A Case Study if the Water Budget of an Orographic Cloud

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A CASE STUDY OF THE WATER BUDGET OF AN OROGRAPHIC CLOUD

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ABSTRACT

An analysis of a precipitating wintertime orographic cloud system is presented. The analysis consists of a study of air parcel trajectories, cloud dimensions and character, and an evaluation of the atmospheric water budget leading to an estimate of condensation rate, precipitation rate and efficiency. The analysis is based upon radiosonde observations taken at three locations along a line intersecting the Continental Divide near Leadville, Colorado. The results show that reasonable estimates of the precipitation, cloud efficiency and air parcel trajectories are determined. Evaluation is based upon general sky conditions, radar observations, and snow board measurements. Suggestions to improve such computations are made.

1.0 INTRODUCTION

A major mechanism for producing wintertime precipitation in the western United States is the forced lifting of air by the topography. The modification potential of these cold orographic clouds was first pointed out by Bergeron (1949) and further developed by Ludlam (1955). They hypothesized that the number of naturally occurring active ice nuclei may be insufficient to optimally convert supercooled cloud water to ice crystals and thus precipitation. If artificial ice nuclei could be introduced into a cloud in the above condition, then a more efficient precipitation yield would occur. Another effect of seeding can be a change in the buoyancy of a parcel due to changes in latent heat release (Grant, et al., 1969; Chappell, 1970). The latent heat effect is generally considered small for cold orographic clouds.

Early modification programs made little attempt to scientifically explain or examine the physical processes operating in the clouds. About a decade ago, Colorado State University (Grant, et al., 1971) began the first modification experiment with good statistical and scientific design. This and other programs (Rhea, et al., 1969) have steadily increased the understanding of the physics of cold orographic clouds. Presently, detailed models of operational modification programs are beginning.

The change from modification experiments to operational programs demands careful transition and design. Also, an eye should be kept on the future development of technology. This paper presents an observational case study of an unmodified cold orographic cloud. Our objective is to carefully observe the cloud and surrounding atmosphere furnishing physical descriptors for use in model development and evaluating the potential application of cloud modification technology. This study was designed as one of the phases of the design study of the Bureau of Reclamation's pilot seeding project (Grant, et al., 1969).

A critical problem in any study of the hydrometeorology in mountainous areas is obtaining accurate estimates of precipitation. Such estimates are critical in the evaluation of seeding results and are complicated by the fact that precipitation varies widely with altitude and local topography (e.g., Hjermstad, 1970). The direct measurement of precipitation over mountainous terrain has been accomplished for rather localized experimental areas and even in these instances the sampling sites were located for their accessability. To expand such special networks to include any location is prohibitive from both cost and safety viewpoints. Alternative techniques of measuring precipitation yield must be developed. This paper further describes the application of one such technique, the atmospheric water balance.

Another problem that arises in the study of modification of orographic clouds is the observation of individual cloud system efficiency in producing precipitation. Evidence to date is largely derived from indirect relationships, for example, ice nuclei counts, that are meaningful only in statistical summary; therefore, individual clouds cannot be directly accessed. In this paper the study of the atmospheric water budget is used to evaluate the efficiency of orographic clouds.

To date there have been several attempts to develop a model of the airflow over a mountain ridge and the resulting precipitation (e.g., Myers, 1962; Elliott and Hovind, 1964; Willis, 1970). Lacking in these efforts is a suitable observational study that actually provides a detailed picture of the atmosphere in space and time. This report presents detailed observations of the wind, temperature and humidity distribution during an orographic precipitation event. Observations like these should become the basis for defining the initial conditions for future numerical models. Especially useful in this capacity are the trajectories of parcels travelling over a ridge.

The analysis presented here should lead to a greater understanding of the small scale meteorological processes in cold orographic clouds. In the analysis some basic assumptions have been rather boldly made concerning orographic clouds. It is hoped that some insight into the validity of these assumptions may be obtained from the results, as well as the more quantitative goals mentioned previously.

2.0 METHOD

The atmospheric water balance study described here is done two dimensionally with coordinates of pressure and horizontal distance along the direction of the wind. The air and terrain are assumed to be uniform in the direction perpendicular to the flow. Along the plane defined by the wind direction and pressure are one rawinsonde site and two radiosonde sites located as shown schematically in Figure 1. The rawinsonde is located upwind of the cloud, one radiosonde is near the crest of the ridge and cloud and the other is downwind of the cloud. Precipitation from the cloud is measured as well as possible over the area using precipitation gauges and snowboard data. These precipitation data are to be used as a check on the aerological analysis.

Balloon ascents are made from each of the three stations at approximately two hour intervals during the precipitation episode. The data received is then used to compute vertical profiles of temperature,mixing ratio, and equivalent potential temperature for all three stations. Profiles of wind speed and direction are obtained from the upwind station alone. The profiles are then plotted in time sequence for each station, resulting in pressure-time cross sections for each of the above parameters at each station. A value of any of those parameters may then be interpolated to any pressure and time desired at the station locations.

Trajectories of individual air parcels are then determined using the assumption that the equivalent potential temperature, θ_e, is conserved.

$$\theta_e = \theta \exp \left[\frac{L\,w}{C_p T_s} \right] \qquad (1)$$

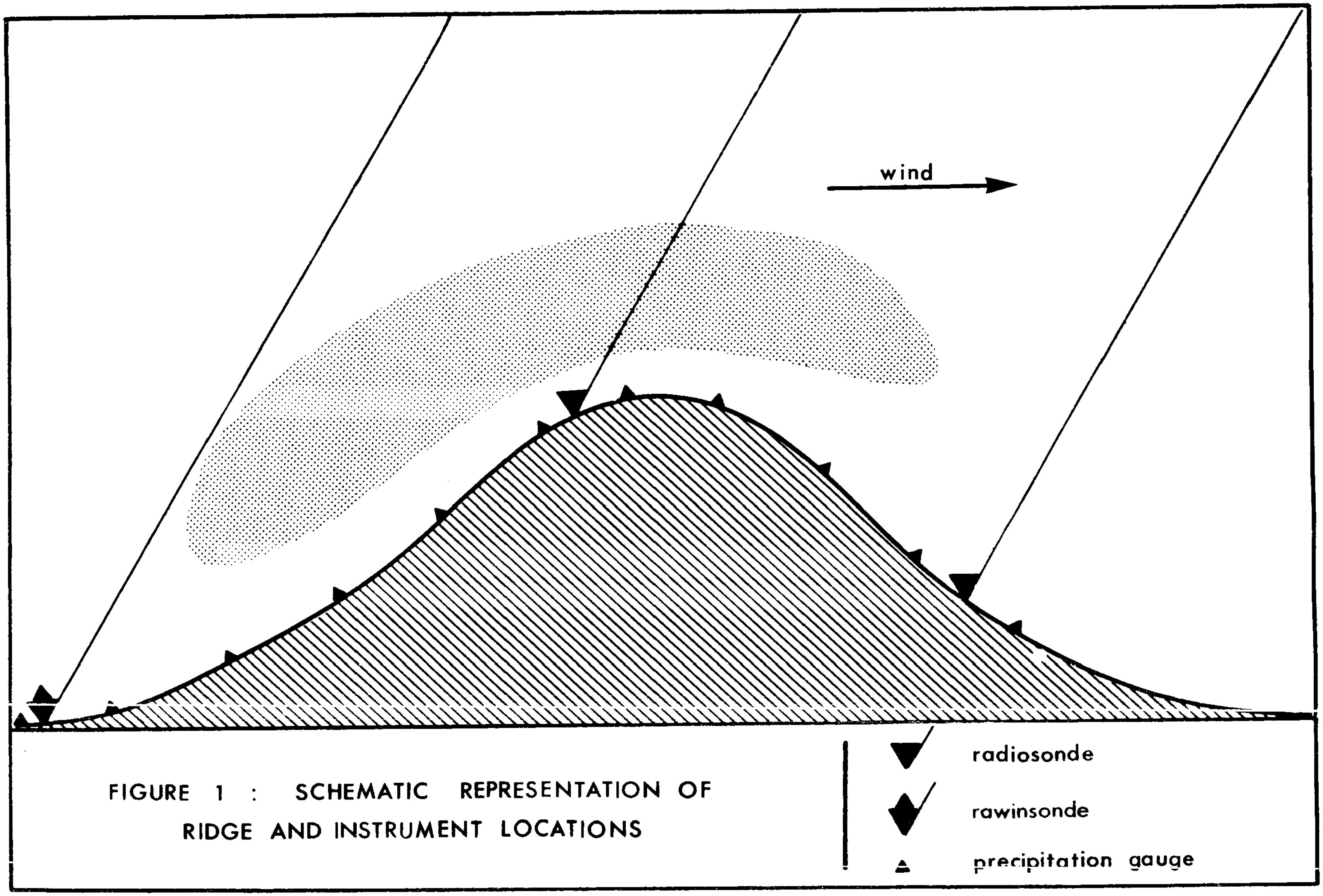

FIGURE 1 : SCHEMATIC REPRESENTATION OF RIDGE AND INSTRUMENT LOCATIONS

Where θ is potential temperature, L is the latent heat of condensation, w is the mixing ratio, C_p is the specific heat at constant pressure and T_s is the temperature at which the parcel would be saturated if lifted adiabatically. The trajectories are based upon the determination of travel times of parcels between stations, the wind analysis, and the restriction to conserve the equivalent potential temperature.

The location of the condensation for individual trajectories then is determined from the initial humidity and temperature of the air parcel lifted along the trajectory to the lifting condensation level (LCL). The locus of points indicating condensation for each trajectory then defines the upwind border of the cloud. The top and bottom of the cloud are limited by trajectories along which condensation is not reached. The downwind edge of the cloud must be subjectively placed.

Integer values of θ_e trajectories are used to define the edges of volumes of air channels through which the air flows without mixing across the isentropes (lines of constant θ_e). The exchange of mass then must take place at the ends. The water balance is computed for each of these channels by evaluating an equation similar to that of Elliot and Hovind (1964) or Rasmussen (1970). Assuming no evaporation from the ground and that the mixing ratios of liquid water and ice are small enough to be negligible for our purpose, the equation may be written

$$C = -\frac{1}{g} \int_{dp} \int_{dl} c_n w \, dl \, dp \qquad (2)$$

C is the rate of net condensation, g is the acceleration due to gravity, c_n is the component of the wind normal to the volume and defined positive outward, w is the mixing ratio of the water vapor, dl is the line increment on the horizontal boundary, and dp is an increment of pressure. Applied to a θ_e channel where all flux takes place at the end and integrating, equation (2) becomes

$$C = -\frac{\Delta l}{g}\left(c_{no}\, w_o\, \Delta_{po} - c_{ni}\, w_i\, \Delta_{pi}\right) \tag{3}$$

where the $_i$ and $_o$ subscripts denote incoming and outgoing respectively. Continuity of mass implies that

$$c_{no}\,\frac{\Delta_{po}}{g} = c_{ni}\,\frac{\Delta_{pi}}{g} \tag{4}$$

solving equation (4) for Δ_{p_o}, substituting into equation (3) and rearranging gives

$$C = \frac{\Delta_{po}\, c_{ni}}{g}\,(w_i - w_o)\,\Delta l \tag{5}$$

The term Δl reduces to the width of the θ_e channel, or unity, and Δ_{pi} is the difference of the pressures of θ_{ej} and $\theta_{ej} + 1$ at the upwind end of the channel or the pressure thickness of the channel.

