Estimates of Air and Moisture Flux into Hailstorms on the High Plains

AUGUST H. AUER, JR.
University of Wyoming, Laramie

AND JOHN D. MARWITZ[1]
Colorado State University, Fort Collins

(Manuscript received 9 October 1967, in revised form 9 December 1967)

ABSTRACT

Based on airborne observations, estimates of air and moisture flux have been calculated for 18 hailstorms: eight in Colorado, one in Oklahoma, and nine in South Dakota. The average air flux for hailstorms in this study was 2.3×10^{11} gm sec^{-1}, while the moisture flux averaged near 2.1×10^{9} gm sec^{-1}.

Precipitation efficiency for eight thunderstorms was found to be near 55%, though two severe hailstorms did exhibit slightly less efficiency.

1. Introduction

Computations of water and energy budgets for hailstorms require an estimate of air and water vapor flux into the cloud base. By knowing the amount of precipitation reaching the ground, one can make certain inferences as to the efficiency of the precipitation mechanism of hailstorms. Once the knowledge is gained concerning the desired ice nuclei concentrations required to attain certain effects, such as increased precipitation efficiency or hail suppression, then the artificial nuclei seeding rate will be governed by the fluxes of air and water vapor through the cloud base. Previous estimates of air and moisture fluxes have been based on unverified assumptions.

During the severe storm seasons of 1964–65 in northeastern Colorado, 1967 in Oklahoma, and 1967 in South Dakota, cloud base updraft speeds of hailstorms were measured and the areal extent of the updraft mapped. The purposes of this paper are two-fold: First, estimates of the air and moisture flux in the updraft core through the base of hailstones will be presented; second, rain-producing efficiencies for some hailstorms will be computed based on the amount of moisture entering the cloud through its base and the amount of rainfall measured at the ground.

2. Air and water vapor flux

Details describing the methods of updraft measurement using aircraft have been published by Auer and Sand (1966). To determine the vertical motion of the aircraft relative to the air, aircraft performance curves relating vertical speed to engine power settings and indicated airspeed were experimentally obtained by flying the aircraft at altitudes that could be expected to be encountered when flying at cloud base levels. This procedure is required since it is occasionally necessary to adjust the aircraft power when updrafts are encountered. For example, the aircraft performance curves for the Colorado and South Dakota studies were determined for altitudes between 2700 and 3600 m MSL. In Oklahoma, the altitudes were reduced between 900 and 1500 m MSL. Thus, these aircraft performance curves were corrected for the effect of air density. The algebraic difference between the vertical speed indicated by the rate-of-climb meter at the time of the updraft observation and the vertical speed indicated by the aircraft performance curve will yield the corrected updraft velocity, believed to be within ±1 m sec^{-1}.

The pilot and on-board meteorologist, while maintaining an aircraft position in the areas of steady updrafts, would attempt to make repeated passes beneath the visible leading edge of the cloud base within 900 m (generally less than 200 m) of cloud base over the flight path parallel to the leading edge of the storm and perpendicular to the direction of motion of the storm. These paths extended from 800 m ahead of the precipitation core to 800 m ahead of the lowest visible leading edge of the hailstorm since experience indicated that this was the area of updrafts. Air which might enter the cloud base in the updraft at levels above the flight altitude (generally within 200 m of cloud base) is assumed to be negligible. Observations obtained during four year's flight experience in this region below cloud base justifies this assumption.

Cloud base for the storms studied in northeastern Colorado and South Dakota averaged 3300 m MSL, while in Oklahoma the single storm mentioned had a cloud base of 1100 m MSL.

The areal extent of the updrafts was determined by noting the time required to fly the length and width of the updraft and monitoring the indicated air speed. A rectangle approximating the updraft was assumed. It is

[1] Present affiliation: University of Wyoming.

Table 1. Summary of updraft data and air and moisture flux calculations from hailstorms observed in northeastern Colorado (1964–65), Oklahoma (1967), and South Dakota (1967). Also included is information on duration of sampling period, observed hailfall and updrafts.

