Trajectories Within the Weak Echo Regions of Hailstorms

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ABSTRACT

Three-dimensional tracks of 21 slow-fall chaff packets have been obtained while the packets were rising in the weak echo regions of eight separate Colorado hailstorms. The chaff packets were released at cloud base in the strong smooth updrafts and tracked with a M-33 track radar. In many cases the chaff was released from an instrumented aircraft. From these data it is shown that the inflow air often has its origin near the surface, the inflow air is typically negatively buoyant below cloud base, there exists a significant non-hydrostatic pressure perturbation in most severe storms, and a vertical velocity maximum typically exists within the weak echo region.

1. Introduction

Since 1970 attempts have been made to release and track slow-fall chaff (<0.30 m sec^{-1}) in the organized updrafts of hailstorms on the High Plains. Twenty-one packets of chaff have been tracked within the weak echo region (WER) of eight separate storms. The technique consisted of releasing a packet of chaff from an aircraft while flying in the strong, smooth updrafts near cloud base of large thunderstorms. In five of the eight storms, the chaff packets were released from our instrumented aircraft which contained a digital airborne meteorological system. At the instant of chaff release a coded event was recorded on the data system so that the time and meteorological parameters were known for each chaff packet. The packets of chaff were tracked by a M-33 track radar. During 1970 and 1971 the chaff locations were manually recorded at 1-min intervals. Observations at 30-sec intervals were obtained in 1972. The characteristics of the radar and storms were such that one knew unambiguously when the chaff entered an echo from the storm which was greater than the echo from the chaff ($\sim$30 dBZ). The automatic tracking gate would begin rapidly moving through the storm.

Although the M-33 track radar has a 1.0° conical beam, the azimuth and elevation angles are accurate to $\sim$0.2° since the beam is conically scanned during tracking. The pulse length is 75 m but since the range notch is also scanned, the accuracy is $\sim$30 m (Booker, *et al.*, 1967). At a range of 30 km the tracking beam volume is $\sim\pi 100^2 \times 30$ m^3. Within a few minutes after release experience indicates that the chaff diffuses over a volume greater than the tracking beam volume.

TABLE 1. Summary of individual chaff tracks obtained in northeastern Colorado.

Release time (LDT)	Maximum vertical velocity (m sec^{-1})	Height above cloud base of maximum vertical velocity (km)
15 June 1970		
1636	27	4.0
1653	22	3.5
1707	19	3.5
1720	10	—
18 June 1970		
1516	15	—
1627	15	—
1638	11	—
9 July 1971		
1623	15	3.0
1654	16	3.0
1717	17	3.0
15 July 1971		
1542	15	1.7
1555	17	1.7
1606	21	1.7
1654	13	1.7
26 May 1972		
1944	14	2.6
21 June 1972		
1416	24	—
1432	15	2.6
1515	9	1.7
25 June 1972		
1601	26	4.2
1645	21	1.9
19 July 1972		
1740	17	3.0

Consideration was given to the possibility that the chaff would accrete an appreciable mass of supercooled water which would then freeze and thereby affect the fallspeed of the chaff. If one assumes a liquid water concentration of 2 gm m^{-3} and that it is collected by a falling fiber of chaff (diameter 180 μm) at 100% collec-

Table 2. Summary of updraft data obtained in the USSR and northeastern Colorado.

	N	W_{mx} (m sec^{-1}) $\bar{x}/\sigma$	H_{mx} (km) $\bar{x}/\sigma$
Cumulus and cumulus mediocris	32	7.6/1.7	1.0/0.1
Cumulus congestus and cumulonimbus (no precipitation)	17	14.1/3.6	2.1/0.7
Cumulonimbus (with precipitation)	7	13.4/3.2	1.6/0.6
Colorado hailstorms	16	17.7/4.7	2.7/0.9

tion efficiency, the chaff would double in mass in approximately 3 min. Because the chaff was rarely tracked for more than 3–4 min above the freezing level and because doubling of the mass would increase the fallspeed of the chaff by 1 m sec^{-1}, it did not seem that icing was significant. If one tracked the chaff in excess of 5 min above the freezing level, icing would become important. The chaff tracks are thus viewed as three-dimensional trajectories of air parcels.