Equation (5) is evaluated for all θ_e channels for the intervals between the upwind and central stations, the central and downwind stations, and finally the upwind and downwind stations. Values put into the equation for the upwind and/or downwind station are time interpolated (for the same parcel) and are chosen at the arithmetic mean pressure at each end of the channel.

If a parcel is sampled before it enters the cloud and again after it leaves the cloud, then the liquid and solid water contents at both ends are zero. Therefore, the net changes in both liquid and solid water mixing ratios are zero, so that a positive $w_i - w_o$ in equation (5) is due to precipitation (P). The condensation computed with data from the windward and leeward radiosondes becomes precipitation (P).

Cloud efficiency is determined by using the results of the water balance. Efficiency (ε) may be defined (Elliot and Hovind, 1964) as the ratio of the net removal of water to the net condensation.

$$\varepsilon = \frac{P}{C} \tag{6}$$

Further insight into the problem of cloud efficiency is the evaluation of the distribution of condensate with temperature since the number of active ice nuclei and available water vary with temperature. At warm temperatures (approximately -20°C and above) the cloud is expected to decrease in efficiency due to a relative scarcity of active ice nuclei. The distribution of condensate with temperature is best determined using the mean temperature of the θ_e channels for the mountain crest station.

In summary, then, the method of analysis of the orographic cloud system is done in three steps: First, the determination of trajectories of air parcels as they flow over the orographic barrier; second, the determination of the existance and characteristics of the cloud system; third, the determination of the atmospheric water balance leading to the estimate of condensation and precipitation and the efficiency of the cloud system.

The method described above is for data taken under ideal conditions. The actual locations of radiosondes were less than ideal and were dictated by existing facilities, power and communications. Because of this deficiency, certain modifications of the method were required. These will be discussed in the analysis section to follow.

3.0 FIELD EXPERIMENT

The experiment was conducted over the Continental Divide between Minturn (MIN) and Fairplay (FPY), the upwind and downwind stations respectively. Camp Hale (CHA) is the centrally located station (Figure 2).

3.1 Topography

The three radiosonde stations are located approximately along the line of heading 150° (from 330°). The line runs from Minturn through the Eagle River Valley for about 19 km. to just north of Camp Hale. About 20 km. downstream of Camp Hale is the Continental Divide - the highest point of the ridge. On the average, the ridge line is about 1500 meters (5,000 ft.) higher than Camp Hale. The topography of the area is favorable to orographic snow events when the wind is from 330°. Fairplay is located 38 km. down the line from Camp Hale.

Although the ridge is a blocking ridge, some of the lower air may be diverted south to the Arkansas Valley, after passing Camp Hale, without following the 150° heading. The results to be presented below show that this diversion probably occurred in our case but the diverted air was largely below cloud base and therefore would not contribute significantly to the water budget.

3.2 Meteorological Conditions

The synoptic setting in which the experiment took place is shown in Figure 3. A rapidly moving (30 kts.) upper trough passed over the western states and was located over eastern Colorado and eastern New

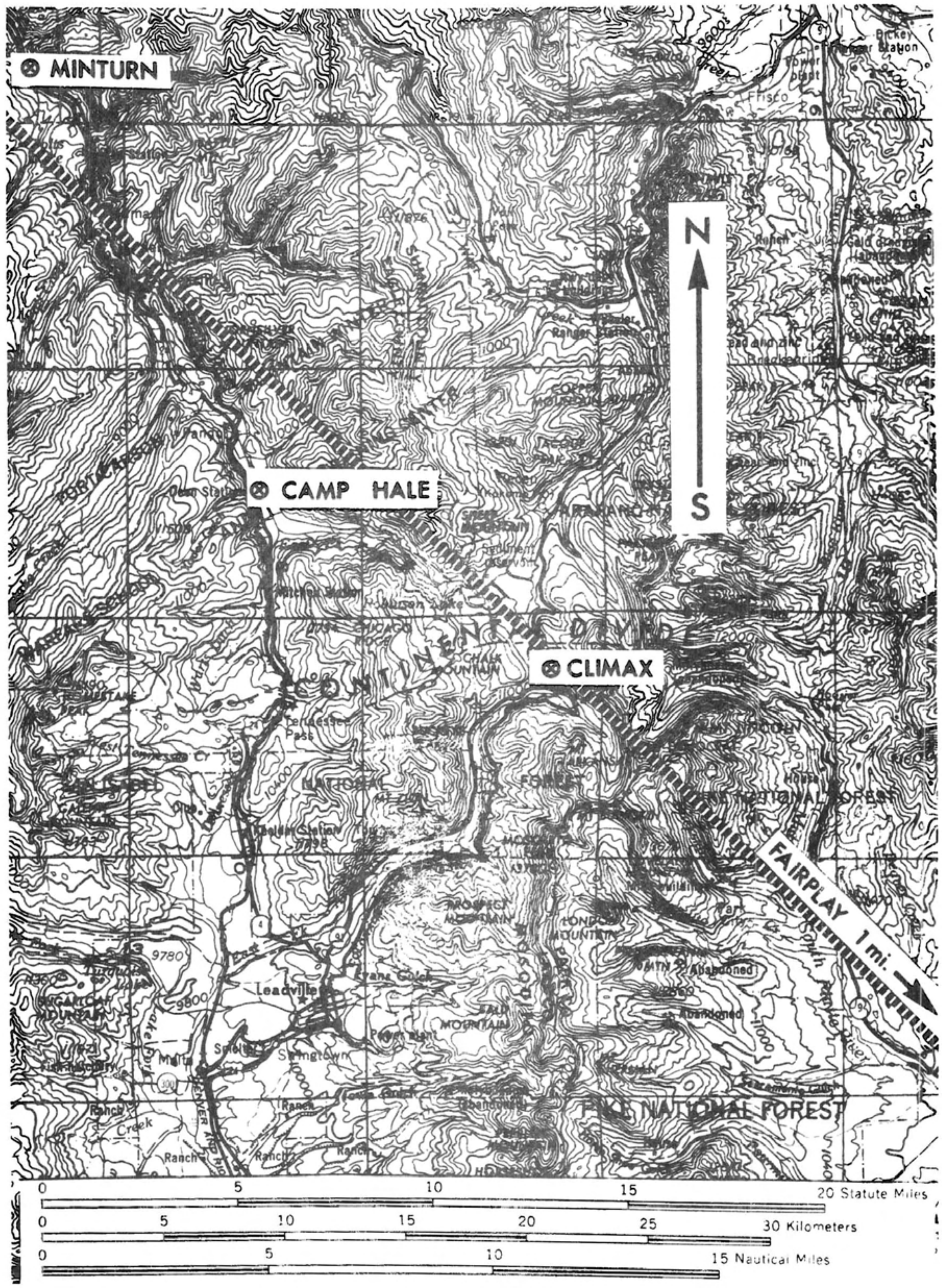

Figure 2. Topographic map of water balance experimental area.

Mexico at 1700 MST, January 15, 1970[1]. As the trough passed over the experiment site the wind shifted to northwest and provided the flow pattern appropriate for the experiment. Quite weak surface pressure gradients were in existence over the experimental site (see Figure 3). With time, however, the low east of the area in the Texas panhandle, associated with the upper trough deepened and the upper trough developed into a cut-off system and slowed down considerably.

Locally the character of the orographic storm appeared to change over the period of study. Precipitation started by 1200 when the lower winds had shifted from about 270° at 0900 to 300°. The upper winds were still westerly but becoming more northerly. All winds continued to shift to the north until they reached 330° at around 1400. Light snow fell until shortly after 1800 when the snow stopped. After a short period of no snow, highly variable snow resumed by 2000 and continued to fall until roughly 2300. A layer of warm air near 600 mb. had reached Camp Hale by 2000 (Figure 4) reducing the stability of the air up to about 525 mb. The snow during this latter period was spotty and typical of convective activity. Also, at 2300 the winds started to shift back to a more westerly direction. By 0000 on the 16th, the winds were back to 300°. The precipitation episode seemed to have three phases: First a period of snow from a stable orographic cloud, then a period of transition with no snow and then a system in which convection dominated over the stable cloud.

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[1]Reference to time in this paper will mean local time (Mountain Standard Time).

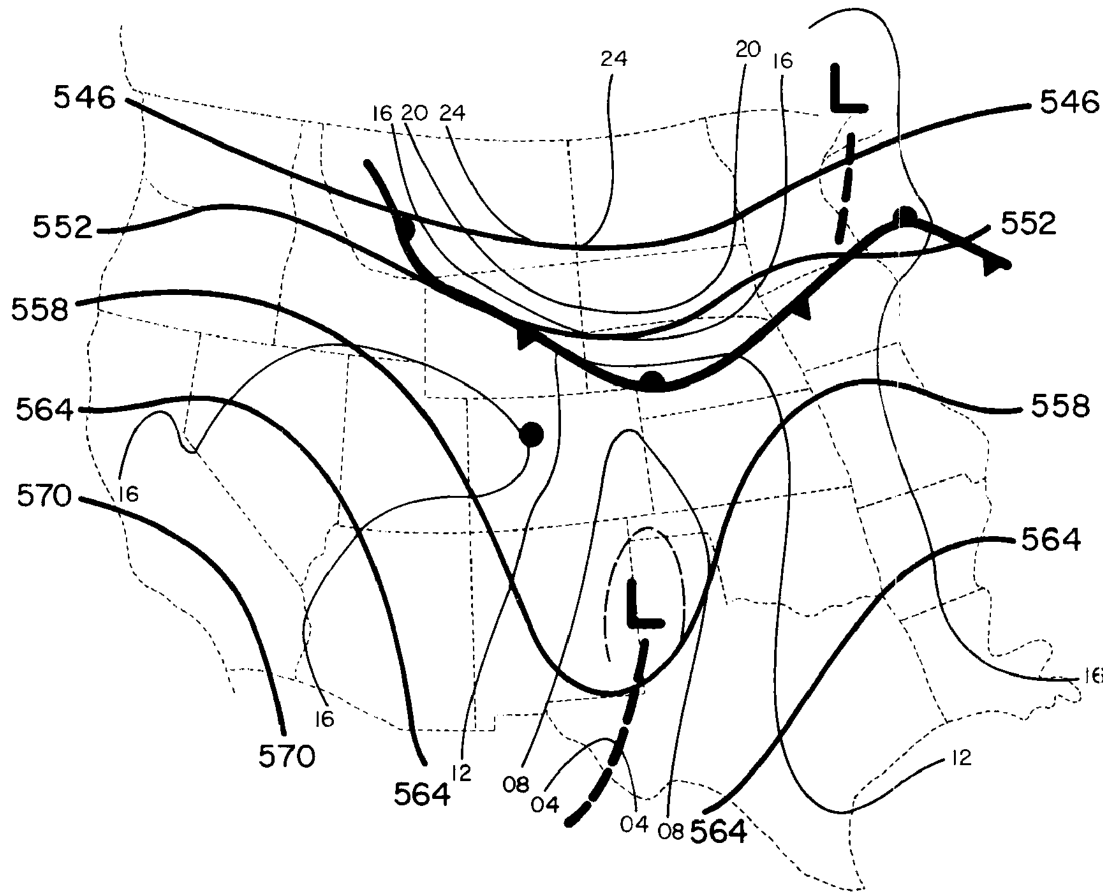


Figure 3. 500 mb contours (heavy solid lines-decimeters) and sea level pressure pattern (thin solid lines - add 1000 to obtain mb) for 1700, 15 January 1970 (0000Z, 16 January, 1970). Fronts and regions of frontal genesis are shown by heavy barbed lines and dashed lines respectively. Solid dot is the experimental location.

