The use of cumulonimbus anvil growth data for inferences about the circulation in thunderstorms and severe local storms

By B. AUVINE and C. E. ANDERSON, *Dept. of Meteorology, University of Wisconsin, Madison, USA*

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ABSTRACT

The cumulonimbus anvil, studied by means of geosynchronous satellite, is used to reveal the circulation characteristics of local storms. Data is given for volume flux and divergence at the top of the storm, and these are compared with previous results by other investigators. Agreement is good, suggesting that satellite study of local storms is both useful and reliable. In regard to thunderstorm anvil outflow, a simple model of a point source in a uniform stream is shown to be a good approximation to observed anvil growth. Some evidence suggesting the interaction of proximate local storms with one another and with the environmental wind shear is presented.

Introduction

The cumulonimbus anvil, an easily detectable feature of a growing thunderstorm, has come to be used by many investigators as a means of studying the circulation characteristics of local storms. These characteristics include the updraft velocities and the upward fluxes of mass, volume, and energy in the main storm column, as well as the rate of storm growth and development. Before proceeding to illustrate the use of the anvil in such studies, we should note here for purposes of later comparison the general methods utilized in previous investigations of thunderstorm fluxes.

Such methods can be divided into three main groups: those relying on terrestrial or aerial photogrammetric techniques, those using aerial or ground based instrumental means, and those employing the use of a geosynchronous satellite such as ATS-III. The first of these techniques has been used successfully by Anderson (1960), who was able to deduce the volume fluxes in a storm by photographically measured cloud anvil growth, by Reuss (1961), who determined the volume, height, vertical velocities, and movement of a storm by means of a series of anvil photographs, and by Fujita & Byers (1962), who used photogrammetry to determine the updraft intensity and detailed structure of a storm.

Instrumentation has also proved useful in studying the cumulonimbus. Research tools have ranged from aircraft (Fujita & Arnold, 1963), and rawinsonde (Newton, 1966), to radar anvil studies by Hitschfeld (1960).

Finally, and most recently, we have the satellite as a means of quantitatively measuring severe storm circulation. Work in this area has been done primarily by Fujita & Bradbury (1968) and Ninomiya (1971) (mass fluxes and divergence at anvil level deduced from upper level cloud motions) and Sikdar (1969), whose method of measuring anvil growth was used in our own study.

It is the intent of this paper to show that this latter means is a reliable method of studying severe local storm circulation, even in areas from which no data other than satellite photographs are available. This will be done, first by comparing our own results with those of others, and second, by showing that satellite data is capable of resolving certain other characteristics of severe storm circulation not ordinarily apparent from conventional data.