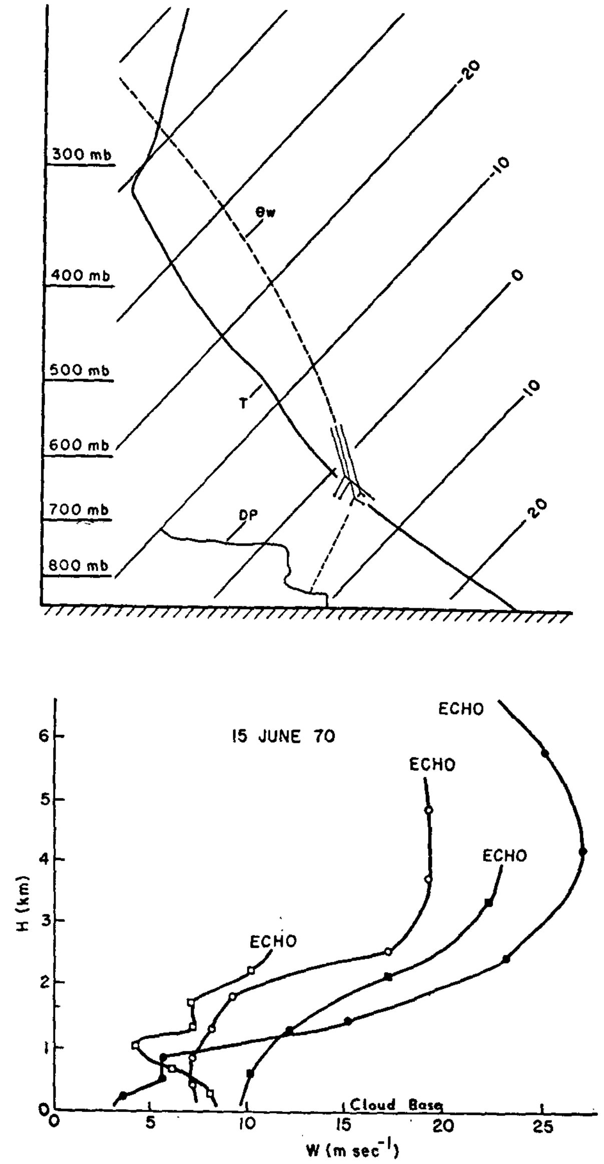


Fig. 1. Radiosonde data (a) and vertical velocity profiles (b) for 15 June 1970. Radiosonde data are plotted on skew T-log$p$ diagrams with the pressure, temperature and dew point indicated for each chaff release. The individual data points on the velocity profiles are at 1-min intervals. The vertical scales are geometrically equal.

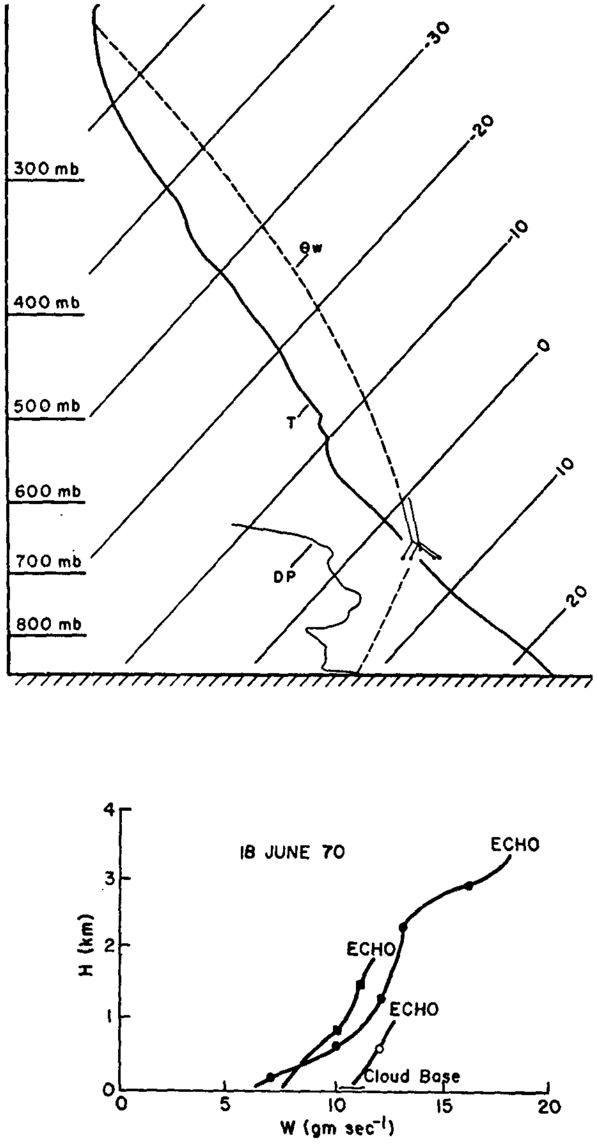


Fig. 2. Same as Fig. 1 except for 18 June 1970.

2. Results of chaff data

a. *Vertical velocity profiles*

The results of the individual chaff tracks are summarized in Table 1. A maximum updraft was observed within the WER before the chaff entered the storm echo in each storm except one (18 June 1970). The mean value of the maximum updrafts for 16 chaff tracks