Photographs of the radar scope at Climax (see Figure 2) available after 1530, agree well with surface observations. From 1530 to about 1730 some cellular activity was observed. This was expected in light of past observations (Furman, 1967; Elliott, 1966). After 1730 there was a marked reduction of activity followed by a marked increase at about 1930. By 2300 the cells had disappeared. The radar pictures were not of sufficient quality to provide a reliable quantitative measurement of echo sizes, densities and movements.

3.3 Data

Data from the rawinsonde and two radiosondes comprised all the essential data for the aerological analysis described in section 1. Pressure, temperature and relative humidity data received from these instruments were analyzed in as much detail as possible. The vertical profiles of temperature, mixing ratio and equivalent potential temperature, generated for each balloon ascent, were plotted in time sequence for each station as discussed earlier. Figures 4, 5 and 6 show the resulting analysis for Camp Hale data. In these figures the light vertical lines are the soundings positioned according to the time of release. The local weather conditions, as composited from surface observations at Minturn and Camp Hale, are shown at the top of Figures 4 - 7. (Camp Hale was the closest location to the ridge line where observations other than precipitation were made. Weather conditions between Camp Hale and the continental divide were not observed.) Wind speeds from Minturn were treated similarly and are shown in Figure 7. The arrows indicate the wind direction at one minute intervals of balloon flight.

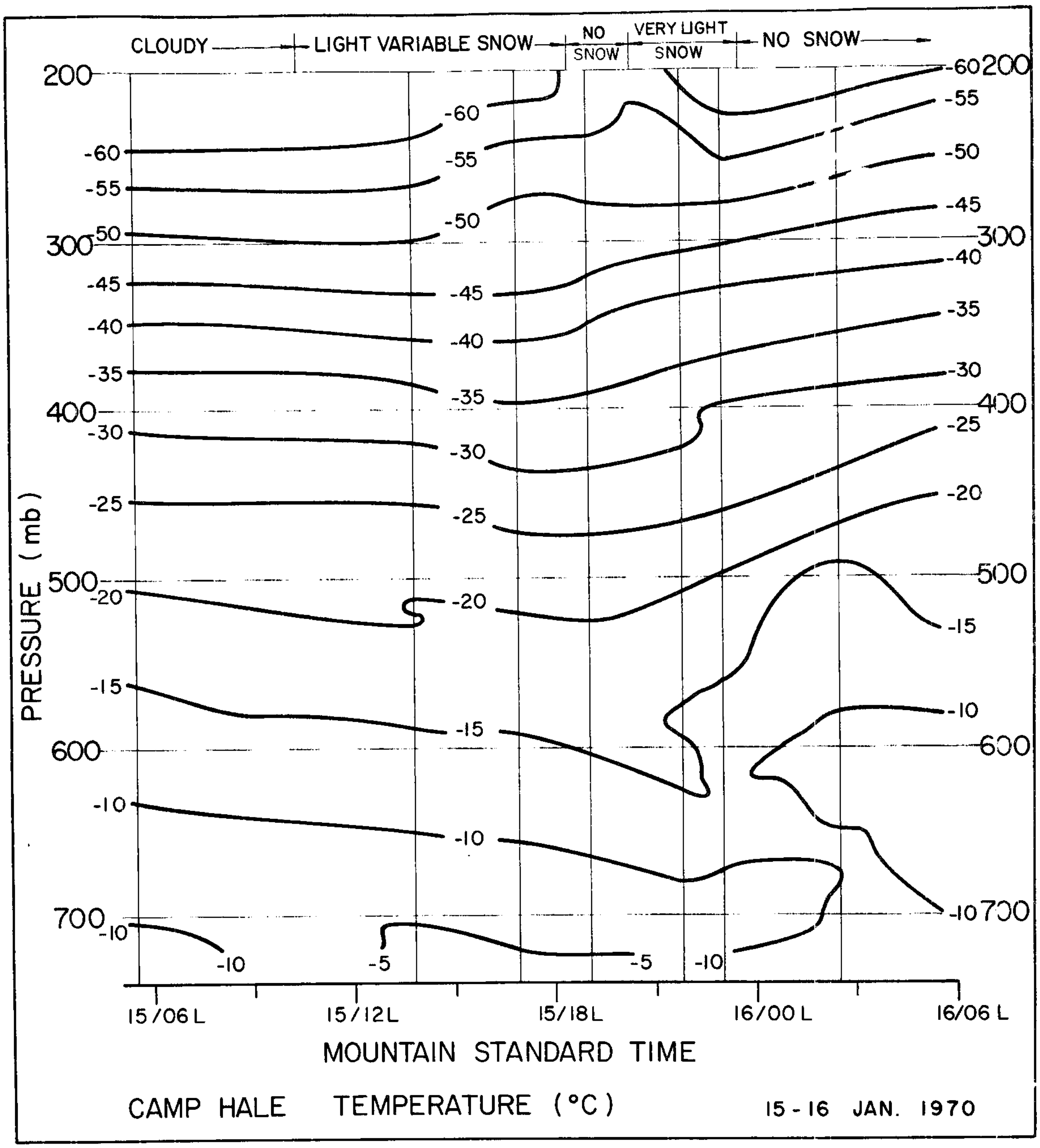


Figure 4. Time-pressure field of temperature at Camp Hale.

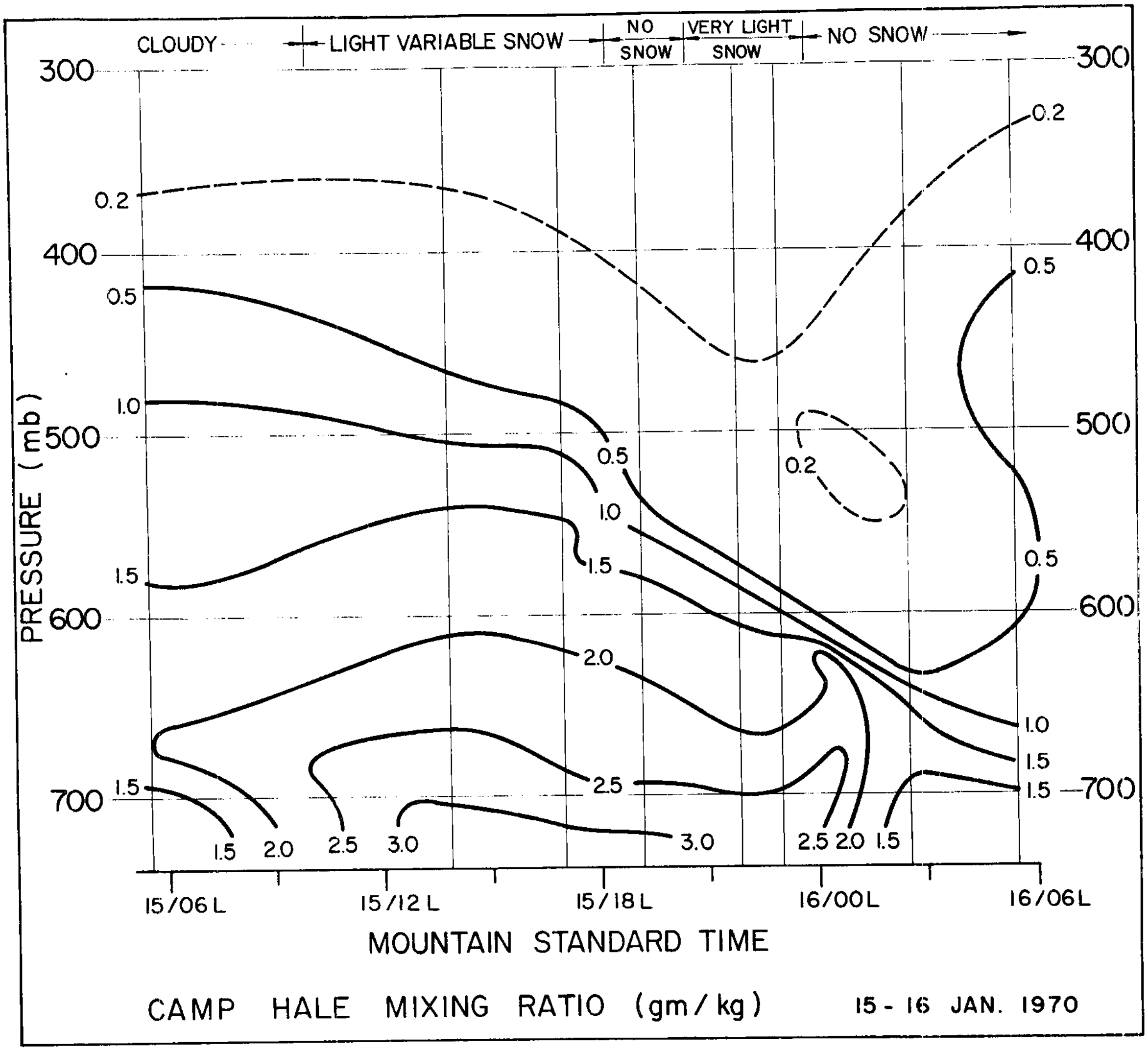


Figure 5. Same as Figure 4, but with mixing ratio.