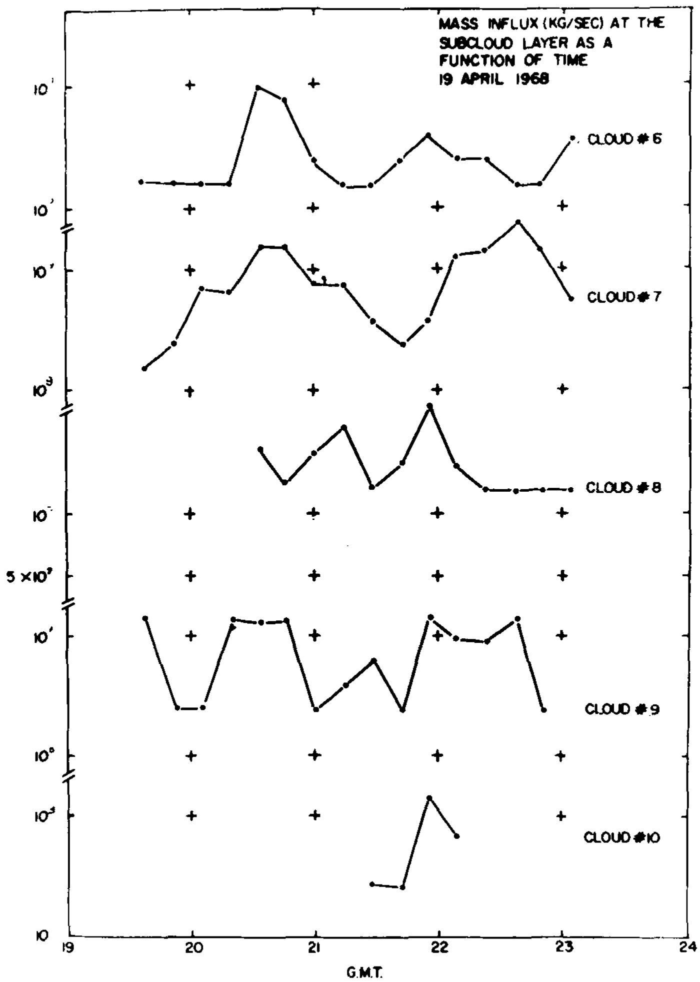

Fig. 1. (After Sikdar et al., 1971.) Mass influx at the subcloud layer as a function of time.

Data analysis techniques

According to Sikdar's model (1970), expansion of cumulonimbus cloud tops aloft in the form of an anvil should be the direct result of convergence at the surface, vertical motion, and subsequent divergence at the top of the convective towers. Implicit in such a model is the question of what proportion of the upward convected air finds its way into the outflow layer. We know that for well developed storms, a considerable amount of air is involved in the cold downdraft (about 60 % of the updraft volume according to Newton) and it is necessary to know the source of this air. Newton (1966) argues that the downdraft is air whose origin is in the mid-troposphere, based on equivalent potential temperature observations and thus his conclusion is that "essentially all the air originating in the updraft remains in the upper troposphere, spreading out mainly in the anvil plume downshear but appreciably also on the upshear side". The mid-tropospheric origin of the cold downdraft finds some observational support by Frankhauser (1968) who found that chaff distributed upwind from a storm is incorporated within the storm at the 500 mb level.

Newton's work used the concept of a steady-state storm and he employed the tilted updraft

