondary maximum is also seen over Mt. Rose and the Carson Range, while minima appear over Lake Tahoe and in the lee of the Carson Range.

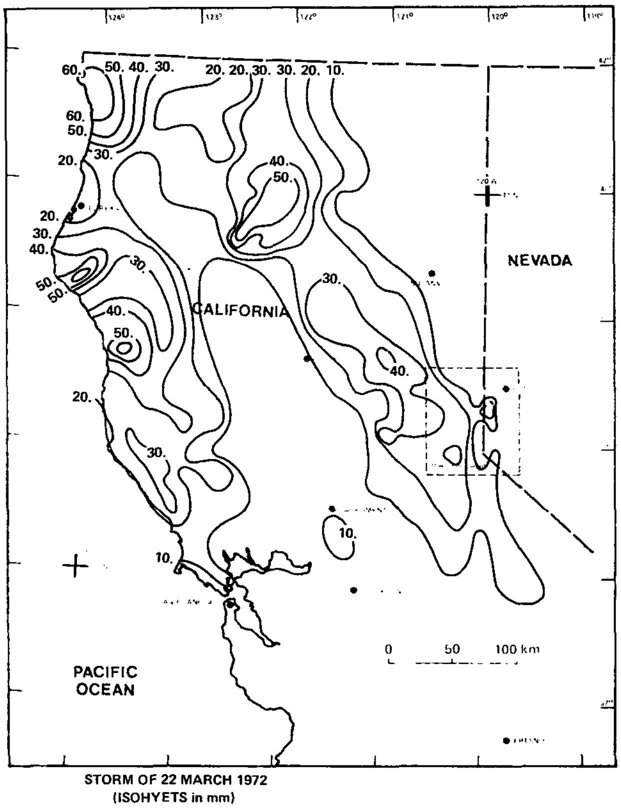

Fig. 4. Distribution of total precipitation over northern California from the storm of 22 March 1972. The region within the dashed rectangle is depicted in greater detail in Fig. 5.

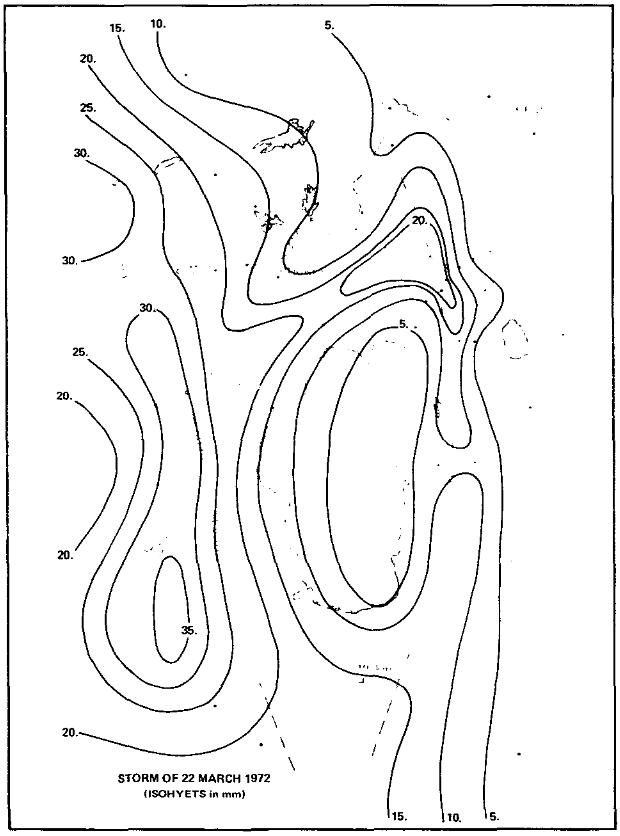

Fig. 5. Distribution of total precipitation within the mesoscale area indicated in Fig. 4 from the storm of 22 March 1972.

b. *Storm of 24 February 1973*

On the morning of 24 February an occluded surface front approached the central California coast just ahead of an upper-level trough. As the front encountered the Sierra Nevada toward midday, it began to lose its identity partly in response to the retrograde motion of the upper-level trough during the succeeding 24 h.

Although two flights were made this day, only the first involved storm traverses at more than one level under conditions sufficiently stormy to warrant discussion here. Details of this flight are shown in Fig. 6a and the corresponding measurements of liquid water content in Fig. 6b. As indicated, the highest clouds had tops between 5200 and 5600 m with temperatures just below −20°C. Although it was difficult to decide from visual observation whether these upper clouds were composed primarily of ice or of liquid water, liquid water contents ~ 0.1 g m^{-3} were recorded on occasion (upper trace of Fig. 6b). At the eastern end of the traverse at 4600 m a rotor cloud and a foehn wall over Washoe Valley were observed. From the indistinct appearance of the clouds along the descending edge of the foehn wall the eastern (leeward) edge of the mountain cloud system was judged to be glaciated. Away from the main mountains the clouds seldom extended above 2700 m during the early part of the flight.

This storm was characterized on the whole by moist, turbulent lower regions and generally drier and more stable upper layers. The middle regions were lacking in significant activity, particularly in the western half. This is evident from the distribution of liquid water content (Fig. 6b) and from the visual appearance of the clouds at the various stages of the flight.

c. *Storm of 27 February 1973*

A cold front which crossed California the previous day remained ill-defined and nearly stationary in Nevada early on 27 February. A trough at the 500 mb level deepened further as it moved toward the California coast. Associated with this short-wave trough was a vigorous cold front which crossed the Sierra during the afternoon and resulted in the severe weather conditions encountered by the research aircraft.