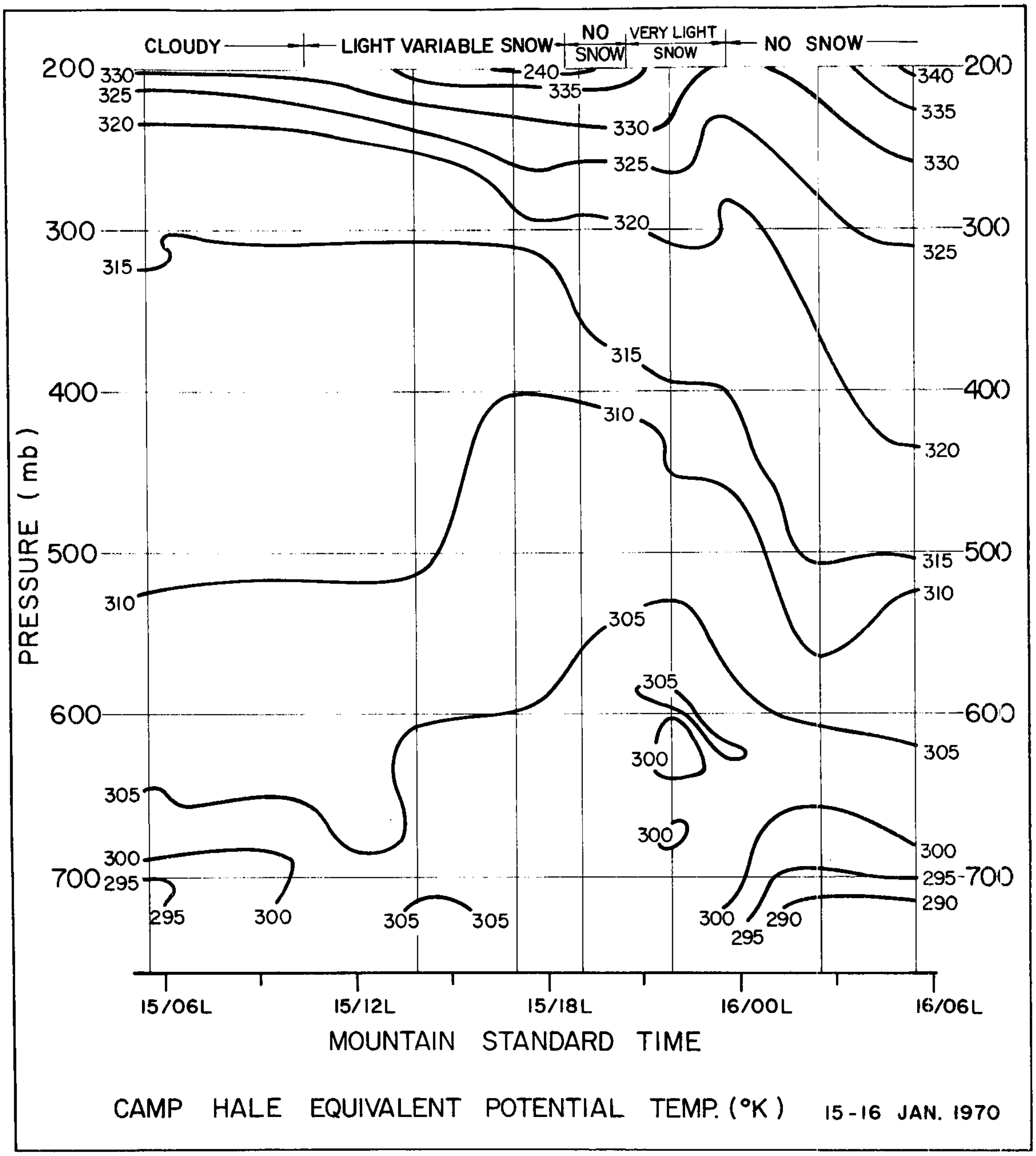


Figure 6. Same as Figure 4, but with equivalent potential temperature.

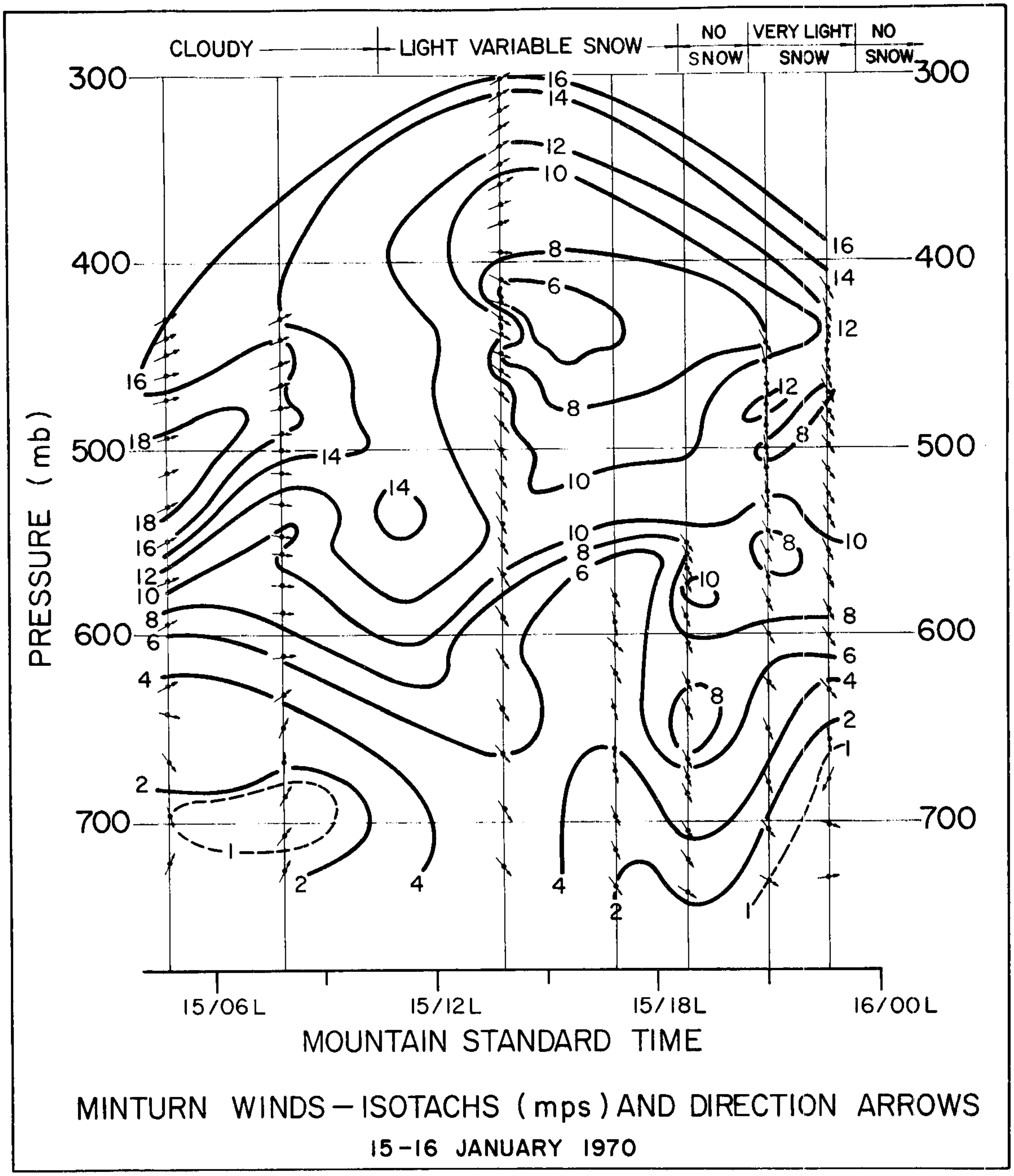


Figure 7. Time pressure field of wind at Minturn. Arrows point direction of wind with top of page as North.

A look at the wind arrows indicates a problem in the Minturn data. Although the first and last minutes of wind data are not determined in the computational method used, the vertical extent of the direction arrows indicates how high the balloon was tracked. Loss of the rawinsonde signal is a result of the topography interfering with the line of sight downstream of Minturn. Most ascents were tracked at least to 500 mb., a height sufficient for the orographic cloud analysis. Above that level increased subjectivity is imposed on the time series analysis.

The time-pressure fields (Figures 4, 5 and corresponding analyses for other stations and Figure 6) are used to determine parameters of a chosen parcel of air when that air is over each of the stations. If the parcel of air is over the middle station (or the air sampled by a balloon released at the middle station) at a chosen time t_o, then interpolation backward in time on the upwind station's time series gives the value of a parameter of the air parcel when it was over the upwind station. That is, if the parcel took one hour to travel from the upwind station to the central station, the parameter's value may be found t_o - 1 hour (and at a pressure determined from trajectories which are discussed later) on the upwind station's time series. A similar interpolation is done forward in time to the downwind station.

Time of travel of an air parcel from one station location to the next is required to reduce the time-height cross section data to the trajectories of the air as it flowed over the mountain barrier. A vertical profile of travel times for air over the central station at t_o is found by first determining the wind speed (V_o) profile of that column of air. (The wind field found at the upwind station is considered nondivergent.) Dividing the speed into distance travelled gives an initial value of the time of travel. Since a parcel's speed changes with time, the initial time of travel is used to interpolate with time and on the same pressure surface in the appropriate directions, a modified velocity. To determine the travel time equation (6) is evaluated.

$$V = V_o + \frac{\partial V}{\partial t_o} \, dt \qquad (6)$$

V is then divided into the distance to give a better estimate of the travel time. The process could be repeated but higher order terms would make only minor contributions. Done at regular pressure levels, this procedure yields profiles of the travel time from the upwind station. The same column of air can then be sampled over all three stations. Minturn wind data are used to evaluate equation (6). Resulting time of travel profiles for 1500 are shown in Figure 8.

Balloon paths from Minturn during or near the precipitation period are shown in Figure 9. This data is used to determine the average drift of the balloon as a function of pressure. The paths also serve as a check on the wind direction. Notice that the balloons launched during the precipitation period have very similar tracks approximately following the coordinate heading of 150°.

Snowboard data are shown in Figure 10. The data were taken on the 16th of January and represent a 24-hour accumulation of snow. The Hoosier Pass data were taken starting from near Alma at 0940 to 1144 at Breckenridge. Fremont Pass data were taken starting at 1145 near Leadville to 1445 near Frisco. As noted, these data are biased toward lower elevations and only provide qualitative checks of calculated precipitation.

