

## A CLOUD FREE VAULT

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### 1. INTRODUCTION

A severe squall line and several isolated storms were observed near Grover, Colorado, on 22 July 1973 by four instrumented aircraft and the NHRE storm monitoring network. The northern segment of the squall line was oriented parallel to the cloud level winds (i.e., NE-SW), while the southern segment was aligned north-south (Figures 1 and 2). The isolated storms were located southeast of this squall line.

Several small tornadoes and funnel clouds, large hail and a strong gust front were observed in association with the southern segment of the squall line. The isolated storms also developed strong gust fronts. The northern segment did not form a gust front, but instead, acquired a large visual "cloud free vault" between the precipitation curtain and the shelf-like updraft pedestal (Figures 3 and 4). This vault region appeared to have the same visual characteristics as the feature described by Marwitz (1972) for the Ft. Morgan storm and by Browning and Foote (1975) in the Fleming storm.

The vault on the Grover squall line expanded to a width of ~6 miles, a length of ~40 miles and extended vertically some 2000 feet above the updraft pedestal, i.e., LCL. The leading edge of this vault exhibited a well defined updraft pedestal. However, the most distinctive visual feature was the vault's "roof." The cloud bases composing the roof displayed a very ragged, scalloped appearance. Some observers might refer to these clouds as mammatus but when observed at close range from aircraft, they do not display mammatus characteristics. An extensive diffusion of sunlight shining through the roof indicated that the cloud layer capping the vault was very thin.

### 2. DATA ACQUISITION

Data were acquired using four instrumented aircraft, two S-band radars and the NHRE surface mesonet network.

The aircraft involved were the University of Wyoming's Queen Air, two NCAR Queen Airls and the NCAR Buffalo -- all equipped to measure the parameters of state. In addition, the Wyoming Queen Air had the capability of monitoring updraft velocities while the NCAR aircraft were instrumented to measure horizontal winds. The flight mission consisted of collecting data near cloud base in the inflow and outflow regions of the storm. The Wyoming

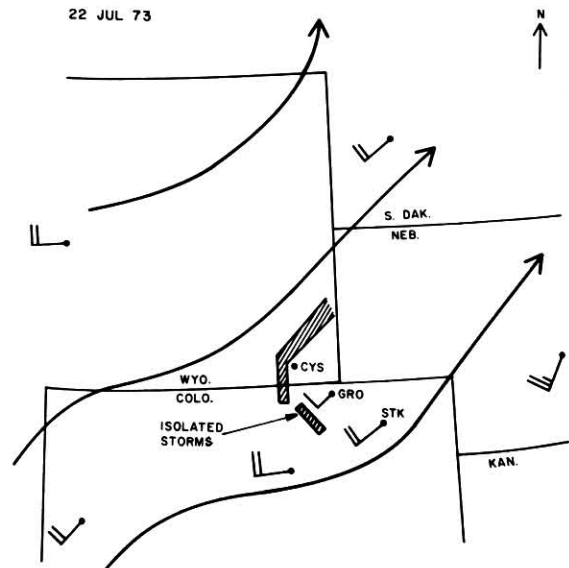


Figure 1. Colorado and surrounding states showing the 500 mb wind barbs and streamlines from 0600 MDT NWS summary. Wind data from Grover and Sterling, Colorado, 1630 MDT soundings are also shown. The squall line and the area of isolated storms are depicted schematically.

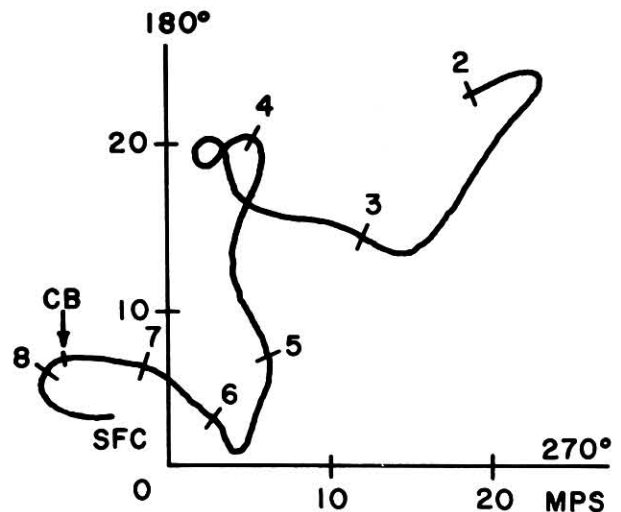


Figure 2. 1630 MDT hodograph from Sterling, Colorado. 100 mb incremented levels shown - CB refers to observed cloud base.