Due to the lateness in the day of the frontal passage, only one research flight was made. Details of the flight profile are presented in Fig. 7a, and the measurements of liquid water content in Fig. 7b. The upper traverse by the aircraft at 6100 m was found to be smooth with a relatively uniform distribution of clouds. The cloud particles at this level were probably mostly ice as judged from the indistinct image of the sun which was faintly visible on occasion and from the lack of significant amounts of liquid water. Conditions within the storm system worsened steadily and its structure became more complicated as the aircraft performed the lower traverses. Toward the western end of the traverse at 3000 m the intensity of turbulence and the degree of the aircraft icing became so great that the research operations had to be aborted; several lightning flashes were seen in the near-dark conditions. As an additional indication of unstable atmospheric conditions, intense precipitation (25.6 mm) fell at Sacramento during the hour from 1600 to 1700 PST. The 1600 PST sounding from Oakland (Fig. 8) indicates that much moisture is present in the lowest layers, resulting in a substantial negative gradient of wet bulb potential temperature between 900 and 800 mb. It is likely that this led to convective instability with orographic lifting. The southerly flow and rather warm temperatures suggest an air mass of perhaps subtropical maritime origin.

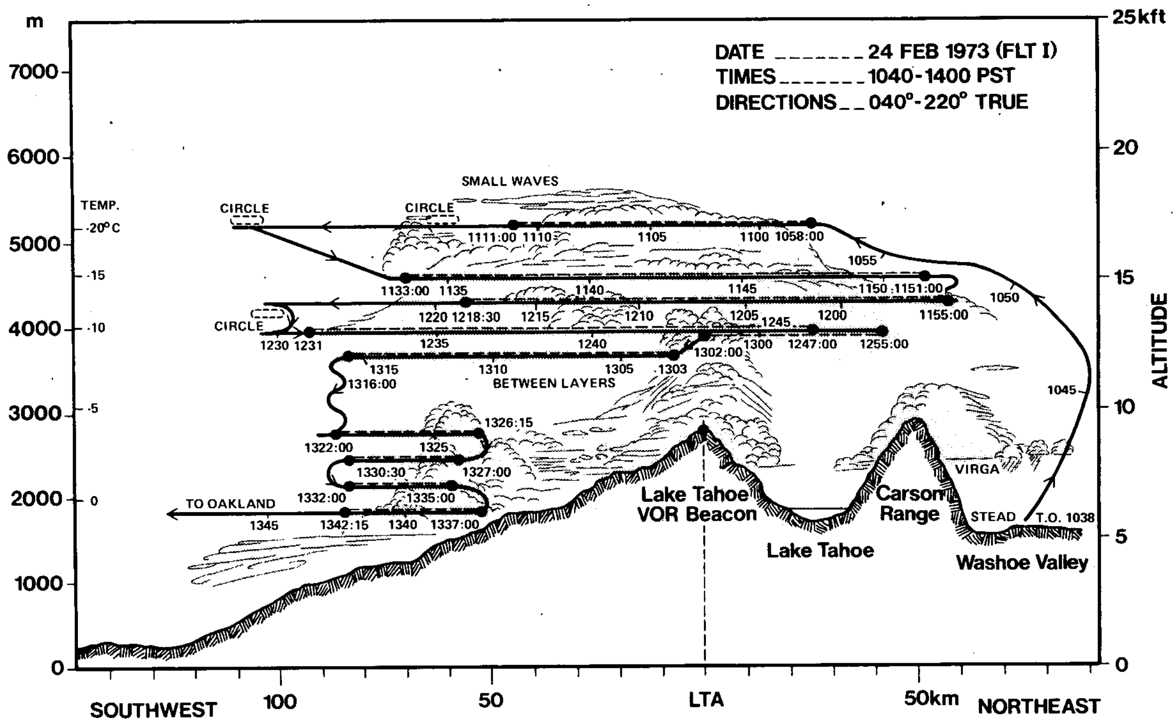

FIG. 6a. As in Fig. 2a except for Flight I of the storm of 24 February 1973.