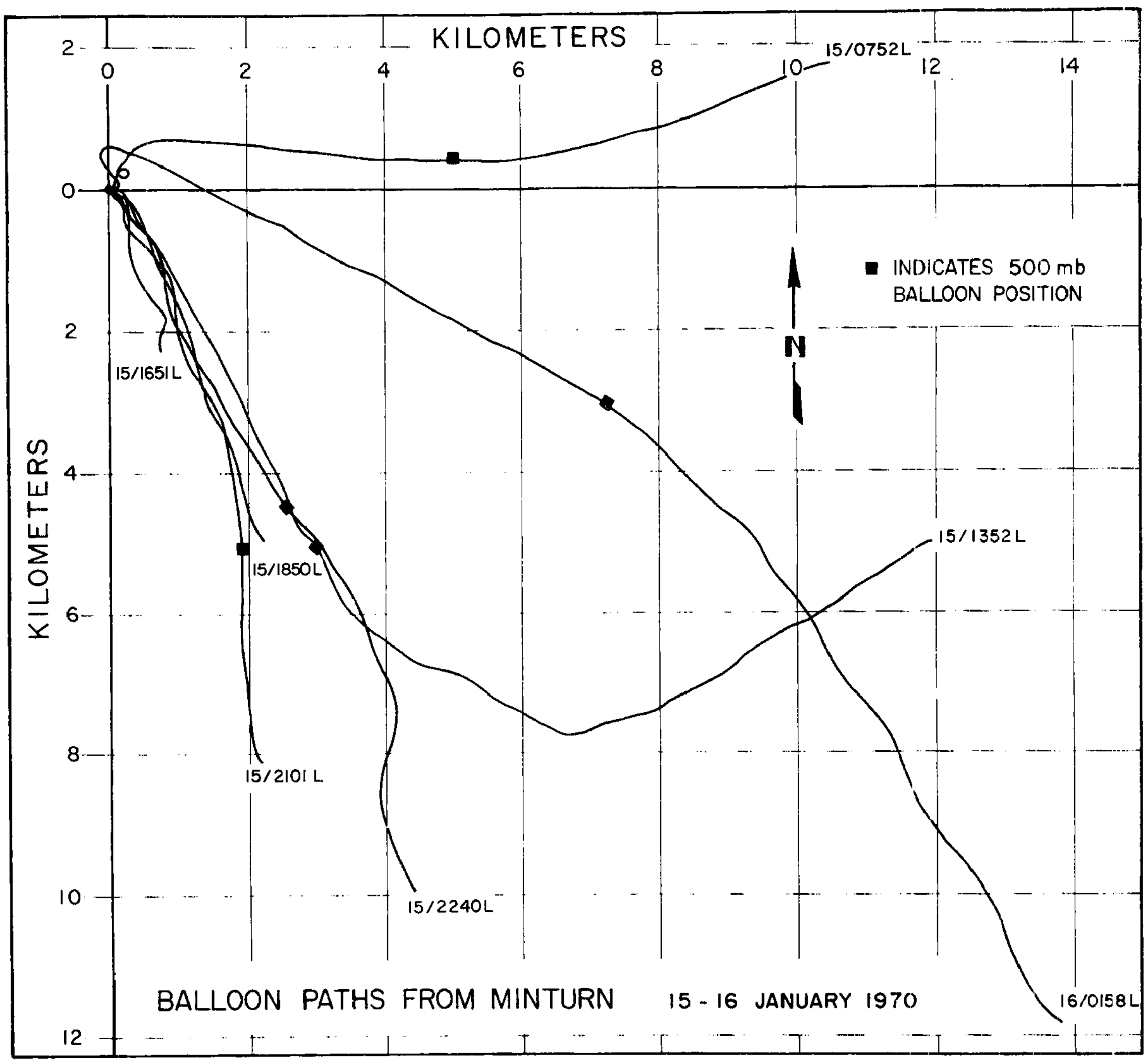

KILOMETERS
0
2
4
6
8
10
12
14
15/0752L
KILOMETERS
2
0
2
4
6
8
10
12
INDICATES 500 mb BALLOON POSITION
N
15/1651L
15/1850L
15/1352L
15/2101L
15/2240L
16/0158L
BALLOON PATHS FROM MINTURN
15 - 16 JANUARY 1970

Figure 8.

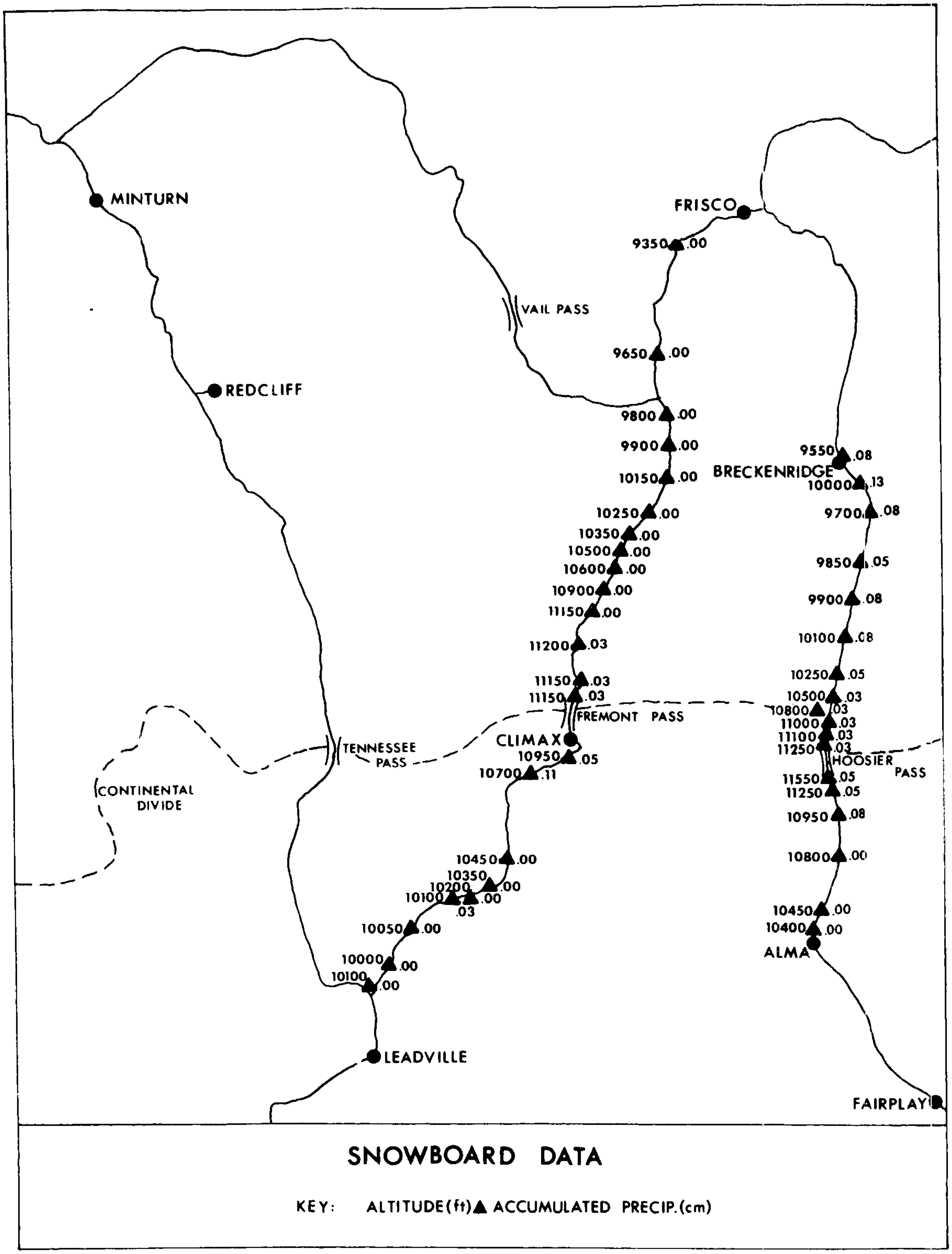


Figure 9. Snowboard data showing water equivalent of snow for 24 hour accumulation. Data was taken during 16 January, 1970.

3.4 Modifications of Method Due to the Field Data

As noted previously, less than ideal field locations of the radiosondes require modifications in the method or the assumptions behind the method. Minturn and Camp Hale locations require the modifications in determining the water balance, cloud efficiencies and trajectories.

Ideally, the upwind station must be located upwind of the cloud. Minturn's balloons, however, passed through the cloud. In the analysis the assumption is made that the amount of cloud water advected is small compared to the vapor advected (about 1 gram of vapor compared to less than .1 grams of liquid and solid water per kg. of air (L.O. Grant, personal communication) and can be neglected. This small error results in an underestimation of precipitation because Fairplay, during the time of the experiment, was not cloudy.

Balloon ascents from the Camp Hale site cause some problems. Because Camp Hale's balloons do not sample the air at its highest point, but considerably upstream of that location, the high point of the trajectories must be subjectively decided. For the lower air, the crest of flow is assumed directly over the ridge line with the crest of flow of the higher air following a slight negative slope (Scorer, 1967).

A third modification required by the non-ideal placement of radiosondes is the computation of downslope evaporation. Between Camp Hale and Fairplay the air parcels ascend until they are roughly over the top of the ridge and descend past the ridge. While the parcels are ascending condensation takes place but during descent only evaporation occurs. The water balance includes both these stages. To get the total net condensation over the experimental area the water vapor added to the

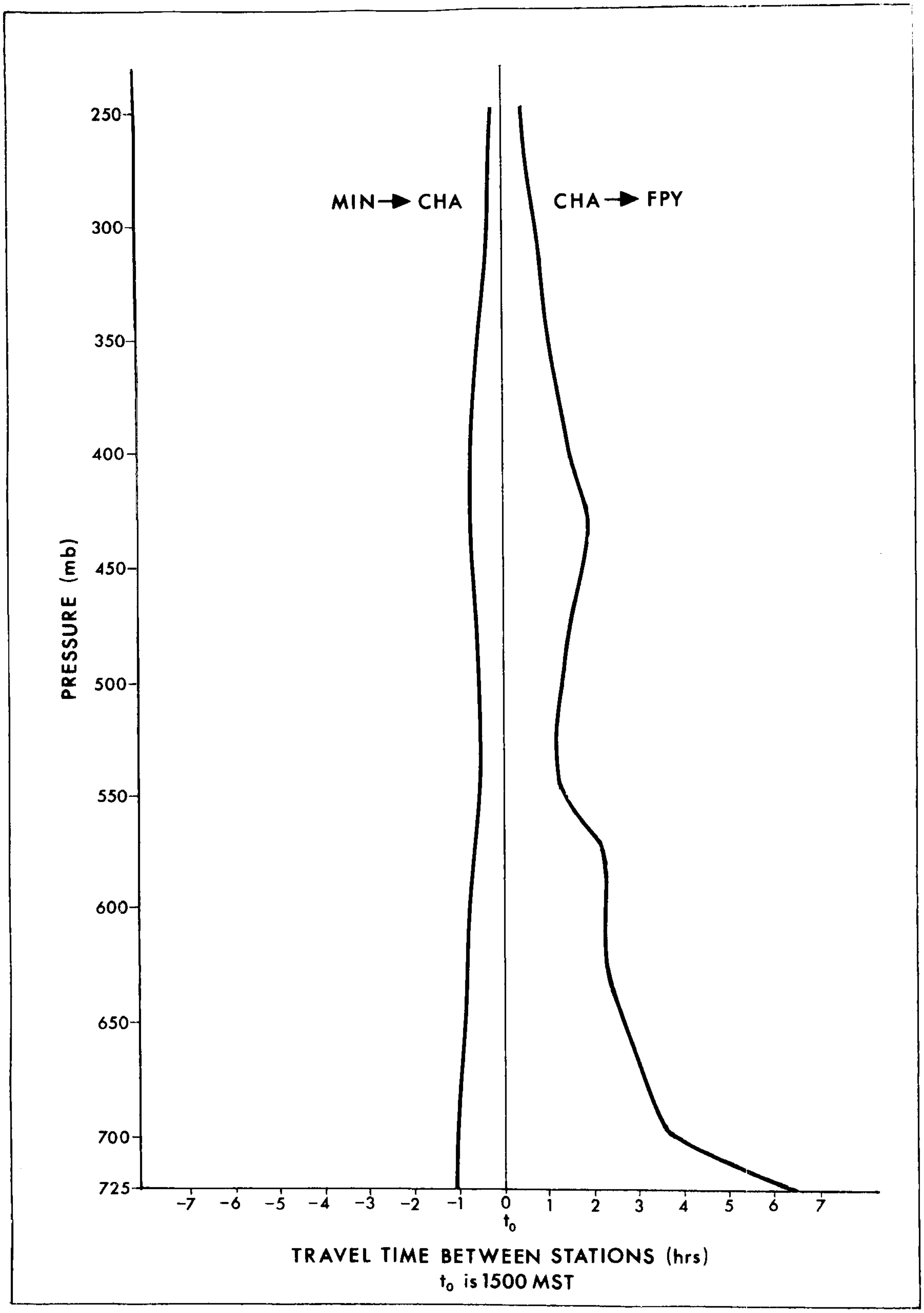


Figure 10. Time of travel profiles for analysis at 1500 computed from equation (1).

atmosphere by cloud evaporation on the downslope side of the ridge has to be removed from the final water balance computation. This is done by obtaining an estimate of the downslope evaporation and eliminating this estimate from the net condensation already computed for between Camp Hale and Fairplay.