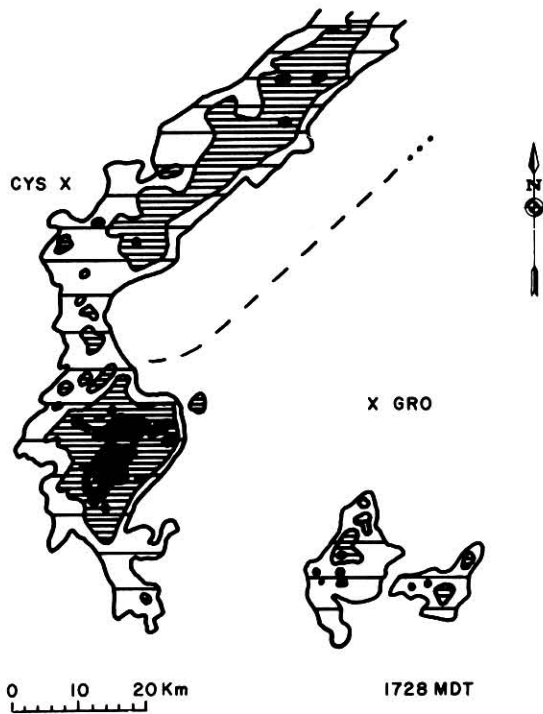


Figure 3. Cloud base PPI radar presentation taken from CHILL radar at Ft. Morgan, Colorado, at 1728 MDT. Contour intervals are 10 dBz and begin at 20 dBz. Dashed line represents the leading edge of the cloud free vault.

Queen Air also made several passes into the cloud free vault. A description of the aircraft and the 1973 flight mission can be found in the NHRE Operation Plan (1973).

The NHRE surface mesonet network consisted of 33 stations located east of Grover, Colorado, covering an area of ~1200 miles<sup>2</sup>. These stations recorded pressure, temperature, relative humidity and winds on strip charts. A detailed discussion of this surface network is presented in the NHRE Summary Report (1973).

Two S-band radars were operated during the study -- the NCAR radar at Grover, Colorado, and the CHILL radar at Ft. Morgan, Colorado. These systems are also described in detail in the NHRE Summary Report (1973).

In addition to the systems described above, four rawinsonde releases were carried out prior to and during the life of the storm -- two from Grover and two from Sterling, Colorado.

### 3. RESULTS

Proximity rawinsonde data (Figure 5) indicated that strong conditional instability was present. Moreover, the release of this instability was capped by a stable layer at cloud base. The height of cloud base was ~760 mb as determined by the Wyoming Queen Air. Updrafts near cloud base were negatively buoyant by 1 to 2C.

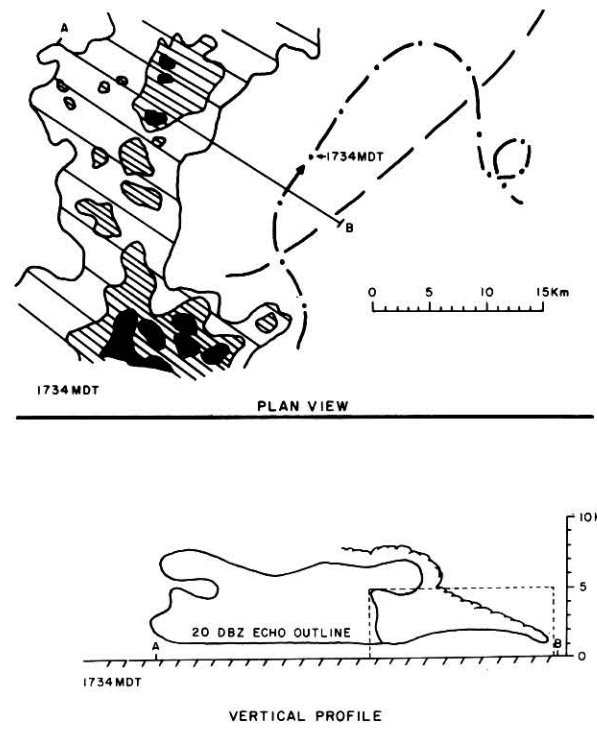


Figure 4. Plan view and vertical profiles of the storm at 1734 MDT. PPI radar echo from CHILL, Ft. Morgan. Dashed line represents the leading edge of the cloud free vault. Dot-dash line represents the flight path of the Wyoming aircraft from 1730 to 1743 MDT relative to the storm. The vertical profile is a composite of horizontal scans from 1734 to 1736 MDT along line A-B as indicated in the plan view.