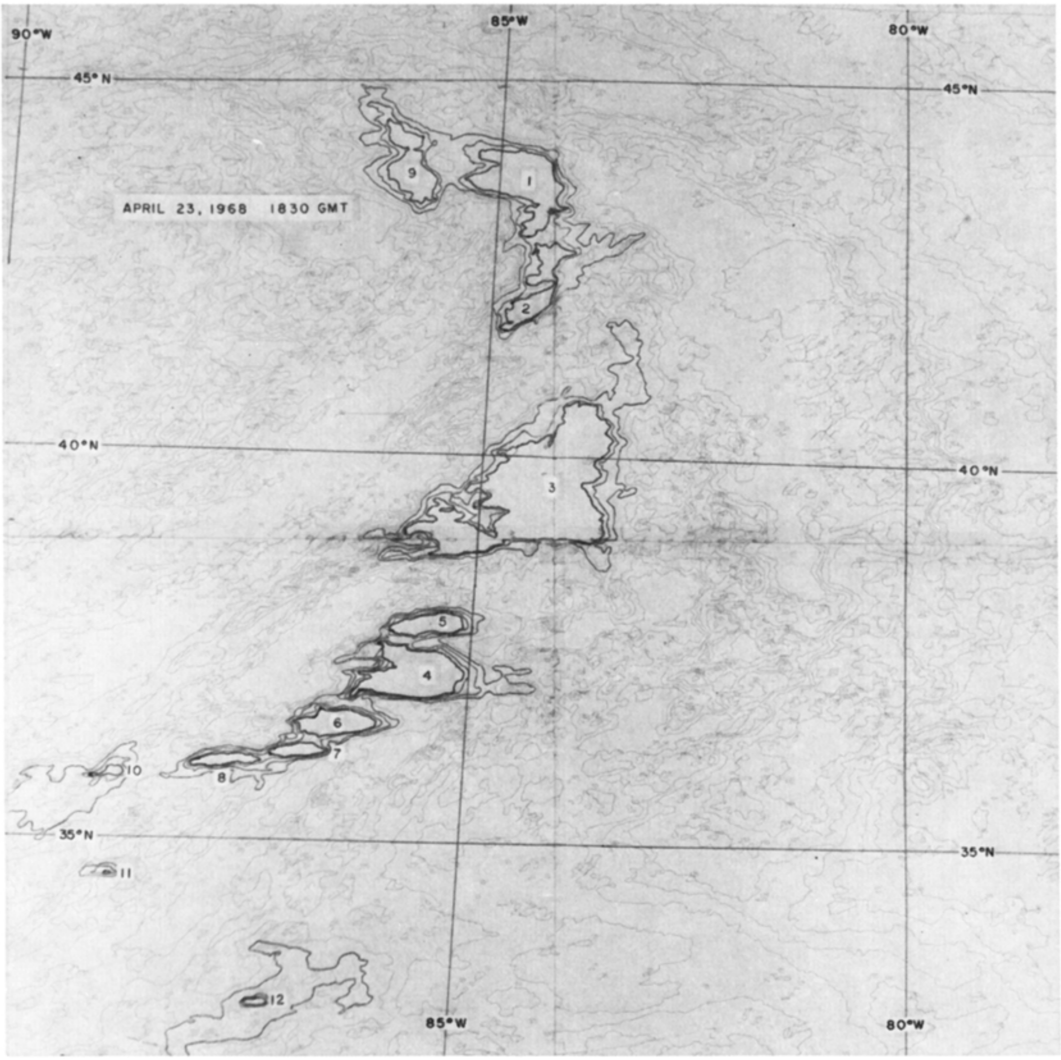

Fig. 2. Brightness contour plot of an ATS-III satellite photograph, 1830 GMT, April 23, 1968.

model proposed by Bates (1961) and Browning (1963). A recent study by Dennis et al. (1970) raises some doubts as to the applicability of this model to the hailstorms observed in N.E. Colorado and South Dakota. Dennis found that new cell development in the form of feeder clouds at the trailing edge seemed to characterize the majority of hailstorms of the northern Great Plains. In these storms, he feels the appropriate model is that suggested by Byers & Braham (1949) wherein the formation of precipitation within the updraft acts as a brake and eventually leads to the collapse of the individual cell. New cell formation acts to perpetuate the storm as an entity. Thus this mode of behavior should lead to quasi-periodic variations in the anvil growth, but such periodic growth does not invalidate the argument that the air in this anvil originates from lower tropospheric air. A recent study by Sikdar et al. (1970), using ATS-III satellite data taken at 14 minute intervals of tornade-producing severe storms over Oklahoma and adjacent regions on April 19, 1968 (see Fig. 1), indeed shows that at least on this occasion one could not characterize there storms as steady-

Table 1. *Anvil deduced volume outflows* (km^3 sec^{-1})

Storm intensity	Volume outflow	Investigator
Moderate	0.26	Anderson (1962)
Giant cell	1.25	Reuss (1961)
Severe	3.2	Sikdar et al. (1970)
Severe (tornado producing)[a]	4.6	Auvine (1970)
Severe (hail producing)[b]	1.1	Auvine (1970)
Severe	6	Fujita & Arnold (1963)
Severe	10	Fujita & Bradbury (1969)

[a] Several storms contributed to the anvil measured.
[b] Anvils produced by single storms.

state. One can draw similar conclusions from Newton & Bates's (1960) radar observation of a pulsating storm and Knoll's et al. (1959) report of a pulsating anvil in one very large storm.

If we accept the concept that the anvil expansion is a legitimate tool for measuring the volume flux in a storm or group of storms, we may proceed to examine how such an anvil expansion may be measured. While one may, of course, attempt to measure the rate of anvil expansion by eye directly from the satellite photograph, a far more accurate method of measurement consists of using the digitized satellite tapes to produce a computer plot of the isopleths of equal brightness (Fig. 2). Such a plot gives a detailed portrait of the anvil and by following the expansion of a particular brightness line from one plot to the next, we may thus determine the expansion of the anvil itself. We are assuming here that the brightness line one is following remains associated with the same cloud material during the interval between measurements. To assure this one must remove the effect of sun angle change which was responsible for steadily decreasing illumination of the anvils during the period of observation. This was done by normalization of the reflectance values according to the cosine of the zenith angle of the sun. This method assumes, of course, that the cloud is behaving as a Lambertian surface. Sekera suggests that this is true for cirrostratus associated with turbulent outflow as would be the case in a thunderstorm cirrus shield. Martin & Suomi (1972) also note that cumulonimbus tops and cloud clusters show evidence of Lambertian behavior, at least for small solar angles. Accordingly, our measurements have been confined primarily to the middle of the day (11 a.m. to 4 p.m. LST), when non-Lambertian behavior should be at a minimum.