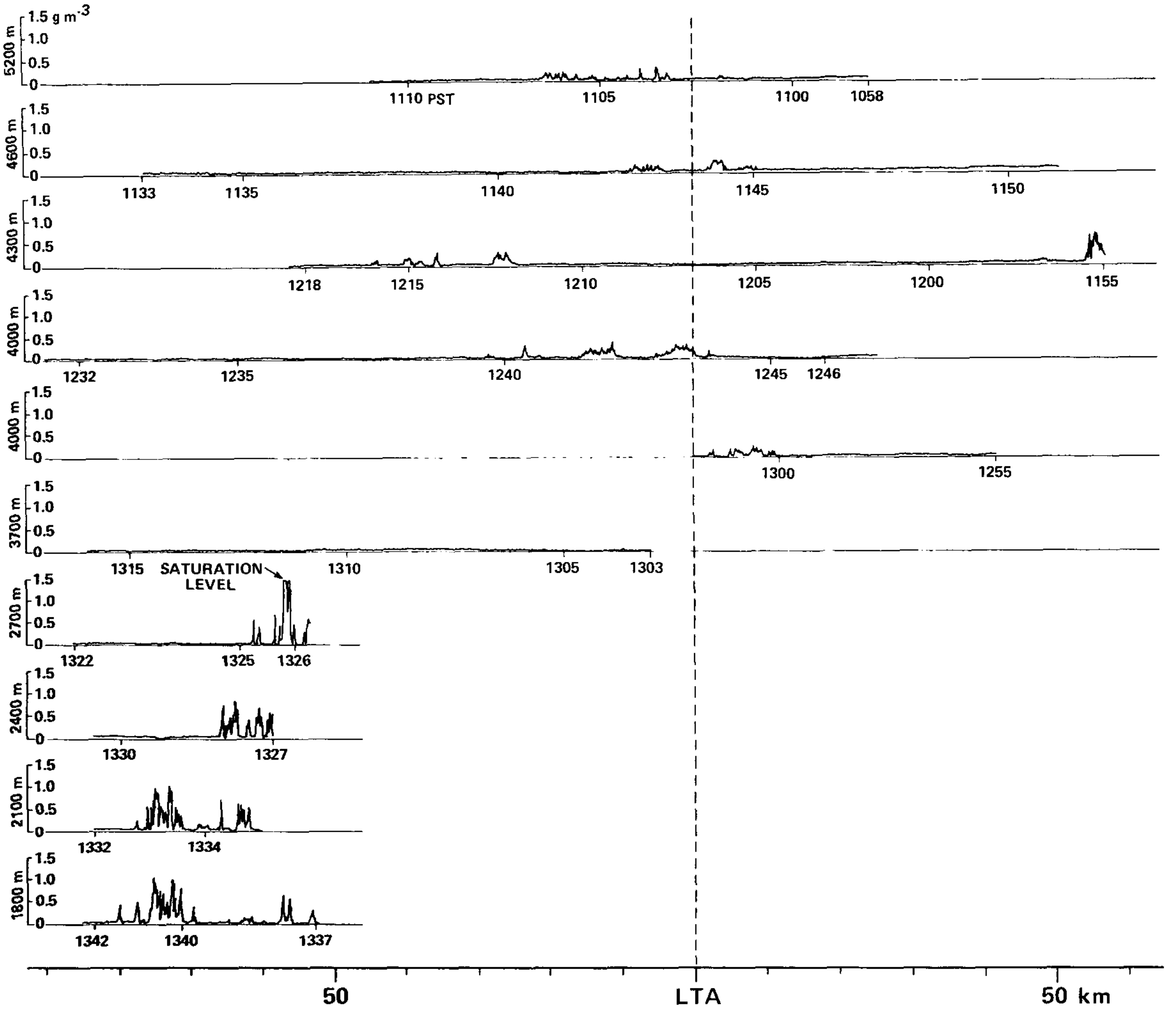

FIG. 6b. As in Fig. 2b except for Flight I of the storm of 24 February 1973.

Although this rather intense storm system had a complicated structure, the generalization may be made that the upper regions were mostly smooth and probably highly glaciated in contrast to the more turbulent lower portions that contained greater amounts of liquid water. In the horizontal there were two distinct pockets of intense activity, the major one over the western slopes and a more diffuse one near the main crest. The mesoscale distribution of precipitation that reached the surface from this storm is shown in Fig. 9, again showing a close association with the topography.

d. Storm of 10 March 1973

Early in the morning of this day a strong, fast-moving cold front approached California and the Pacific Northwest, while at the 500 mb level a broad wave increased in amplitude. The surface winds associated with this system were the strongest experienced in the Reno area in many months. A dust storm was seen at the northern end of Pyramid Lake to the north of Reno.

Two research flights were made this day. Particularly noteworthy during the first flight (Fig. 10a) was the rapid reduction of turbulence as the aircraft climbed through the approximately 3800 m level and the strong vertical lifting experienced in clear air near 5100 m, very likely a result of the Sierra lee wave since many lenticular-shaped clouds were present. Toward the west a vast deck of stratocumuli was seen to extend to the horizon. During the second traverse at 4900 m the aircraft track happened to lie between, although below, the tops of the cumulus towers so no liquid water content was recorded. The measurements of liquid water content (Fig. 10b) thus reflect those of the lowest three levels only. While glaciation was apparently common above, as judged from the indistinct appearance of the sun, these plots show that the lower layers contained significant amounts of liquid water. Characteristic features of the storm during the first flight included a rapid development, particularly in the regions of high liquid water content in the lower layers along the western boundary and over the crest.