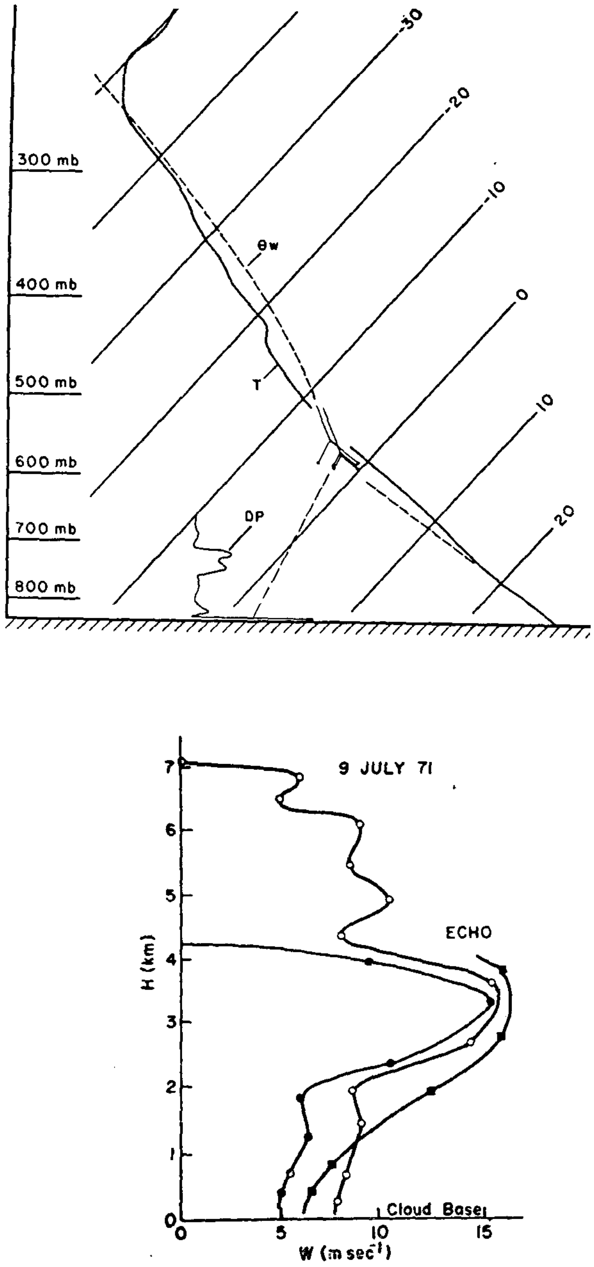


FIG. 3. Same as Fig. 1 except for 9 July 1971.

obtained in seven different storms was 18 m sec^{-1}, while the mean height of the maximum updrafts occurred 2.7 km above cloud base (see Table 2). The updraft profiles for those storms in which the chaff was released from our instrumented aircraft are presented in Figs. 1b–5b. Although each storm has certain unique characteristics and, therefore, generalizations are somewhat hazardous, the following points were noted: 1) in seven storms out of eight, maximum updrafts occurred within the WER and from 1–4 km above cloud base; 2) in three storms out of five in which multiple chaff tracks were obtained, the height of the maximum updraft did not vary appreciably even though some of the tracks were obtained over one hour apart; and 3) the maximum updrafts varied from 10–25 m sec^{-1} and sometimes varied by a factor of 2 within an individual storm even though the height of the maximum updraft did not vary.

Soviet scientists have obtained similar kinds of data in convective storms. Their results were obtained by towing zero lift balloons and corner reflectors to cloud base by means of other lifting balloons. The zero lift balloons were separated near cloud base and tracked by radar as they followed the air trajectory. Strong similarities among the various tracks are evident when one inspects their individual tracks. The diagram presented by Sulakvelidze *et al.* (1967) containing the averaged updraft profiles is reproduced in Fig. 6. A summary of their results are presented in Table 2. The Soviet observations were the first to reveal the

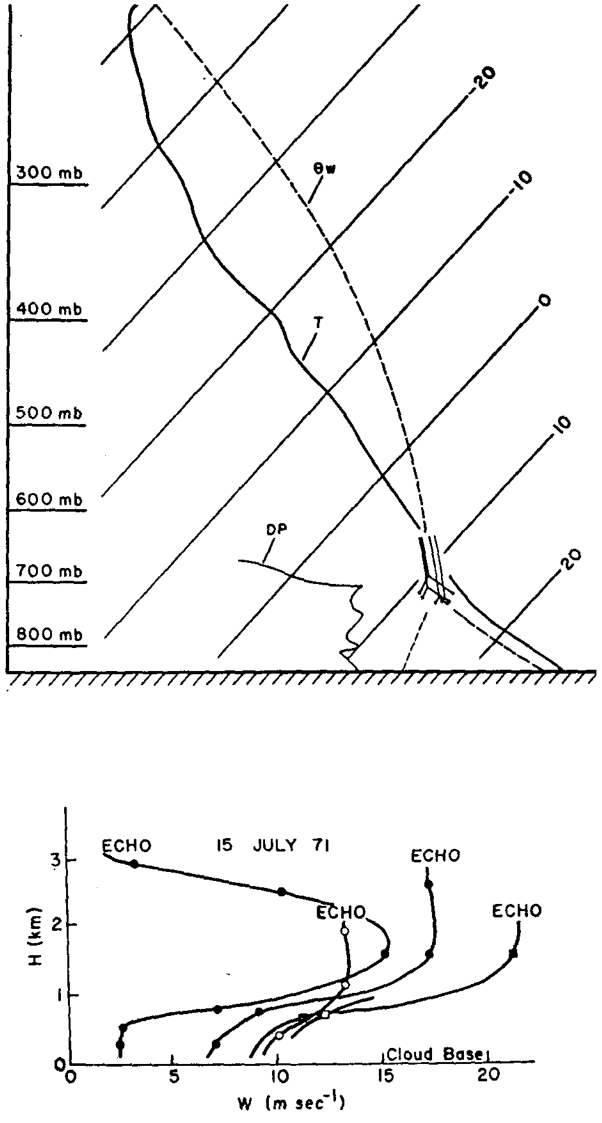


FIG. 4. Same as Fig. 1 except for 15 July 1971.

low magnitude and low height of the maximum up-updrafts. From 32 tracks in cumulus and cumulus mediocris, the mean ($\bar{x}$) updraft maximum (W_{mx}) was 7.6 m sec^{-1} with a low standard deviation (σ) of 1.7 m sec^{-1}. The mean height above cloud base of the maximum updraft (H_{mx}) was 1.0 km with a standard deviation of 0.1 km. The maximum updraft and height were approximately double (14 m sec^{-1}) for cumulus congestus and cumulonimbus and still displayed a surprisingly low standard deviation. These new vertical velocity observations agree very well with those previously obtained in the Soviet Union.