Estimation of the downslope evaporation is done by computing temperature and mixing ratio profiles for an imaginary station at the top of the ridge (designated TOP). The air above this station is assumed to be initially saturated and travelling adiabatically between the top and Fairplay. For each θ_e channel, the temperature at TOP is equal to the temperature at Fairplay minus the dry adiabatic warming due to descent and compression, plus the cooling due to evaporation between Camp Hale and Fairplay. Expressed as an equation.

$$T_{TOP} = T_{FPY} + \gamma d \ \Delta Z + \frac{L}{C_{pd}} \ (w_{TOP} - w_{FPY}) \tag{7}$$

Here γd is the dry adiabatic lapse rate (-9.8°C/km.), ΔZ is the distance the parcel descends between the top of the ridge and Fairplay, L is the latent heat of evaporation and C_{pd} is the specific heat of dry air, w_{TOP} is the mixing ratio at the top (assumed saturated) and w_{FPY} is the mixing ratio at Fairplay. w_{TOP} is an exponential function of T_{TOP} so equation (7) can be evaluated numerically. An initial guess of T_{TOP} (and thus w_{TOP}) is found by time interpolation on the Camp Hale temperature time series. Evaluated for each θ_e channel, equation (7) gives a temperature profile at TOP.

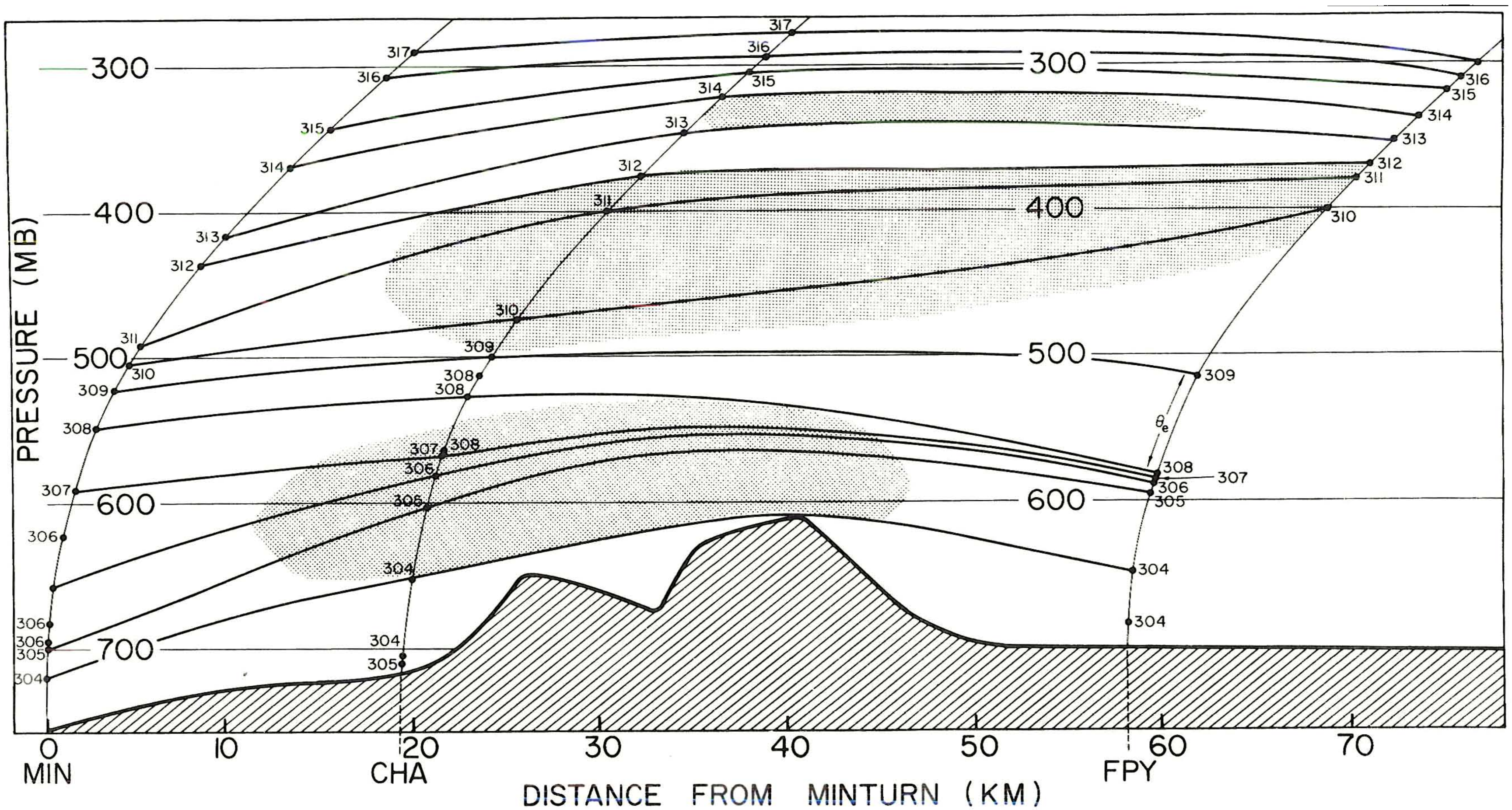
With the temperature profile known, a profile of mixing ratio is easily found. However, measurements of relative humidity by the type of radiosondes used in near saturated conditions is known to be low (Air Weather Service, 1955). To put the computed values to w_{TOP} on the same basis as the measured w_{FPY} (the difference in mixing ratios, not their magnitude, is important here) w_{TOP} is multiplied by the Camp Hale relative humidity time interpolated to the ridge top. (A minimum value of 15% relative humidity was used where the radiosonde was motor boating.)

With this modification of w_{TOP}, equation (5) is used to estimate downslope evaporation between TOP and Fairplay. The assumptions of negligible cloud water and ice as well as the subjective determinations of minimum trajectory pressure, and downslope evaporation computations are incorporated into the analysis. Results of that analysis are presented in the following section.

4.0 RESULTS

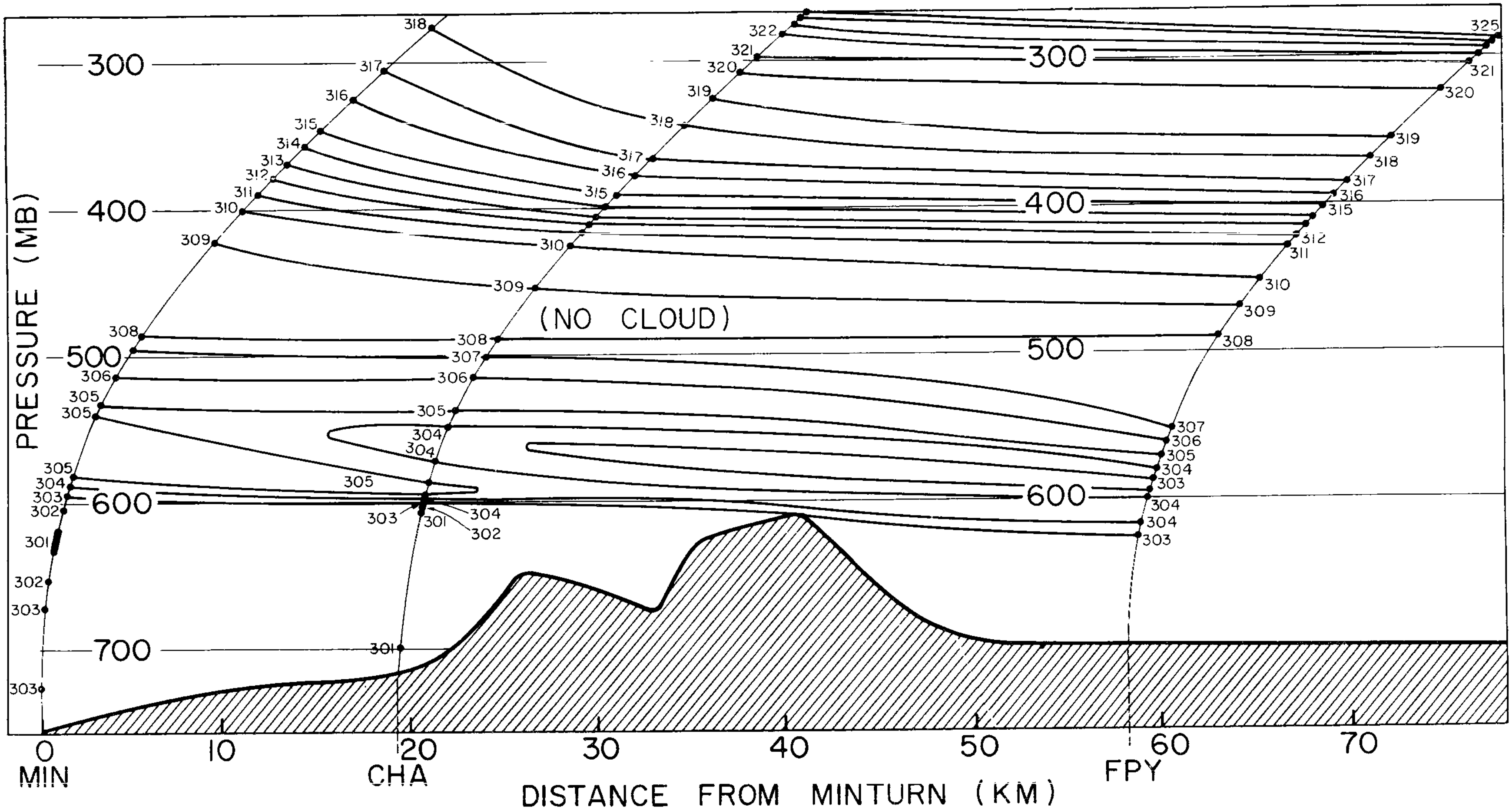
4.1 Trajectories

Figures 11, 12 and 14 are the isentrope analyses for 1500 and 2100 and are shown because they are representative of trajectories that are produced by the analysis. The balloon ascent curves are the result of the adjustment for balloon drift. The first three analysis times (1200, 1500 and 1800) show a smooth flow of air over the ridge. At 1200, all θ_e tubes rise between Minturn and Camp Hale and as they go over the ridge. The lowest air going over the barrier is at about 670 mb. over Minturn. The 1500 analysis (Figure 11) shows all but the top two channels rising with the lowest air going over the ridge at 720 mb. over Minturn. By 1800 some channels are descending between Minturn and Camp Hale and only air below about 500 mb. rises as it traverses the ridge. The lowest air getting to Fairplay is at 650 mb. at Minturn. At 1200 the nature of the isentrope analysis is radically different. Isentropes that go across the mountains beneath 475 mb. are horizontal as shown in Figure 12. There are also isentropes that "circle back" forming a volume of air with significantly unstable lapse rates of θ_e. Unstable lapse rates along with a steady northwest wind imply a mixing layer between about 590 and 530 mb. The mixing layer is compatible with the ground observations that the precipitation is convective in nature. Also, the height of the layer agrees with radar observations made during similar cloud cases for the area by Furman (1967). All the channels going across the barrier are horizontal or descending. Since there is precipitation, there must be upward vertical motions and, under the



15 JANUARY 1970 1500 M.S.T. ANALYSIS OF TRAJECTORIES AND CLOUDS DETERMINED USING SATURATION WITH RESPECT TO WATER

Figure 11.