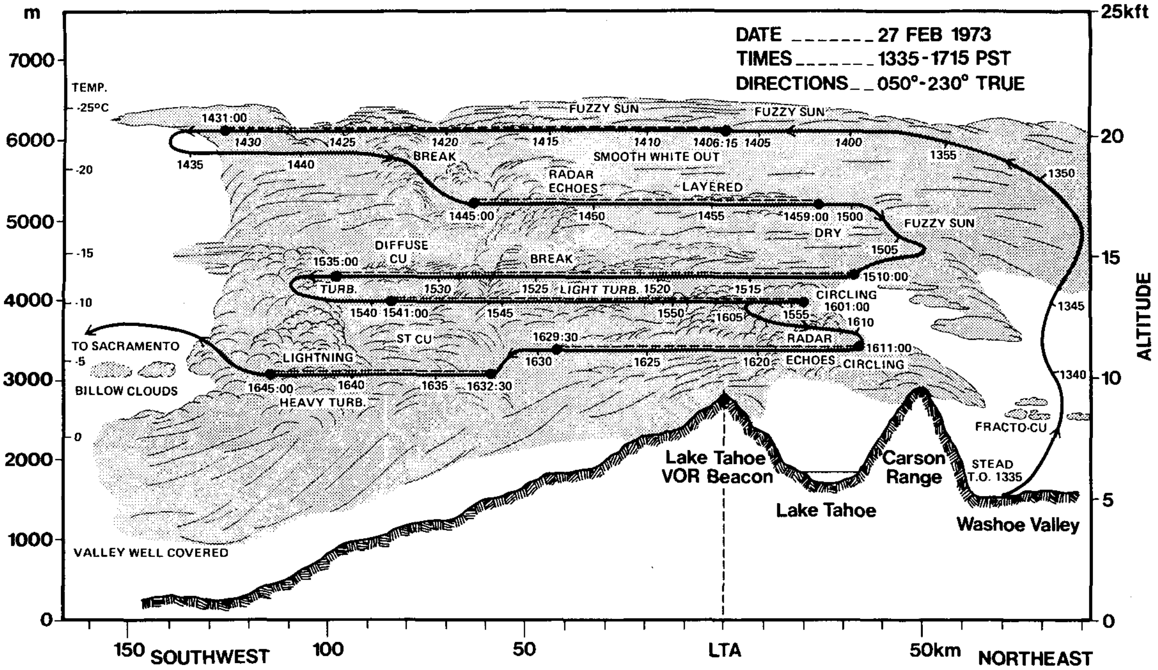

FIG. 7a. As in Fig. 2a except for the only flight of the storm of 27 February 1973.

At the time Flight II took off from Sacramento the winds were gusty and had just shifted sharply as a result of the frontal passage. It had been raining lightly but steadily. The clouds overhead were just beginning to exhibit more structure, although they remained uniformly dark toward the mountains in the east. The first clouds that were penetrated had bases at an altitude of about 850 m and were relatively dry. As the aircraft continued its climb out toward the northeast (Fig. 11a), the average water content was found to increase until the upper half of the main cloud mass was reached, where glaciation again predominated. The relative dryness of these upper clouds is seen by the record of liquid water content (Fig. 11b). During that portion of the flight when the tape recorder had been inadvertently switched off (dashed parts of track), some relatively high liquid water contents (~0.5 g m^{-3}) were noted from the visual display to exist toward the western end of the tracks at 4300 and 4000 m.

Compared with the storm during the first flight, a distinct intensification had occurred by the time the second flight ended. The cloud tops extended above 6700 m (compared with about 5500 m during the first part of Flight I) and the entire system had moved

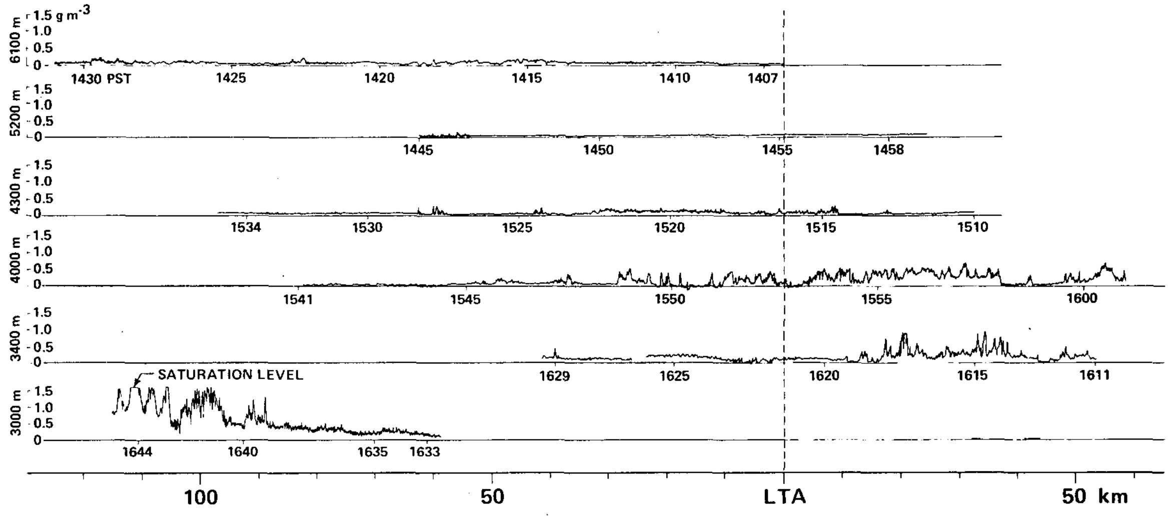

FIG. 7b. As in Fig. 2b except for the only flight of the storm of 27 February 1973.

considerably farther eastward. Furthermore, there was no longer any obvious stratification to the clouds. The largest amounts of liquid water definitely seemed again to be concentrated in the lower western regions and over the main crest.

4. Conclusions

During these investigations of winter storms over the central portion of the Sierra Nevada Mountain Range some common features have been noted, despite the considerable variability in their intensity and duration. In particular, the overall structure and organization of the storms studied were broadly similar and related to the underlying terrain in a particular way. Some of these common characteristics are summarized schematically in Fig. 12. The solid lines are meant to depict roughly the spatial limits of cloudy air, while the dashed lines subdivide the storm into several sections differing in some characteristic from the others. It is to be realized, of course, that such a representation is very crude and specific storms can and do deviate considerably from this. Nevertheless, the depiction is conceptually useful and the pattern seems to be typical of