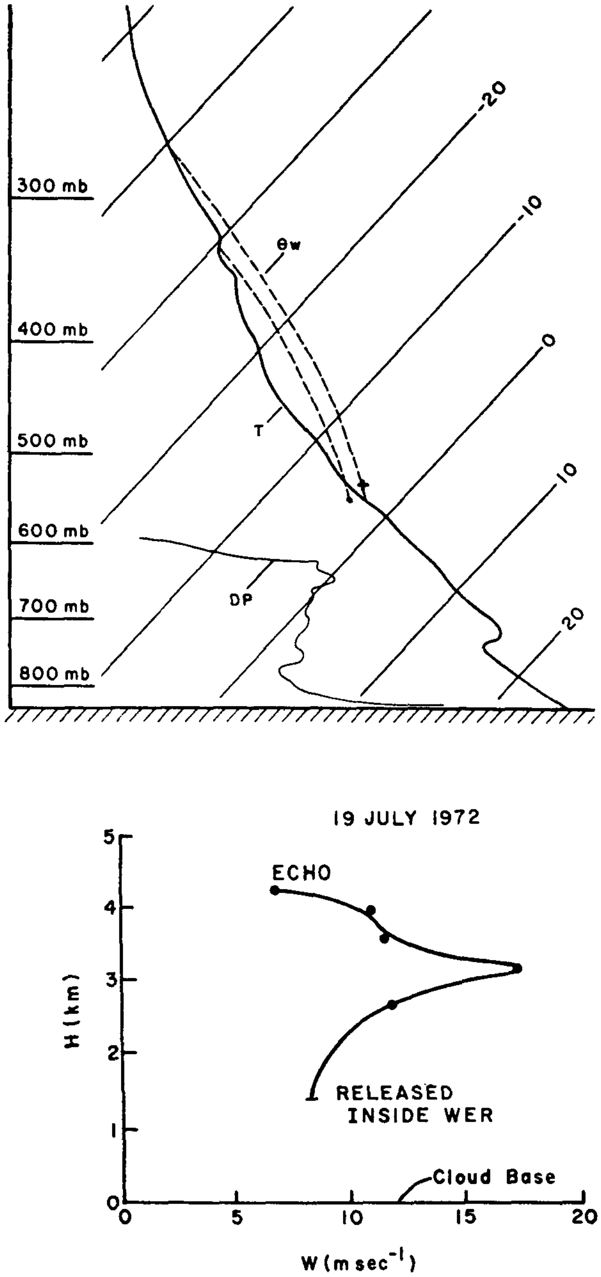


Fig. 5. Same as Fig. 1 except for 19 July 1972. Data points are at 30-sec intervals and chaff was released within the WER and 1.4 km above cloud base. The temperature profile is denoted by a dot when the chaff was released and by a plus sign approximately 20 sec later while still within the WER.

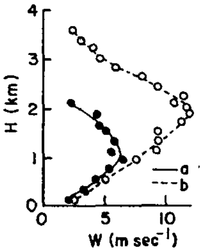


Fig. 6. Averaged updraft profiles above cloud base for cumulus and cumulus mediocris (open circles) and for cumulus congestus and cumulonimbus (solid circles). [After Sulakvelidze *et al.* (1967).]

b. Horizontal trajectories

Two types of horizontal chaff trajectories have been observed from the storms in which multiple chaff tracks were obtained. The first type was one in which the directions and speeds were relatively constant along each trajectory and for each chaff track. This observation suggests that there are certain storms which have a horizontal velocity vector within the WER which is relatively constant both in space and time. This type occurred on 18 June 1970, 9 July 1971 and 21 June 1972. It may be seen from Table 1 that the tracks were distributed over a 1-hr period in all three cases. The horizontal trajectories for the storm of 21 June

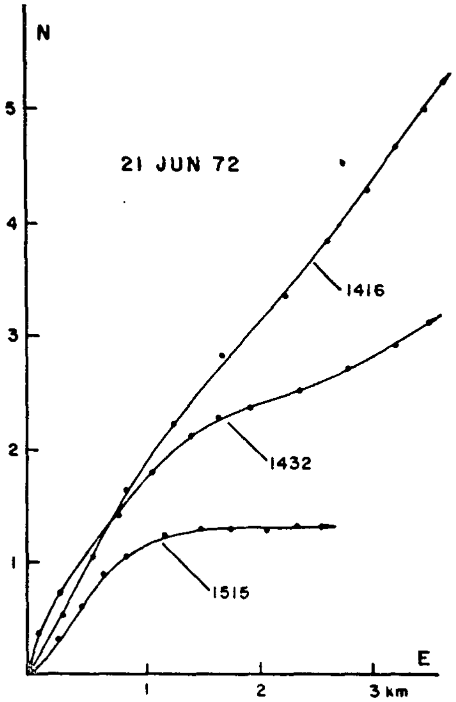


Fig. 7. Horizontal chaff trajectories for 21 June 1972. The individual data points on each trajectory are at 30-sec intervals.

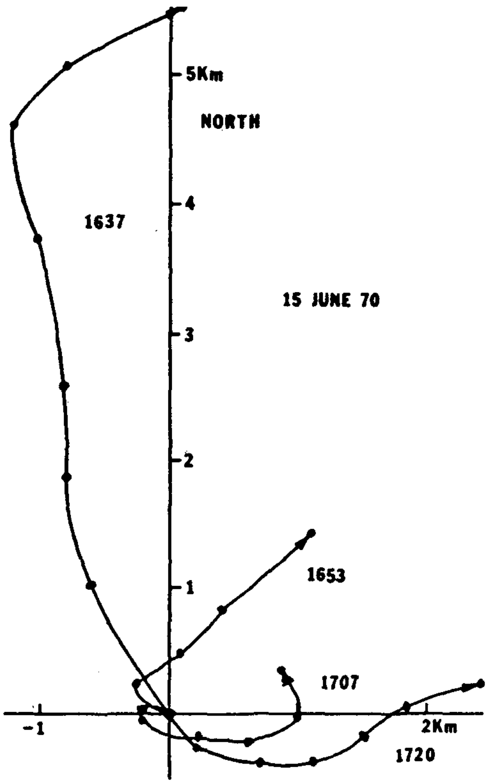


FIG. 8. Same as Fig. 7 except for 15 June 1970.