Thermodynamic and kinematic data from three regions -- the inflow air, the air within the cloud free vault and the gust front air near the southern segment of the squall line -- were synthesized. A well defined boundary was observed between the inflow air and the air within and beneath the cloud free vault. This boundary was clearly established by data from the Wyoming aircraft. The vertical cross section in Figure 6 shows the boundary as indicated by strong horizontal gradients of specific humidity ( $q$ ), potential temperature ( $\theta$ ), equivalent potential temperature ( $\theta_e$ ) and virtual potential temperature ( $\theta^*$ ). It was also found that the air within the vault contained no significant updrafts or downdrafts and was generally quiescent and non-turbulent except at the boundary where moderate turbulence was recorded.

Examination of Figure 6 leads one to speculate on the source of air within the cloud free vault. Of the several possibilities, most can be eliminated immediately. For example, the vault air could not have entered directly from the environment ahead of the storm, because of differences in the derived state parameters across the boundary. Neither could the air have descended through the roof of the vault. Were this the case, the vault roof would have evaporated. Since  $\theta_e$  was not the same across the

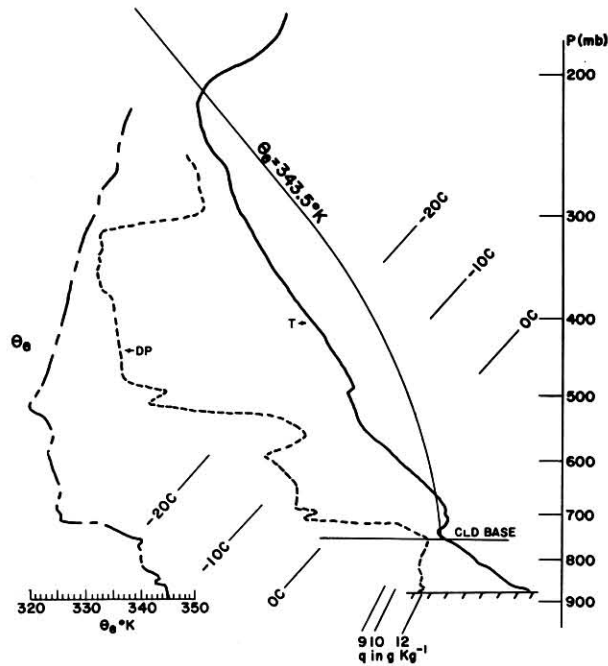


Figure 5. Sterling, Colorado, sounding at 1620 MDT plotted on a skew T-ln P diagram. Temperature (T) and dew point (DP) traces indicated.  $\theta_e$  at cloud base was 343.5K. Also shown is the vertical profile of  $\theta_e$ .

boundary, the vault air was not simply a result of a pseudo-adiabatic precipitation process ( $\theta_e = \text{constant}$ ). As may be seen Figure 6 indicates a difference in  $\theta_e$  of 12C between the inflow and vault air. The horizontal and vertical wind data from the NCAR aircraft (not presented) showed the cloud pedestal to be an updraft region. It was therefore concluded that the air within the vault had its primary source in the inflow, but had undergone limited modification through mixing with entrained mid-level air.

In contrast, synthesis of mesonet and aircraft data from storm components near the southern end of this storm system revealed large contrasts between the subcloud air ahead of the storms and the subcloud air behind the gust fronts (Figures 7 and 8). The surface analysis of  $\theta_e$  at 1838 MDT (Figure 7) showed a core of very low  $\theta_e$  values ( $\theta_e = 321\text{K}$ ) associated with the gust front air. Due to a lack of radar data from 1800 to 1855 MDT it was not possible to attribute this core of low  $\theta_e$  air a particular storm cell. However, comparison of 1855 MDT radar data with data from the NCAR aircraft showed that this core of low  $\theta_e$  air had as its origin components of the storm system which were not oriented parallel to the mid-level winds. These surface values of low  $\theta_e$  were similar to values encountered at  $\sim 1000$  feet AGL by the three NCAR aircraft at the same time and location. Comparison of  $\theta_e$  values at the surface and from the aircraft with the  $\theta_e$  vertical profile in Figure 5 shows that the gust fronts produced by the southern storms of this system contained  $\theta_e$  values corresponding to air near 500 mb. In fact, it may be seen that only a shallow layer

near 500 mb had such low  $\theta_e$  values. These data were interpreted as indicating that a portion of the gust front air had its origin near 500 mb. It may also be noted that as a consequence of significant entrainment,  $\theta^*$  anomalies across the gust front were as high as 8C (Figure 8). Since  $\theta^*$  is inversely proportional to density, the density gradient was much greater for the storms which produced a gust front as compared to the northern segment of the squall line which produced the cloud free vault.