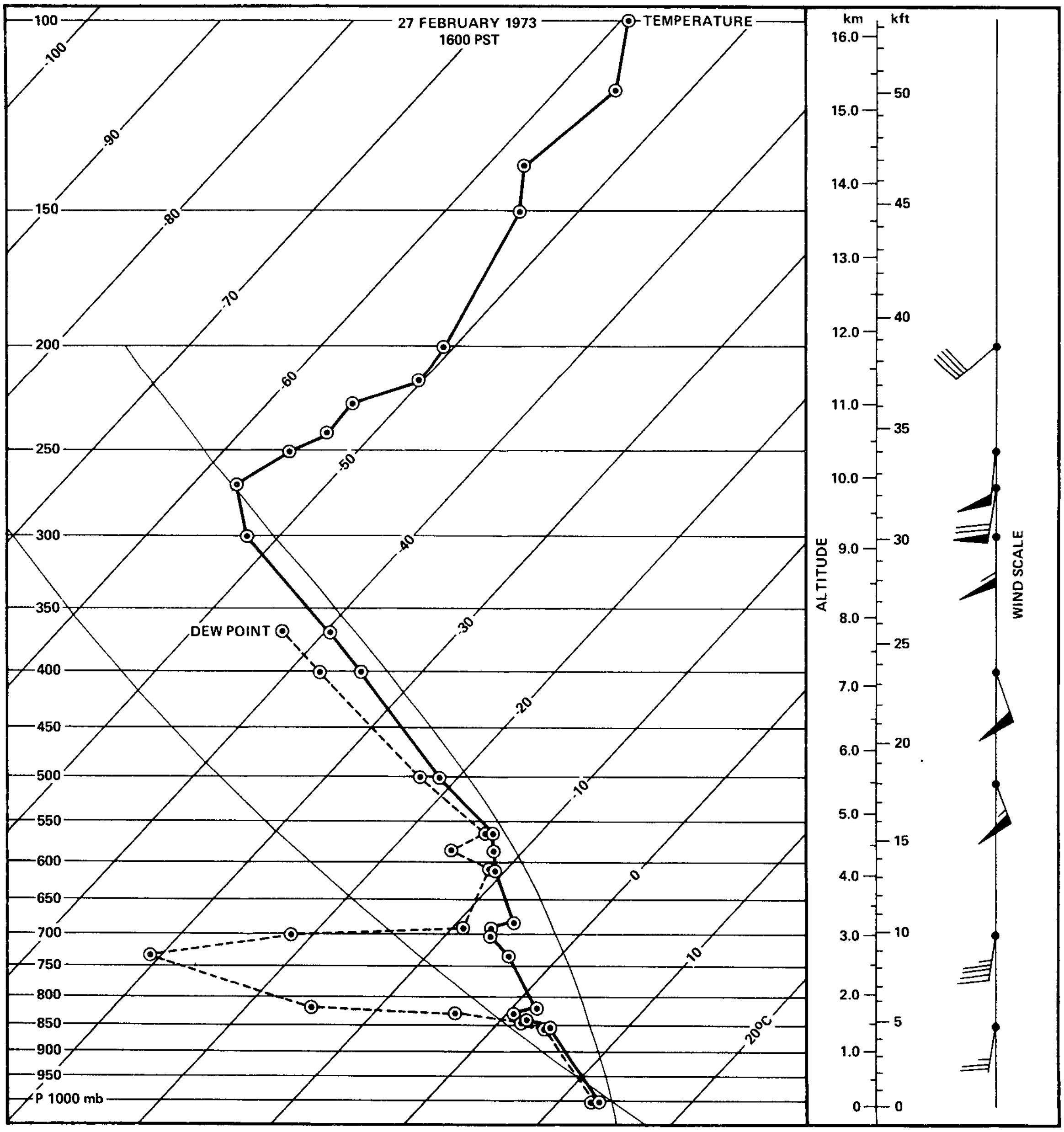

Fig. 8. The vertical sounding from the 1600 PST radiosonde ascent at Oakland on 27 February 1973.

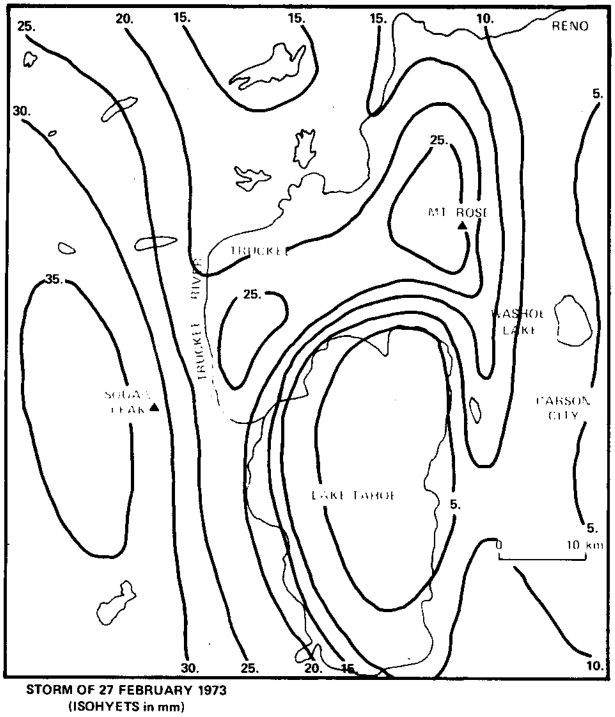

FIG. 9. Distribution of total precipitation within the mesoscale region from the storm of 27 February 1973.

most storms near the peak of their development over the mountains.