1972 are presented in Fig. 7. The other type of trajectory was one in which the velocity vector varied in space and/or time. The 15 June 1970 case was an example of the latter type (see Fig. 8). Until we are able to obtain simultaneous tracks of more than one chaff packet, we cannot isolate the cause of the variation.

The chaff data have shown that a propagational component of echo motion exists and is sometimes equivalent in magnitude to the translational component (Marwitz, 1972a). The chaff tracks produce a reasonable estimate of the translational component (especially in the case in which the velocity vector is constant in space and time). The difference between the chaff motion and the echo motion is attributed to propagation. Using the available data for 18 June 1970, Marwitz (1972a) deduced that the storm had a propagation vector from 340° at 15 m sec^{-1}. The available data for the 21 June 1972 case suggests that the storm propagated toward the south-southeast at 15 m sec^{-1} (see Fig. 9).

The horizontal winds within the WER as observed by the chaff on 15 June 1970 and 21 June 1972 were observed to exceed the environmental winds near cloud base by a substantial amount. The environmental winds for 21 June 1972 are shown in Fig. 9. There is no way one can exchange or mix environmental momentum to explain the observed winds within the WER. Substantial horizontal acceleration of the low-level inflow air must have occurred.

a. *Meteorological parameters at cloud base*

The University of Wyoming operated a modified C45H Beechcraft type aircraft during 1970 and 1971 and a B80 Queen Air type aircraft in 1972. Both aircraft were equipped with digital data acquisition sys-

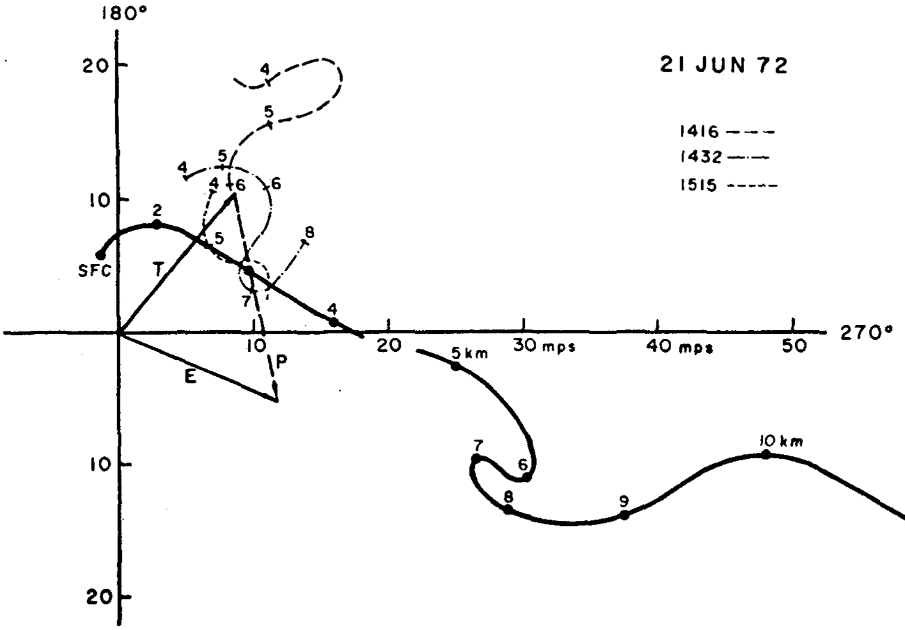


FIG. 9. Hodograph of environmental winds (dark line) and horizontal motion of chaff within the weak echo region (thin dashed and dotted lines) for 21 June 1972. T and P denote translational and propagational component of echo (E) motion, respectively.

tems. The recorded variables included pressure altitude, heading, VOR, DME, manifold pressure, indicated airspeed, rate-of-climb, temperature, dew point, turbulence and time registration. In addition, the systems were also capable of recording ten separate coded events for each of three crew members. The system used for measuring turbulence has been described by MacCready (1962). The device computes $\epsilon^{\frac{1}{3}}\rho\rho_0^{-1}$, where ρ is the air density at flight altitude, ρ_0 the air density at sea level, and ϵ the dissipation rate of turbulent energy.

The temperature, dew point and pressure were calibrated in 1971 and 1972 by flying by an instrumented tower and by flying intercomparison flights with the NCAR Buffalo aircraft. One tower fly-by and one long (~1 hr) intercomparison flight were accomplished in 1971 and 1972 (Duchon *et al.*, 1973). In addition, several short (~10 min) intercomparison flights were obtained during the season when the opportunity presented itself. The temperature, dew point and pressure agreed within ±0.4C, ±0.5C and ±3 mb, respectively, on each check. Even though there were no in-flight calibrations in 1970, the data system and ground calibrations were the same as in 1971 and 1972. It is therefore assumed that the accuracy of the system in 1970 was equivalent to that in subsequent years.