We have also assumed that the cloud material of the anvil as it moved outward did not experience significant changes during the intervals between measurement.

Finally, if we wish to convert the area growth of our anvil into a volume flux, we must assume some thickness for the anvil

Table 2. *Volume fluxes* (km^3 sec^{-1})

Storm intensity	Inflow	Outflow	Investigator
Light to moderate	0.16	—	Braham (1952)
Moderate	—	0.26	Anderson (1962)
Light	0.04 (est)	—	Weickmann (1963)
Moderate	0.46 (est)	—	Weickmann (1963)
Severe	4.6 (est)	—	Weickmann (1963)
Hailstorm (S.D.)	0.51	—	Dennis et al. (1970)
Hailstorm (S.D.)	0.41	—	Auer & Marwitz (1968)
Hailstorm (Colo.)	0.98	—	Auer & Marwitz (1968)
Hailstorm (Okl.)	1.3	—	Auer & Marwitz (1968)
Giant cell	—	1.25	Reuss (1961)
Severe	—	2.2	Newton (1966)
Severe	—	3.2	Sikdar et al. (1970)
Severe	—	4.6	Auvine (1970)
Severe	6.0	6.4	Fujita & Arnold (1963)
Severe	—	10	Fujita & Bradbury (1969)
Hailstorm (Colo.)	0.63	—	Goyer (1971)

Table 3. *Estimates of divergence as deduced from anvil growth*

Divergence (sec^{-1})	Investigator
4.6×10^{-4}	Arnett (1962)
3.0×10^{-4}	Sikdar et al. (1970)
1.6×10^{-4}	Ninomiya (1969)
5.0×10^{-4}	Auvine (1970)
1.3×10^{-4}	Fankhauser (1971)

itself. One guide to this thickness would be the albedo of the anvil. The values of brightness for the anvil divided by the maximum possible brightness gives an albedo of about 80 % for our plots which would seem to indicate, according to Neiburger (1949) and Kondrat'yev (1964), clouds having a near maximum albedo and a thickness of better than a half-kilometer. Ludlum (1966), in addition, has found that the anvils he investigated were an average of one kilometer thick. Thus an anvil thickness of one kilometer was chosen for our calculations. Conversion of other investigator's results from mass to volume flux was accomplished by means of the Standard Atmospheric density at 300 mb (3.16×10^{11} g/km^3).

In addition to determining volume flux from the anvil expansion, it was also possible to determine the divergence at the top of the storm from the equation:

$$(1/A)\ (dA/dt) = \text{horizontal divergence}$$

where A is the anvil area and t is time.

In all calculations computer plots spaced 45 min apart were used to determine area change with time and a planimeter was used to measure areas.

Discussion of results

After converting those results given in terms of mass flux to volume flux, we note in Tables I and II a surprisingly good agreement among these various investigators and also a good correspondence between the inflow and outflow volumes for storms of similar intensity. Judging by these data, one would estimate that there is an order of magnitude difference in the fluxes between storms of severe and moderate strength. The great size and intensity of the updrafts found in severe storms would seem to account for this difference.

Tables 1 and 2, then, would seem to establish the validity of the method detailed in this paper. In particular, our assumption that air inflow approximates the air outflow at the top of the storm seems justified.