15 JANUARY 1970 2100 M.S.T. ANALYSIS OF TRAJECTORIES (NO CLOUD FORMED BY ANALYSIS)

Figure 12.

above conditions, these motions must be in the form of buoyant eddies. The 0000 analysis shows a return toward stable flow with a couple of closed off isentropes over Camp Hale as the remnants of the 2100 unstable layer. Summarizing, trajectories through 1800 show smooth orographic flow while those at 2100 show a distinct mixing layer dying out by 0000.

4.2 The Water Budget

The application of equation (5) to compute the water budget has been described. This equation was evaluated for all θ_e channels at six times and for the following special intervals: Minturn to Camp Hale, Camp Hale to Fairplay, TOP to Fairplay and Minturn to Fairplay. Elimination of the downslope evaporation (TOP to Fairplay) from the Camp Hale to Fairplay intervals results in the synthetic interval Camp Hale to TOP. Condensation for this interval plus the condensation for the Minturn to Camp Hale length gives the total net condensation. The results of equation (5) for Minturn to Fairplay give precipitation.

Figure 13 shows graphically the results of these computations. In Figure 13a the difference between the CHA-FPY curve and the CHA-TOP curve is the downslope evaporation (TOP to Fairplay). The solid and the dotted curves in 13a are summed to give the solid curve in 13b or the total condensation. The precipitation is the dotted line in Figure 13b.

With the exception of 0900, the results are in very good qualitative agreement with the surface observations discussed in section 2.2. In that section it was pointed out that light precipitation started by 1200, stopping briefly, shortly after 1800 and very light and variable snow fell from about 2100 to roughly 2300. The 0900 analysis is not valid because the wind direction existing at the time does not satisfy the analytical assumptions. Also, it was noted earlier that there were no observations (other than daily precipitation) made between Camp Hale and the ridge top where the strongest orographic lifting takes place. Thus, unobserved snow may be falling downwind of Camp Hale. Still, with these qualifications, good qualitative agreement is obtained between the observed snowfall and the computed snowfall of Figure 13b.

To obtain the average precipitation (or condensation) per unit area the values presented in Figure 13 must be divided by the length of interval involved. The assumption has been made that all condensation, thus the precipitation, due to orographic lifting takes place between Minturn and the ridge top. This distance is about 4×10^6 cm (40 km.). The result of dividing the precipitation values is presented in Table I. Negative precipitation implies no precipitation. The total condensation per unit area is shown. Comparison of these results with the ground measurements (Figure 10) is very difficult to make for this set of data. The snow was light and the data taken between ten and fifteen hours after the orographic snow. Frontal passage with snow in the afternoon of the 16th may also have effected the Fremont Pass data.

TABLE I

Cloud Base Precipitation and Total Condensation
From Figure 13b in Units of Grams Hour^{-1} cm^{-2}

15 - 16 January, 1970

Time	0900	1200	1500	1800	2100	0000
Precipitation	0.12	0.09	0.08	0.00	0.00	0.01
Condensation	0.13	0.10	0.09	0.00	0.02	0.05

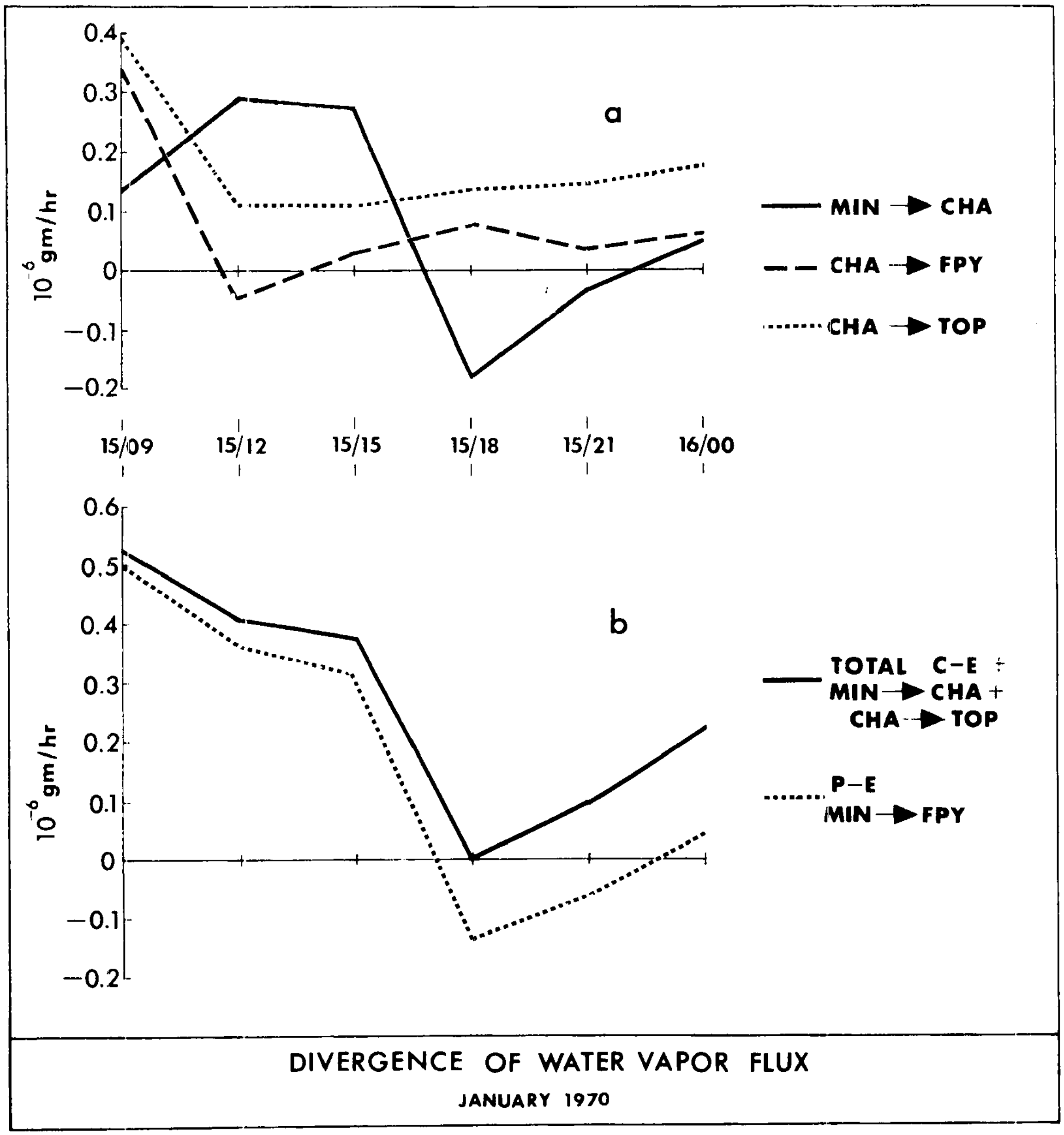


Figure 13. Results of water budget computations.

Recording gauges at Redcliff and Camp Hale were not sensitive enough to measure the light precipitation that was observed to fall. Although no direct verification is possible, observations and measurements agree well with the light and varying precipitation rates computed from equation (5).

4.3 Error Analysis for the Water Budget

By varying temperature and relative humidity in mixing ratio computations, but keeping trajectory and wind analyses the same, a simple estimate of the effects of possible radiosonde measurement errors can be made. Differences of combinations $\Delta T = 1°C$, ΔT - 5°C, ΔRH - 5% and ΔRH - 10% are used for determining the magnitude such errors would make in water budget computations. To see the effect of such errors at single stations Camp Hale data is varied in combinations (ΔT, ΔRH) of (0°, 10%), (1°, 0%) and (5°, 0%) and new values of C - E for 1500 are obtained for the MIN→CHA and CHA→FPY intervals. Changes of (1°, 0%) and (0°, 10%) are also applied to all three stations to observe the effects of possible errors that are common to all three stations. Table II shows the resulting condensation differences.

TABLE II

Induced Errors in Water Budget Computations
1500 M.S.T. 15 January, 1970
10^{-6} gm/hr, ΔC = C modified - C unmodified