Fig. 10 contains six segments of the flight on the Fort Morgan storm of 15 June 1970 (Marwitz, 1972b). The square block near the center of each segment is the location of the lowest potential temperature. Fig. 11 contains time series of potential temperature θ (a), specific humidity q (b), turbulence, $\rho\rho_0^{-1}\epsilon^{\frac{1}{3}}$ (c), isobaric equivalent potential temperature θ_E (d), and vertical velocities W (e). The vertical velocities were determined by adjusting the recorded rate-of-climb for clear air climb or descent based on the indicated airspeed and manifold pressure. During the three flight segments shown, the indicated airspeed changed at a rate less than 10 kt (30 sec)$^{-1}$. The other flight segments were not shown because the airspeed changes were too large. The release times of three packets of chaff are indicated. It may be noted from Figs. 11a, b and c that the updrafts at cloud base are cold, moist and smooth. A comparison of virtual temperatures in the environment against those in the updrafts clearly indicates that the updrafts are negatively buoyant by 1–2C. Negatively buoyant updrafts are a common phenomenon in severe hailstorms in northeastern Colorado and has been clearly documented on several cases.

Fig. 11d contains the time series of θ_E. The θ_E in the updrafts and an environmental sounding uniquely define the amount of positive energy released during a pseudo-adiabatic ascent. The higher the θ_E the greater the positive energy. Fig. 11d shows that even though the updrafts are negatively buoyant at cloud base, the highest θ_E, and hence, the highest positive energy release, occurs in the updraft air.

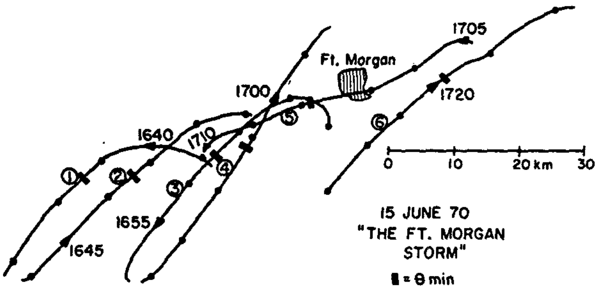


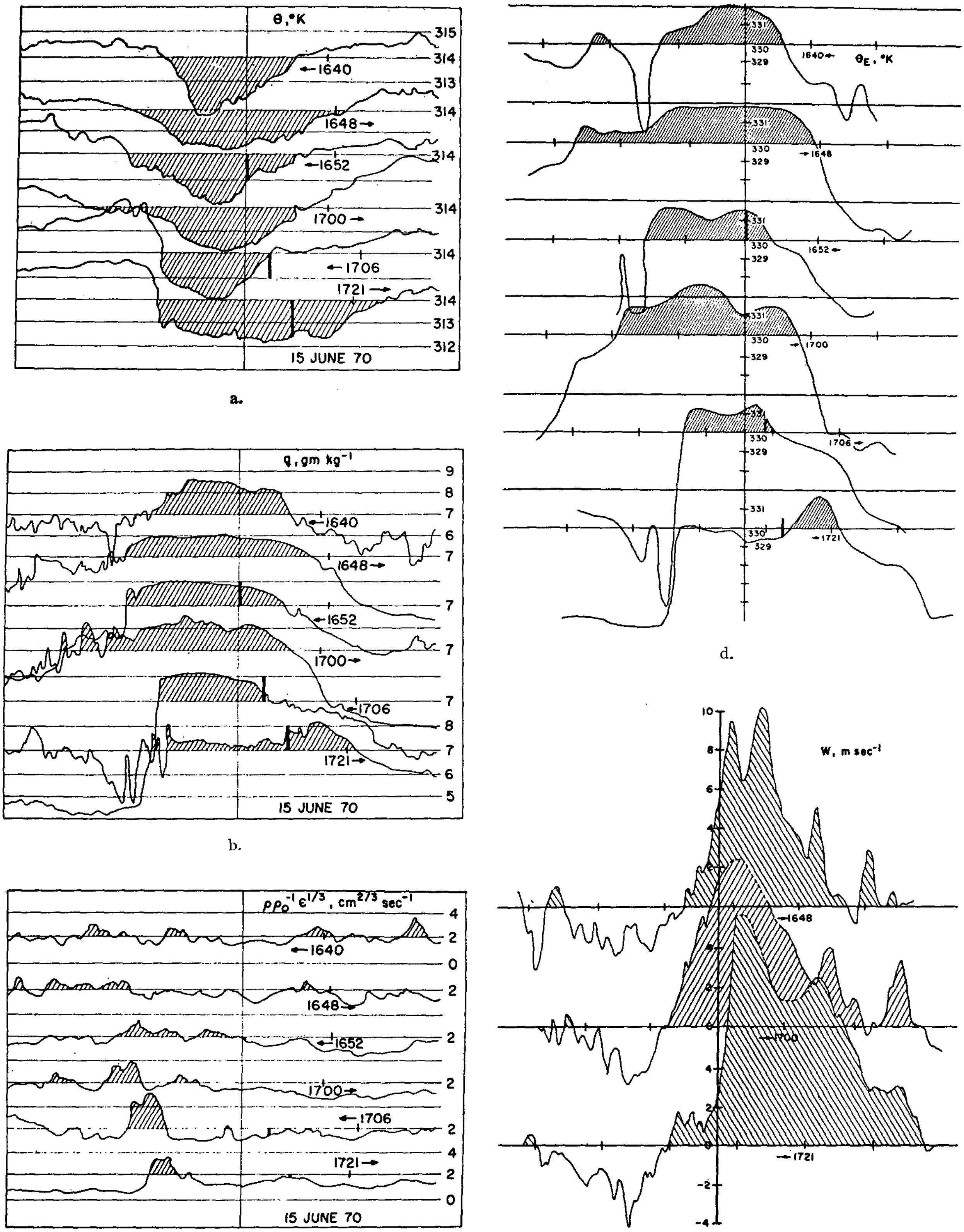
FIG. 10. Segments of the flight track for the University of Wyoming aircraft for 15 June 1970. The square block near the center of each segment denotes the location of the lowest potential temperature. The time marks are at 1-min intervals.