On the basis of the data available, it is speculated that the occurrence of the cloud free vault and the lack of severe weather along the northern segment of the squall line could be attributed to minimized entrainment. Lacking entrainment, the outflow failed to gain sufficient density to overcome the momentum of the inflow air. Thus, the outflow air did not initiate a gust front, but instead, accumulated between the precipitation curtain and the updraft pedestal. Lacking a gust front the inflow received no dynamic assistance. On the contrary, it appears that the cloud free vault continued to expand and separate the inflow from the main echo until finally the storm dissipated. In contrast, the southern components of the storm system, which (by their orientation to mid-cloud winds) experienced stronger entrainment and developed into more severe storms.

#### 4. THE IMPORTANCE OF CLOUD FREE VAULTS

The presence of a cloud free vault on a squall line is postulated as being an indicator of insufficient entrainment for gust front formation. The case study suggests that when a squall line is oriented parallel to the mid-level winds there is reason to expect that the squall line will not reach as high a level of severity as one oriented more normally to these winds. The presence of the vault indicates the eventual dissipation of squall line type storms. It has, therefore, a short term predictive value with respect to storm severity - especially as applied to gust fronts.

Furthermore, it was pointed out that as a cloud free vault expands, it will eventually disassociate the inflow region from the main body of the storm.

These two findings may have ramifications to squall line seeding by rocketry. Attempts to seed a squall line storm containing a cloud free vault by shooting vertically pointed rockets in the vicinity of the vault will probably fail. The seeding material would likely be dispersed in clear sky above the roof of the cloud free vault.

#### ACKNOWLEDGMENTS

These data were collected while participating in the National Hail Research Experiment (NHRE). The NHRE is sponsored by the National Science Foundation (NSF).

#### REFERENCES

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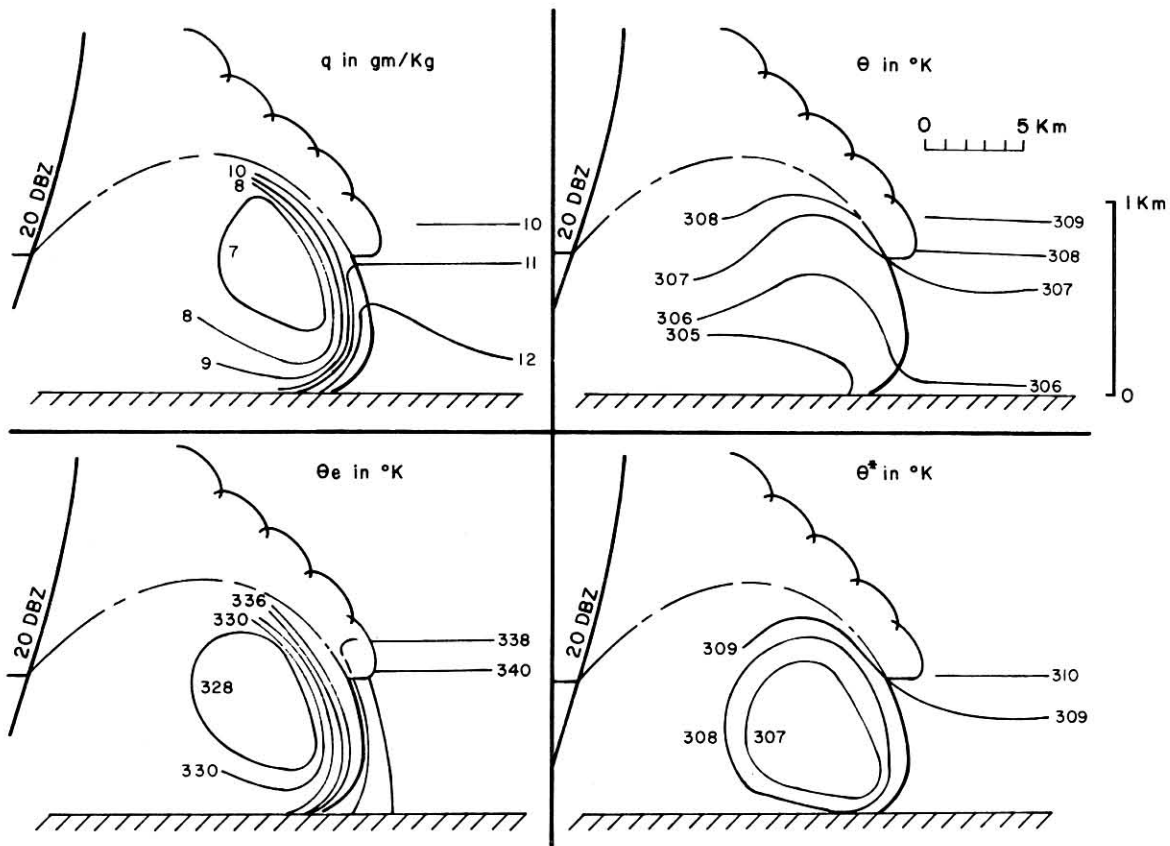