Another approach towards establishing the soundness of using anvil growth measurements to estimate severe storm properties is to compare our derived values of divergence with

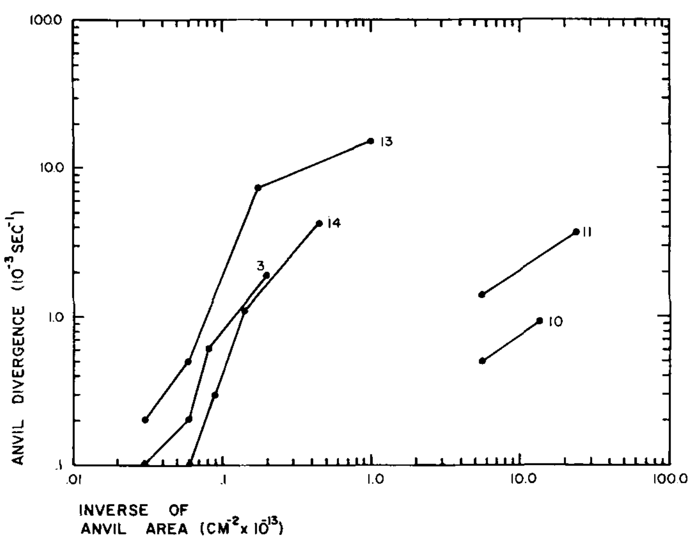

Fig. 3. The log of the anvil divergence as a function of the inverse of the anvil area for various storms on April 23, 1968. The numbers next to the curves refer to the clouds numbered in Fig. 7.

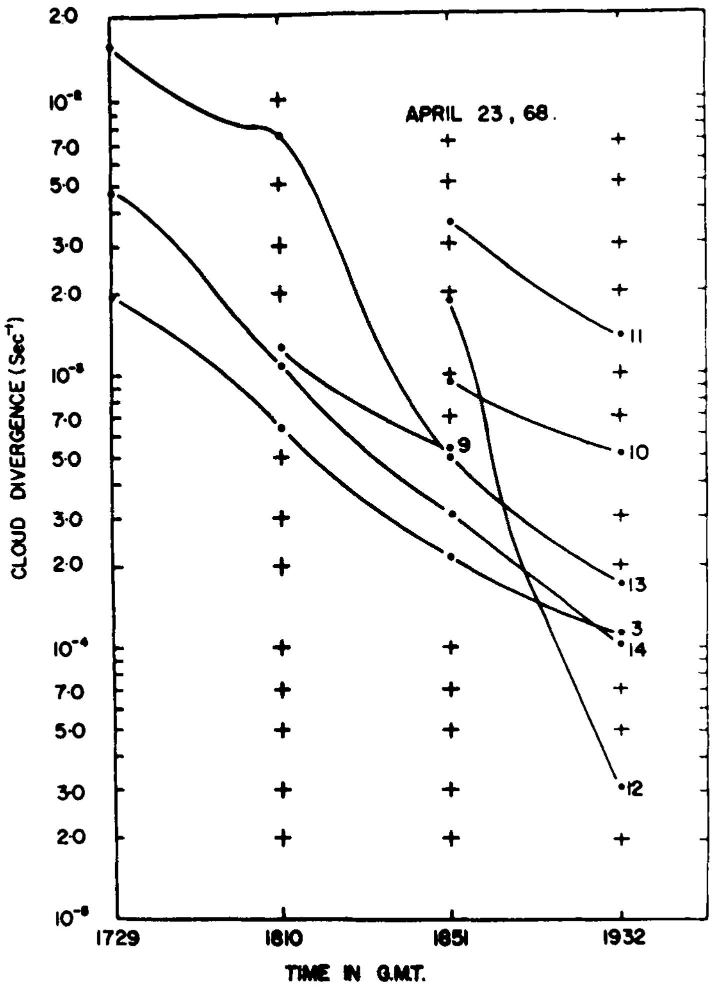

Fig. 4. Divergence in the cloud shield as a function of time.

those of others. Ninomiya (1969), Sikdar et al. (1970), and our own studies have used ATS III data to gain estimates of the horizontal divergence associated with the storm cloud outflow. Ninomiya used wind fields estimated from cloud displacement vectors instead of anvil area change to compute his values, however. Table 3 shows good agreement between all investigators. It is noteworthy that the divergence values obtained by satellite compare favourably with the value of divergence obtained by Arnett (1962) from aircraft-based wind measurements, and with the average value Frankhauser (1971) obtained from the radar observed expansion of the anvil.