b. Radiosonde data

In 1970 two radiosondes were released daily from the Fort Morgan airport (0600 and 1000 MDT). In 1971 and 1972 from four to six radiosondes were released from four separate locations in northeastern Colorado. In each case a sounding has been chosen because the available observations indicated that it best represented the inflow and environmental air mass. For example, for 15 June 1970 the 1700 sounding from Denver was chosen to represent the environmental air mass above cloud base and the subcloud air was assumed to be dry adiabatic above the observed maximum temperature at the surface.

The environmental soundings and the observed temperature, dew point and pressure for each packet of chaff which was released from our aircraft are presented in Figs. 1a–5a. The data on each case clearly indicates that the updraft air at cloud base had its origin very near the surface. This has been observed many times and seems to be quite reasonable. The more important observation is that every case (except 18 June 1970 again) revealed that the air at cloud base was negatively buoyant. Although the data in Fig. 1a for 15 June 1970 indicated the updrafts were buoyant, the aircraft data in the local environment (Fig. 11) clearly indicated negative buoyance. The Denver radiosonde used for this case is probably not representative of the subcloud environmental air.

One is not much encouraged to compare the observed vertical velocity profiles with those predicted by models driven by buoyancy alone. This is especially so when observing such cases as 15 June 1970 (Fig. 1) where the observed vertical velocities varied from 10 to 21 m sec^{-1} at 2.0 km above cloud base while the amount of positive energy released varied by less than 10%. In fact, the *highest* θ_W was recorded for the *slowest* chaff. The case for 15 July 1971 (Fig. 4) is even more sobering in that one-dimensional models will predict the maximum vertical velocities to occur ~8 km above cloud base when, in fact, maximum vertical velocities were observed 1.7 km above cloud base. On the other hand, it is clear that even using the unentrained parcel theory,



a.

b.

c.

d.

e.

Fig. 11. Time series of the indicated parameters recorded by aircraft during flight segments shown in Fig. 10. Time marks are at 1-min intervals with time inverted on alternate flight segments such that southwest is on the left margin.

one would *under*-predict the observed vertical velocities for 9 July 1971 (Fig. 3) and 19 July 1972 (Fig. 4).

An important deduction which has become quite evident from the chaff data is that certain storms develop a substantial pressure perturbation. The horizontal pressure perturbation in the form of a meso-low acts to accelerate the low-level inflow air toward the storm such that horizontal velocities are sometimes observed which do not exist in the environment [see Fig. 11 in Marwitz (1972b) and Fig. 9 in this article]. A non-hydrostatic vertical pressure gradient is also present in certain storms to transport the negatively buoyant surface air to a level above cloud base where it becomes buoyant. Undoubtedly the cold air outflow often forces the surface air aloft but if this were the only process at work in negatively buoyant air, then the vertical velocity near cloud base would decrease until the air parcel became buoyant. In almost every case the vertical velocity began to increase from its release altitude despite a negative buoyant force. The existence of a positive non-hydrostatic pressure gradient is the only explanation. Pressure perturbations at the surface were first observed by Stout (1957). More detailed observations have shown that the meso-low exists in the inflow region and ahead of the gust front (Fujita, 1963; Barnes, 1972). Thus, the meso-low can be partly due to the weak echo region being a "hot column" and partly due to the hydrodynamic interaction analogy presented by Newton (1963). The non-hydrostatic pressure field inside the WER (whose existence the chaff data has now revealed) is not the same as that discussed by Newton. He assumed a solid cylinder analogy which produces a non-hydrostatic pressure field *outside* of the storm. Van Thullenar (1960) deduced the existence of a non-hydrostatic pressure field inside the updraft area of severe thunderstorms based on a theoretical argument. Fujita (1963) has applied van Thullenar's equation to Browning and Ludlam's (1962) Wokingham storm. A pressure excess of 2 mb and a deficit of 4 mb were required to produce a maximum updraft of 30 m sec^{-1} and a downdraft of 20 m sec^{-1}.

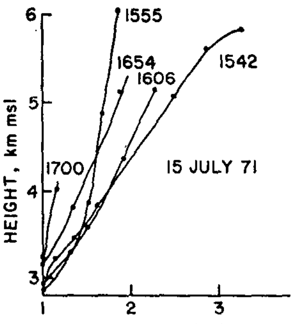


Fig. 12. Height of chaff vs length along horizontal trajectory for 15 July 1971, showing the local slope of the air trajectories. The individual data points are at 1-min intervals.

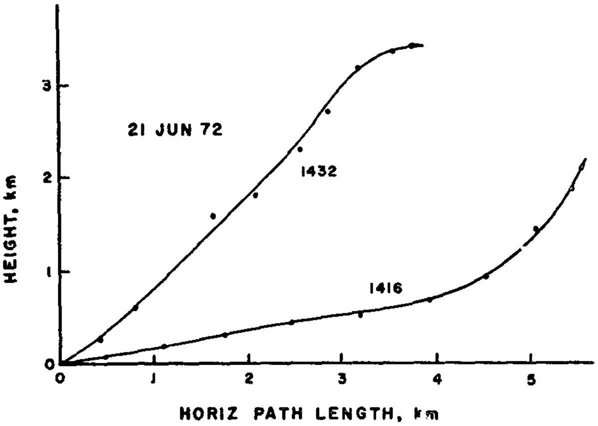


Fig. 13. Same as Fig. 12 for 21 June 1972 with data points at 30-sec intervals.