In general, the highest liquid water contents, sometimes in excess of 1.5 g m^{-3}, are found at the lower levels and in the strongly convective region indicated in Fig. 12 to lie between 40 and 75 km upwind of LTA. The uppermost region over the main crest (LTA) and to the northeast usually contained much ice and was often completely glaciated. The observation that the maxima of surface precipitation lie some 10–30 km upwind is consistent with a picture of precipitation containing particles with moderate fallspeed (a few meters per second) and developing in the high liquid water convective cells, resulting in fallout reaching the ground some tens of kilometers downwind.

Except for the low-level flow over the Carson Range, there generally existed a fair correspondence between the amount of liquid water in the clouds and the intensity of the turbulence encountered by the aircraft. The activity of the storm at intermediate levels downwind of the convective zone and also in the lower regions over Lake Tahoe was generally weak; clouds were often absent or very scattered in stratified layers and the amount of surface precipitation minimal. Frequently, smooth airflow, lenticular cloud forms and foehn walls were observed in the lee of the Carson Range. The western slopes may be identified with generally convective conditions, the eastern regions with stable flow. An upslope region of strong turbulence, particularly when associated with much liquid water, is consistent with a picture of lifting instability being released when low-level moist layers of air are forced to ascend the mountain barrier. The requisite vertical distribution of moisture and temperature may in turn

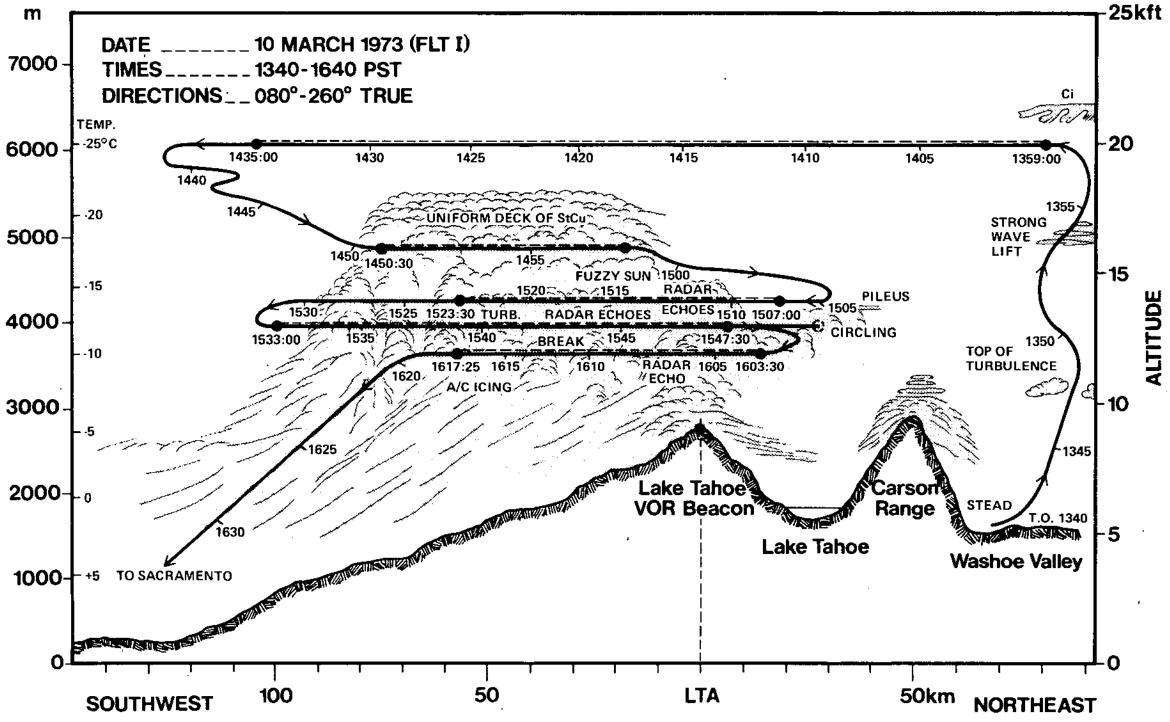

FIG. 10a. As in Fig. 2a except for Flight I of the storm of 10 March 1973.

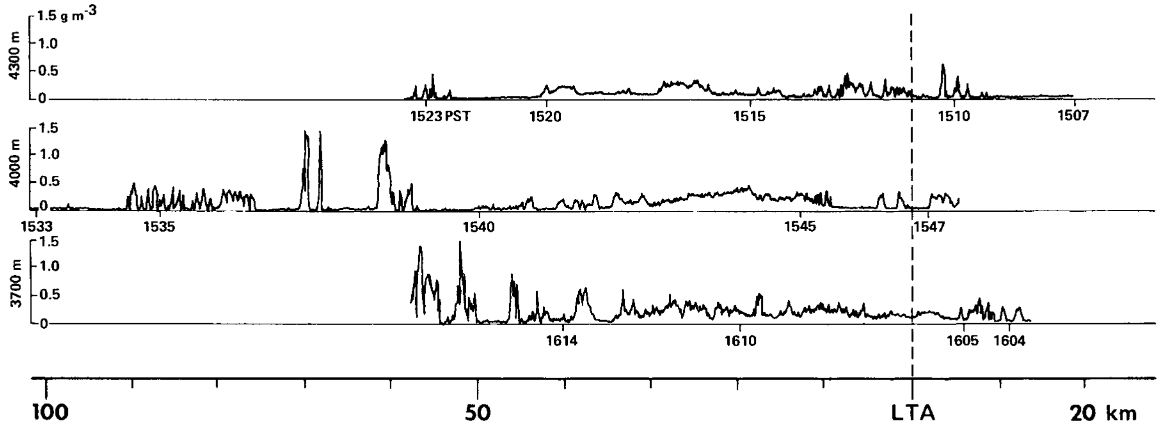

FIG. 10b. As in Fig. 2b except for Flight I of the storm of 10 March 1973.