Date	Sampling period (min)	Maximum hail diameter (cm)	Updraft speed (m sec^{-1})	Updraft area (km^2)	Air flux (10^{11} gm sec^{-1})	Moisture flux (10^9 gm sec^{-1})
NE Colorado						
8 July 1964	55	3.8	3.5	48	1.4	1.3
27 July 1964	60	1.3	4.0	109	3.3	2.0
14 June 1965	60	5.1	3.0	55	1.5	2.3
21 June 1965	60	0.9	3.5	41	1.1	0.7
23 June 1965	65	1.3	4.5	79	3.0	2.7
24 June 1965	50	0.6	5.5	72	3.6	4.8
2 July 1965	60	5.1	5.0	102	4.4	4.8
10 July 1965	70	5.1	5.0	172	6.6	5.8
Average					3.1	3.1
Oklahoma						
30 May 1967	40	1.3	4.0	103	4.4	6.6
South Dakota						
14 July 1967	20	1.3	4.5	27	1.2	1.6
24 July 1967	20	1.3	5.0	21	0.9	0.8
25 July 1967	25	0.6	2.5	41	0.9	0.6
25 July 1967	20	0.6	3.5	41	1.2	0.8
25 July 1967	60	0.6	5.0	82	3.3	2.1
26 July 1967	10	2.5	3.5	62	1.9	1.9
27 July 1967	45	1.0	4.5	10	0.4	0.6
2 Aug. 1967	35	1.9	4.0	21	0.7	0.7
2 Aug. 1967	30	1.3	3.5	41	1.2	1.2
Average					1.3	1.1
Overall average					2.3	2.1

readily known that updrafts do not assume the simple geometric shape of rectangles, but rather have a curved shape around the leading edge of the precipitation curtain. In the first approximation, however, the simplification of a rectangle is permissible. With this simplification and observation technique, estimates of updraft areas are felt to be valid within ±20%. Updraft values quoted in this paper are averages found over the sampling interval, generally 1 hr.

Values of air flux were computed to be the product of the updraft speed, updraft area, and density of the air at the sampling altitude. Observations of cloud base temperature and pressure-altitude were also taken while flying in the proximity of the cloud base. These two meteorological parameters uniquely define a cloud base saturation mixing ratio which, when multiplied by the air flux, will yield a corresponding water vapor flux.

The verification of hailfall from the storms studied in northeastern Colorado was obtained from cooperator hail reports collected in the Colorado State University network and by field surveys immediately after the storm. In the Oklahoma and South Dakota storms, hail reports were provided by mobile observers dispatched through the storm area. The thunderstorm was classified a "hailer" if hail fell within ±30 min of the airborne sampling period.

A summary of the updraft measurements of the air and moisture flux computations for the hailstorms sampled in 1964, 1965 and 1967 are presented in Table 1. It can be seen from Table 1 that the average air flux for hailstorms in this study was 2.3×10^{11} gm sec^{-1}. The average moisture flux into a hailstorm was 2.1×10^9 gm sec^{-1}. Braham (1952), using balloon data from the Thunderstorm Project, listed average values for air flux for small, air-mass thunderstorms of 0.5×10^{11} gm sec^{-1} and moisture flux of 0.6×10^9 gm sec^{-1}. Estimates by Weickmann (1963) have indicated that air flux may range between 0.2×10^{11} gm sec^{-1} for a moderate strength storm to 83.0×10^{11} gm sec^{-1} for a system of hailstorms. Fankhauser's (1966) measurements of moisture flux, based on radiosonde observations and low-level convergence patterns from aircraft winds, yielded 28.0×10^9 gm sec^{-1} for a heavy hailstorm in Oklahoma. Newton (1966), making the assumption that all the air beneath the base of an advancing storm cell of a squall line is drawn into the thunderstorm, obtained air flux values of 7.0×10^{11} gm sec^{-1} and moisture flux amounts of 8.8×10^9 gm sec^{-1}. This he implies is representative of Oklahoma traveling severe storms.

Table 1 also shows that the amount of air and moisture flux into hailstorms observed in Colorado typically runs two to three times the amount of air flux calculated for hailstorms in the South Dakota area. The range of the air and moisture flux values for all areas was found to be more than one order of magnitude.

3. Precipitation efficiency

Braham (1952) calculated precipitation efficiencies by comparing the total amount of measured precipitation at the ground to the total moisture inflow of individual, small, air-mass thunderstorms with a typical lifetime of 25 min; he inferred that only about 10% of the water vapor entering these thunderstorms is eventually measured as precipitation at the ground. It should be pointed out here, however, that these storms exhibited air flux values of one to two orders of magnitude less than measured elsewhere. Newton (1963, 1966) computed an estimate of the rain-producing efficiency for a segment of a squall line by evaluating what fraction of the flux of water vapor, computed from the indicated mass flux and mixing ratios, is realized as mean precipitation measured at a ground network. The mass flux in his computations originated in the layer between the surface and 700 mb and was determined from wind observations taken over a 4-hr period. For the two cases cited, Newton suggested a value of 50% for the estimates of precipitation efficiency. Fankhauser (1966) computed his rain-producing efficiency by taking the ratio of the rainfall rate, determined by 10-cm wavelength radar, to the net moisture convergence rate (a mean value determined from an aircraft flight at the 800-mb level). On the basis of a single thunderstorm, Fankhauser concluded that about 60% of the moisture (passing through the 800-mb level) which entered the hailstorm is used in the production of rain at the surface.