An apparent inconsistency exists in the data for 15 July 1971 (Fig. 4). The potential temperature was 2C *colder* while the specific humidity was 2 gm kg^{-1} *higher* than any observed in the subcloud environment. This observation was supported by the other available radiosondes as well as a line of 11 hygrothermographs over which the storm passed. The hygrothermographs were calibrated twice each day. The origin of the inflow air is not clear. We propose that the explanation of the apparent inconsistency was that a substantial amount of downdraft air in which evaporative cooling had occurred was recirculated and mixed into the updrafts. A more careful set of observations are required to verify this tentative explanation.

c. *Slopes of updrafts*

The slope of the rising air parcels within severe thunderstorms has often been predicted but these are the first direct observations available. Since the chaff tracks approximate a three-dimensional trajectory of the rising air, the slopes of the updrafts were computed for each chaff track. The slope of the updrafts for 15 July 1971 and 21 June 1972 are presented in Figs. 12 and 13, respectively. The height at various times is plotted on the ordinate with path length on the abscissa. Since these are on a 1:1 scale, the local slope is presented directly. Based on the results thus far obtained, the slopes vary from 0° to 90° with 30° to 60° being most common. Because the slope of the updrafts is the resultant vector of the vertical and horizontal velocities, one must accurately predict both vectors in order to predict the slope. Both vectors are significantly affected by non-hydrostatic pressure perturbations. Until we are able to predict or parameterize the non-hydrostatic pressure fields, we cannot accurately predict the slopes of updrafts.

4. Summary

Precise three-dimensional trajectories of 21 packets of chaff have been obtained within the WER of eight severe thunderstorms. The trajectories were obtained by releasing individual packets of chaff from an aircraft while flying at cloud base in the organized updraft region. The packets were tracked with an M-33 track radar. For five of the storms the aircraft was equipped with a well-calibrated meteorological recording system so that the state parameters were known.

Since the fallspeed of the chaff was low (<0.30 m sec^{-1}) and icing did not appear to significantly affect the fallspeed during the short period in which the chaff was tracked above the freezing level, the chaff trajectories were viewed as air parcel trajectories.

The chaff data have confirmed earlier, similar-type data by Soviet scientists in which maximum vertical velocities were observed within the WER (10–25 m sec^{-1}) and at low altitudes (1–4 km above cloud base). The horizontal velocities of the air within the WER as measured by the chaff were sometimes substantially greater than the environmental winds which indicates the inflow air had undergone acceleration. The aircraft data at cloud base revealed the updrafts to be typically cool, moist and smooth. Even though the updrafts are often negatively buoyant at cloud base, they contain the highest wet bulb potential temperature and, therefore, the greatest positive energy for release above cloud base. The horizontal acceleration of the inflow air, the vertical acceleration of the air directly above cloud base in the presence of a negative buoyant force, and the substantial differences between the observed vertical velocity profiles and what would be predicted using buoyancy as the driving force all point to the existence of a non-hydrostatic pressure perturbation in most severe thunderstorms. Since the non-hydrostatic pressure fields affect both the horizontal and vertical velocities, we cannot reliably predict the slopes of updrafts.

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REFERENCES

Barnes, S. L., 1972: Morphology of two tornadic storms: An analysis of NSSL data on 30 April 1970. *Preprints 15th Radar Meteorology Conf.*, Urbana, Ill., Amer. Meteor. Soc., 69–76.

Booker, D. R., L. W. Cooper and H. E. Hart, 1967: Updraft and air flux studies utilizing instrumented aircraft and super-pressure balloon-transponder systems. Final Report, Contract E 22-79-67(N), 35 pp.

Browning, K. A., and F. H. Ludlam, 1962: Airflow in convective storms. *Quart. J. Roy. Meteor. Soc.*, **88**, 117–135.

Duchon, C. E., P. G. Stickel, C. J. Biter and C. G. Wade, 1973: Field calibrations and intercomparison of aircraft meteorological systems. Paper presented at 53rd Annual Meeting, Amer. Meteor. Soc., St. Petersburg.

Fujita, T., 1963: Analytical mesometeorology: A review. *Meteor. Monogr.*, **5**, No. 27, 77–125.

MacCready, P. B., Jr., 1962: Turbulence measurements by sailplane. *J. Geophys. Res.*, **67**, 1041–1050.

Marwitz, J. D., 1972a: The structure and motion of severe hailstorms. Part I: Supercell storms. *J. Appl. Meteor.*, **11**, 166–179.

——, 1972b: The structure and motion of severe hailstorms. Part III: Severely sheared storms. *J. Appl. Meteor.*, **11**, 189–201.

Newton, C. W., 1963: Dynamics of severe convective storms. *Meteor. Monogr.*, **5**, No. 27, 33–58.

Stout, G. E., 1957: Mesometeorological systems from dense network stations. Paper presented at IUGG meeting, Toronto.

Sulakvelidze, G. K., H. Sh. Bibilashvili and V. G. Lapcheva, 1967: *Formation of Precipitation and Modification of Hail Processes.* Translated by Israel Program for Scientific Translations, Jerusalem, 208 pp.

van Thullenar, C. F., 1960: Pressure difference between a cumulus cloud and its environment. *Cumulus Dynamics*, Oxford, Pergamon Press, 103–108.