result in part from the differential advection of air at various levels ahead of an approaching front or upwind of the mountain ridge which then acts as a preferential barrier to the flow of low-level air. In any case the result is an almost discontinuous alteration in the flow pattern, cloud structure and liquid water content as the air rises over the mountains. Our observations in this regard are similar to those of Marwitz (1974) in the San Juan Mountains of Colorado. In contrast to the convective upwind zones, the tendency of the downwind regions to exhibit greater stability may well be a manifestation of the cloud physical processes themselves through the preferential removal of condensate from the upper regions of the upwind cloud mass. Surface observations are consistent with this hypothesis in that precipitation upwind of the crest consists primarily of graupel whereas the precipitation downwind of the crest is almost entirely in the form of ice crystals with well-developed facets. Other possibilities, perhaps of a more dynamical nature, would have to be examined as well in a more detailed investigation.

It is of interest to compare these results with those of Hobbs (1975) obtained in the Cascade Mountains of Washington State, some 1000 km to the north. There, frontal systems are more distinct and tend to retain their identity better during passage over the Cascades (~1 km high), while the Sierra (~2.5 km high) tends

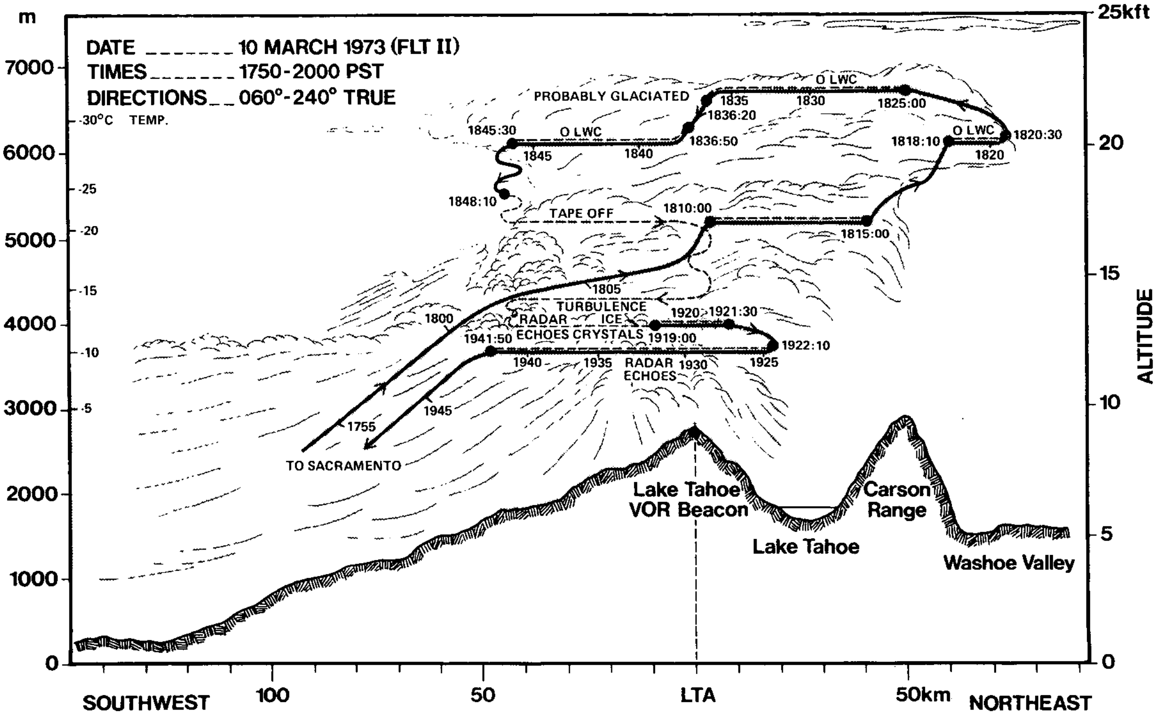

FIG. 11a. As in Fig. 2a except for Flight II of the storm of 10 March 1973.