Figure 6. Vertical cross section (scaled 10:1) of the cloud free vault at ~1800 MDT. The region shown is outlined by the dotted rectangle in Figure 4b. The leading edge (with respect to storm motion) of the 20 dBz echo is shown as well as the visual cloud vault. The heavy black line on the nose of the vault represents the boundary between the vault air and the inflow air. Thin black lines in each of the four parts show the fields of specific humidity ( $q$ ), potential temperature ( $\theta$ ), equivalent potential temperature ( $\theta_e$ ) and virtual potential temperature ( $\theta^*$ ).

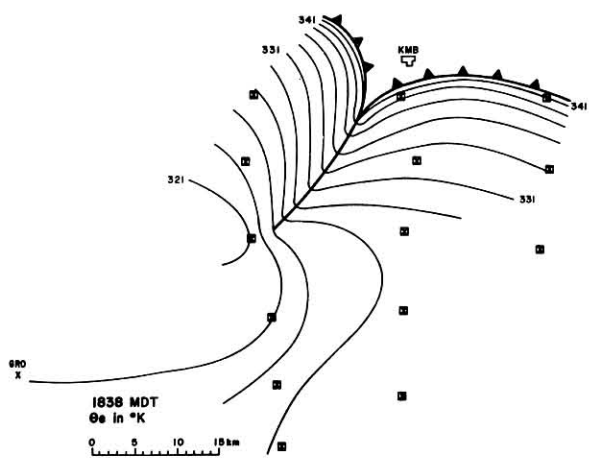


Figure 7. Analysis of  $\theta_e$  at 1838 MDT at the surface based on continuous data from 14 NHRE meso-network stations. Frontal positions determined by space to time conversions of this same data.

Hail Research Experiment Tech. Report No. 75/1, May, 27-34.

Marwitz, J. D., 1972: The structure and motion of severe hailstorms. Part III, severely sheared storms. *J. Appl. Meteor.*, 11, 189-201.

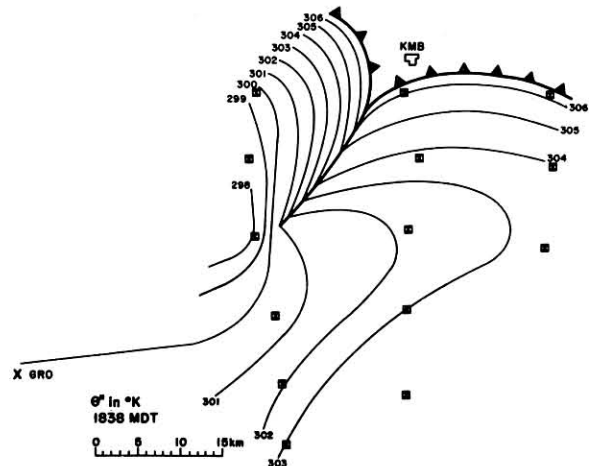


Figure 8. Analysis of  $\theta^*$  at 1838 MDT at the surface based on continuous data from 14 NHRE meso-network stations. Frontal positions determined by space to time conversions of this same data.

National Hail Research Experiment, 1973: Summary Report, Data Report No. 73/2, December, 7-8; 33-42.

National Hail Research Experiment, 1973: Operations Plan 1973, 34-50; Appendix A.