Following the above procedures, which differed only in their measuring techniques and not in the definition of precipitation efficiencies, estimates of precipitation efficiency were also calculated for a number of thunderstorms, some producing hail, occurring in northeastern Colorado during the 1965 season. Precipitation efficiency is defined here to be the ratio of the measured precipitation rate at the surface to the moisture flux through the cloud base. Simultaneous average values of both the precipitation rates and water vapor fluxes were calculated for the sampling periods, typically averaging near 60 min. It has been previously shown (Auer and Sand, 1966) that severe thunderstorms in northeastern Colorado do exhibit persistent, or "steady-state" updraft characteristics; for this reason, the comparison of simultaneous measurements of surface precipitation rates and moisture flux at cloud base for a given storm cloud is assumed valid for the precipitation efficiency computations.

A technique of estimating rainfall rate was used which combined PPI radar photographs to depict hailstorm movement with rainfall reports from a raingage network. PPI radar echo movement from time-lapse photography was projected onto available precipitation data from a raingage network. Isochrones marking the beginning and end of precipitation, i.e., the beginning and end of the passage of the radar echo, are superimposed on the rainfall isohyetal analysis. The area of the isohyetal pattern for each time increment is then determined; this yields a depth of rain over an area of coverage per unit of time, or a rain rate.

Precipitation efficiencies for eight thunderstorms are presented in Table 2. It can be seen from Table 2 that

TABLE 2. Comparisons between moisture flux values and rainfall rate for thunderstorms and some hailstorms observed in northeastern Colorado during 1965.

Date	Maximum hail diameter (cm)	Moisture flux (10^9 gm sec^{-1})	Rainfall rate (10^9 gm sec^{-1})	Efficiency (per cent)
12 June 1965	None	3.4	3.3	97
14 June 1965	5.1	2.3	1.3	57
21 June 1965	0.9	0.7	0.4	57
23 June 1965	1.3	2.7	1.5	56
24 June 1965	0.6	4.8	2.5	52
2 July 1965	5.1	4.8	1.0	21
10 July 1965	5.1	5.8	2.0	35
27 July 1965	None	1.5	1.8	120

two of the three hailstorms which produced 5.1-cm diameter hail at the ground had calculated efficiencies less than 35%. Two storms which were not known to produce any hailfall exhibited efficiencies of 97% and 120%, the latter possibly being explained by a storage of water aloft followed by rainfall with little or no accompanying updrafts. Thunderstorms producing hail of intermediate size (diameter of 0.6–1.3 cm) yielded precipitation efficiencies around 55%. This value is seen to compare favorably with the more recent estimates of precipitation efficiency quoted above.

Additional aircraft flights should be undertaken to provide a greater climatology of updraft speeds and dimensions. These measurements, combined with airborne temperature and humidity observations in the updraft regions, will lend insight to severe storm dynamics and precipitation processes within such storms.

Acknowledgments. This research was made possible by the National Science Foundation under Grant NSF G-23706 to Colorado State University, ESSA-NSSL under Contract E-22-79-67-N to Weather Science Inc., and the U. S. Department of the Interior, Bureau of Reclamation, Contract 14-06-D-5979 to South Dakota School of Mines, Institute of Atmospheric Sciences.

REFERENCES

Auer, Jr., A. H., and W. Sand, 1966: Updraft measurements beneath the base of cumulus and cumulonimbus clouds. *J. Appl. Meteor.*, **5**, 460–466.

Braham, R. R., Jr., 1952: The water and energy budgets of the thunderstorm and their relation to thunderstorm development. *J. Meteor.*, **9**, 227–242.

Fankhauser, J. C., 1966: Some physical and dynamical aspects of singular cumulonimbus observed by instrumented aircraft and radar. *Proc. Twelfth Conf. Radar Meteor.*, Boston, Amer. Meteor. Soc., 405–413.

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

——, 1966: Circulations in large sheared cumulonimbus. *Tellus*, **18**, 699–712.

Weickmann, H. K., 1963: A realistic appraisal of weather control. *Z. Angew. Math. Phys.*, **14**, 528–543.