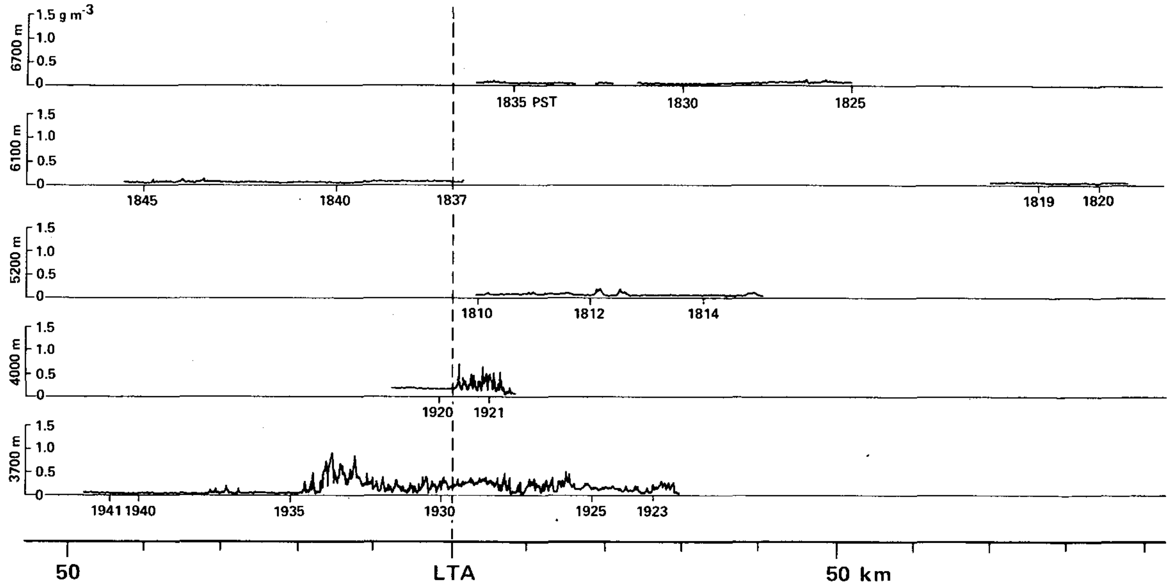

FIG. 11b. As in Fig. 2b except for Flight II of the storm of 10 March 1973.

to have a greater disrupting influence. Hobbs presents time averages of liquid water content measurements which show maximum values of 0.4 g m^{-3} at 1 km altitude on the upstream (western) side of the mountains. Occasional readings as high as 2 g m^{-3} were obtained during frontal passage suggesting an orographic effect similar to that over the Sierra. Also, as in the case of the Sierra, there was significant production of ice particles in these upwind convective regions which grow and fall out up to 100 km downstream. Although certain similarities exist in the character of the airflow over the two mountain ranges, the greater complications arising from the enhanced overturning of the atmosphere along the upwind slopes of the Sierra, particularly under frontal and post-frontal conditions, makes it much more difficult to devise any reasonable airflow model corresponding to the one developed by Fraser *et al.* (1973) for the Cascades.

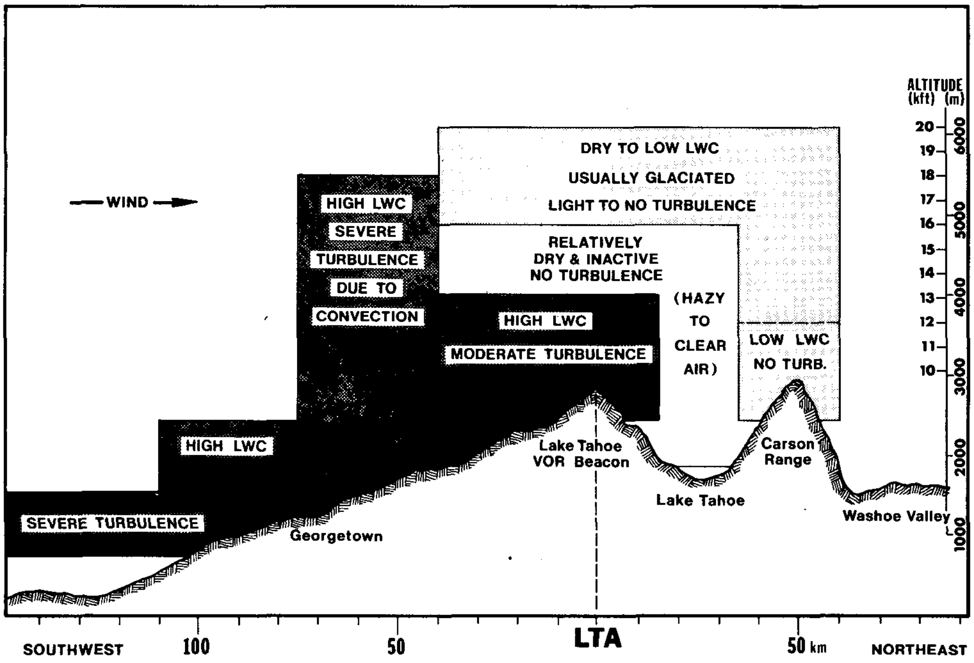

FIG. 12. Composite summary of the distribution of liquid and solid water and of turbulence derived from the storm investigations during the two-year period 1971–73.

On the basis of our observations we may tentatively conclude that the greatest opportunity for cloud seeding under winter storm conditions could lie in the strongly convective regions upwind of the crest where high liquid water contents exist and efficient vertical mixing occurs. Seeding downwind of this region may be much less effective both because of the reduction of vertical mixing and because of the formation of ice particles by natural mechanisms possibly including graupel multiplication processes in the upwind deep convection (Hallett and Mossop, 1974; Mossop and Hallett, 1974).

In order to formulate useful generalizations, it has been necessary to present the data as if the cloud systems were two-dimensional, that is, homogeneous along a line parallel to the mountain crest. This can be true only in a broad sense. Lateral inhomogeneities must arise, and indeed are observed, both because of the lateral variation in terrain and because of inhomogeneities in the structure of the synoptic systems themselves. Moreover, the inevitable ambiguity between position and time which occurs in observational programs employing only one aircraft was emphasized in these studies by the sometimes rapid development of certain storms, particularly those involving frontal passages. Although recognized as important, we were not in a position to resolve the additional ambiguity of the mesoscale effects associated with the fronts themselves from those influenced by the topography, as was done by Hobbs *et al.* (1975). Also, it is apparent that more information on ice crystal sizes and habits, as well as on droplet size distributions, would have helped enormously in our understanding of the physical processes operative in these complicated storm systems. Despite these obvious shortcomings, it is felt that the observations herein presented are basic and provide an important perspective to the nature and organization of storms over mountainous terrain.

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