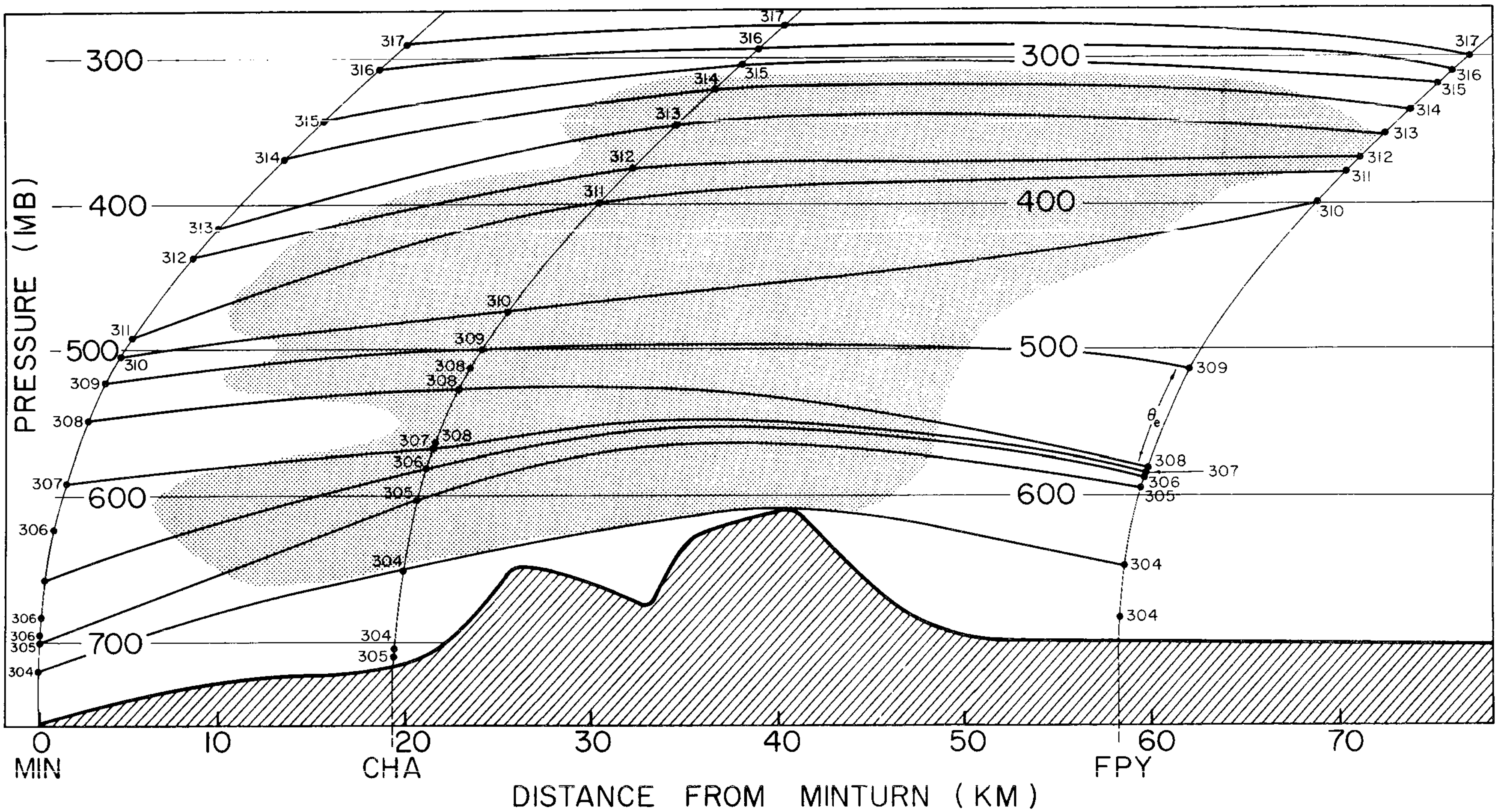
Station	Error T(°C)	Error RH(%)	(ΔC) MIN-CHA	(ΔC) CHA-FPY	(ΔC) MIN-FPY
CHA	0	5	-0.01	+0.02	----
CHA	0	10	-0.08	+0.10	----
CHA	1	0	-0.04	+0.06	----
CHA	5	0	-0.48	+0.44	----
All	1	0	-0.05	-0.03	-0.04
All	0	10	+0.09	-0.00	-0.04

The errors are generally small $-\Delta T = 5°C$ exceeds accepted radiosonde errors and do not destroy the validity of the curves in Figure 13.

4.4 Cloud Dimensions

Clouds resulting from the analysis described previously are of two different types. The first three times show substantial cloud while the last three times show little or no clouds (see Figures 11 and 12). The clouds are, in general, too small to be realistic. Three likely factors are involved. As mentioned earlier, the radiosondes never measured 100% humidity. The reasons for this are not in the scope of this paper but the radiosonde humidity data are known to be low, especially in clouds (Air Weather Service, 1955). Secondly, ice processes have been ignored. The third factor is significant mixing due to small scale motions. This factor is perhaps most important in the latter times as the mixing leads to a flattening of the isentropes. Along or in combination, these effects tend to reduce the cloud size determined by the analysis.

In an attempt to compensate for the above effects, the LCL is found using saturation with respect to ice (Figure 14). For the first three times, where significant clouds were predicted using saturation with respect to water, substantial increases in cloud sizes result. For the last three times, the changes are little or none. Unfortunately, there were no successful photographic observations or measurements of the cloud dimensions so that even during the period of stable flow the results cannot be verified.



15 JANUARY 1970 1500 M.S.T. ANALYSIS OF TRAJECTORIES AND CLOUDS DETERMINED USING SATURATION WITH RESPECT TO ICE

Figure 14. Same as Figure 11, but with saturation with respect to ice.

4.5 Cloud Efficiencies

Cloud efficiencies (ε) are obtained by dividing the values of the precipitation curve by the total condensation curve in Figure 13b. In case of negative or zero precipitation the efficiency is meaningless. This occurs at 1800 and 2100. At 0000 the snow had stopped at Minturn and Camp Hale and ridge top. (θ_e lapse rates at Camp Hale at 0000 were unstable). The meaning of the efficiency at 0000 is then uncertain. Resulting efficiencies are presented in Table III. These results show high cloud efficiencies for the period during which the snow was falling from the stable orographic cloud. At other times little information results.

TABLE III

Cloud Efficiencies
15 - 16 January, 1970

Time	0900	1200	1500	1800	2100	0000
ε	0.94	0.90	0.85	X	X	0.19

Another indicator of cloud efficiency is the distribution of condensate with temperature. Wintertime natural orographic clouds are thought to be inefficient at relatively warm cloud top temperatures due to a less than optimum number of active ice nuclei (Grant, et al., 1971). Addition of artificial ice nuclei would then increase the efficiency and snowfall of these clouds. The total percent rate of condensate of the five valid times are shown in Figure 15. Temperatures used here are the average channel temperatures of about - 10°C to -20°C (Fletcher, 1966).

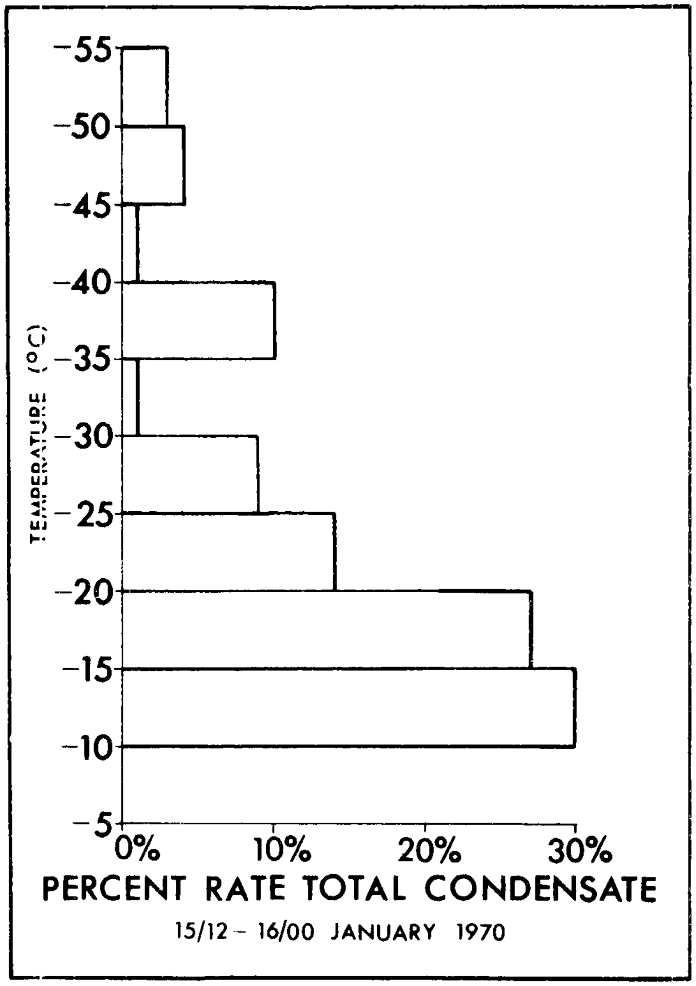


Figure 15. Distribution of the percent rate of total condensate with the mean θ_e channel temperature above Camp Hale.

The condensation seems to take place at relatively warm temperatures with active nuclei or crystals being supplied from colder parts of the cloud since no artificial nuclei are introduced into the cloud.

5.0 EVALUATION AND CONCLUSIONS

The water balance and cloud top temperature analyses have been done to help the evaluation and control of cold orographic cloud modification programs. How well have these analyses done what was expected of them? Finally, how can they be made better?

The answers to the above questions for the water budget analysis lie mainly in the quality of the data. The generally good precipitation and trajectory results imply that the rawinsonde and radiosonde data may be of satisfactory quality to perform the analysis. However, certain problems in this particular set of data make a quantitative assessment difficult. It was pointed out that the non-ideal location of the radiosondes forced three modifications in the analytical method. These changes were the increased subjectivity of the highest point in the trajectories, the assumption of negligible liquid water and ice in the cloud at Minturn and the required computation of cloud evaporation on the downslope side of the ridge. (The subjectivity induced in the trajectories is only important to the downslope evaporation part of the water balance computations. It enters into the ΔZ used in evaluating equation (7).) Certainly the analysis would be better off without these modifications.

Although the analysis is done six times, only one system is examined. Repetition would add much to the evaluation of the technique. Repetition on a cloud with a greater precipitation rate would be especially valuable. Such a cloud would have larger differences of water vapor between radiosonde locations. These differences would be larger compared to random measurement errors, thus making the water balance more accurate. Also, larger precipitation rates would most likely improve the comparison between computed and ground measured precipitation.

Trajectories found in the water balance seem realistic for the period of basically stable flow. During the period of what appears to be significant convective activity, the trajectory analysis cannot be expected to give the real air flow. At these times the water balance can still be performed, although perhaps with less confidence, because vapor that gets mixed out of one θ_e channel is mixed into another. The sum of all channels should be reasonably accurate. Another problem in the trajectory analysis is in determining the lowest air that goes over the ridge. Low level wind data near the ridge would help in this determination.

The attempt to estimate cloud dimensions did not work out very well. The problem is centered in the difficulty of determining when a parcel becomes saturated. The question of whether to use ice or water saturation exists, but a larger vector is in the radiosonde measurements. In all other aspects of the water balance analysis the differences between radiosondes are important so that systematic errors in radiosonde measurments tend to cancel. However, the lifted condensation level is found using only one sounding which is known to measure less vapor than actually exists in clouds. Until more accurate moisture data are available, estimation of cloud dimensions by the technique used cannot be accomplished.

Cloud efficiencies are important to the evaluation of orographic cloud modification. The values computed seem reasonable but are only as accurate as the water balance. Until improvements are made in the data the efficiencies computed can only be regarded as estimates.

The results of the water balance analyses are successful in a qualitative sense. Prospects for successful quantitative results seem good if the data can be improved and the unmodified analytical method can be used. Even so, the analysis would not be practical on an operational basis because of the large amount of aerological data needed. With the details of the water balance and flow over amountain ranges known, the ideas and observations behind the analysis can be incorporated into models.

Several conclusions relevant to the evaluation and control of modification project can be drawn from the work presented in this paper. When the analysis was begun there was a question concerning the ability to measure small differences in water vapor that occur on the small scales by radiosondes. Apparently, this can be done with reasonable success. An interesting result of the analysis is the flatness of the trajectories. The slope of the trajectories is less than the average slope of the ground. The implication is that not all the air on the windward side of the ridge goes directly over the ridge. Finally, the cloud changed with time from one with relatively smooth flow and general stability to one of significant buoyant motions. A similar transition has been seen in a detailed cloud top temperature analysis of a cloud in southwestern Colorado (Balick, 1971). More work will be needed to determine if this change is characteristic of orographic clouds in these areas. Still, this set of data shows that for the case examined an assumption of a steady state orographic cloud is not valid even on the scale of a few hours.

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