It should be emphasized that although these techniques measure the average divergence within a given area, it is not valid to assume that all parts of the area are equally divergent. This point is illustrated in Fig. 3, where $1/A$ versus divergence is shown for a number of different severe storm complexes over the Ohio River Valley and adjacent areas, as observed by ATS III on April 23, 1968. The areas and divergence were measured from computer plots as described earlier. Fig. 3 illustrates that as the area increases the divergence decreases proportionately. Thus for a given severe storm or severe storm complex, the divergence computed will depend on the size of the area included in the measurement. This conclusion is in accord with the observation of many investigators that surface patterns of convergence will depend to a large extent on the scale chosen. Methods using Gauss's Theorem to compute the divergence, therefore, give results applicable to the area used for computation only.

Fig. 4 shows the rapid decay of divergence with time for these storms when we use the concept of the average divergence measured over the entire anvil area. The reason for this behavior is explained by the formula used in our calculation:

$$\text{Average divergence} = (1/A)\ (\mathrm{d}A/\mathrm{d}t)$$

It is obvious that if $\mathrm{d}A/\mathrm{d}t$ is constant or only slightly increasing, then the divergence has to decrease with area. Fig. 5 shows $\mathrm{d}A/\mathrm{d}t$ to be fairly constant for a given cloud complex. This is consistent with our findings in Fig. 4, since if the area is proportional to time (Fig. 5) and the rate of area change is constant, then the divergence must vary inversely with time.

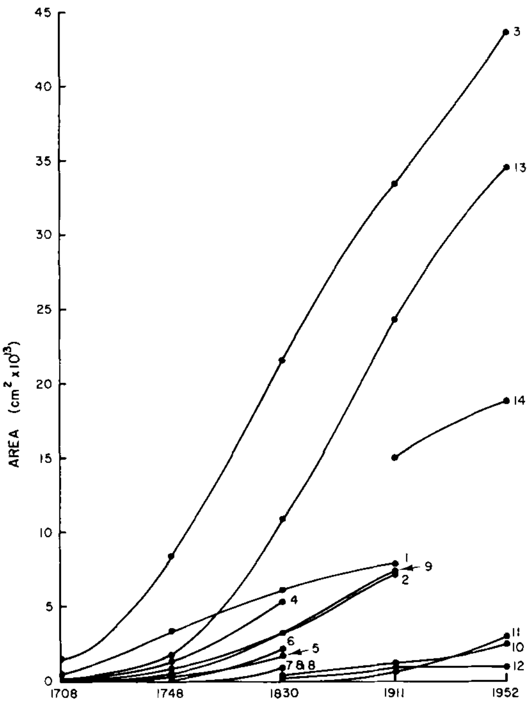

Fig. 5. Cloud shield area as a function of time.

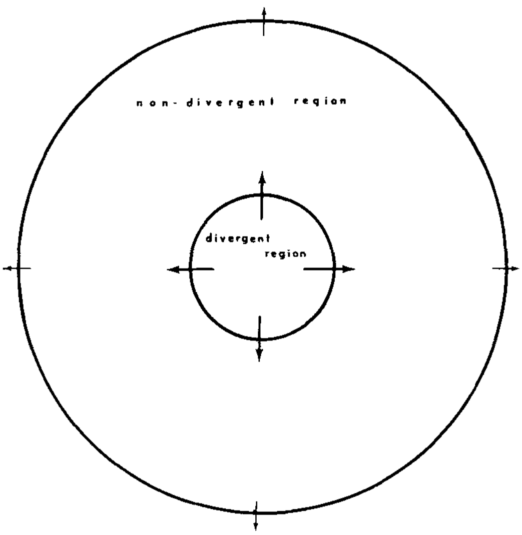

Fig. 6. A model of airflow within the thunderstorm anvil assuming calm environmental winds. A divergent core is surrounded by a ring of non-divergent cloud.

These results suggest that we are dealing with a highly divergent core region surrounded by a region of non-divergent flow as seen in Fig. 6. This model, when reduced to its most simplistic form gives the flow pattern associated with a simple two-dimensional point source (see, for instance, Milne-Thompson, 1969, pp. 197–201), with a velocity distribution which may be derived as follows:

$$\mathrm{d}A/\mathrm{d}t = \text{constant} = (2\pi r)\ (\mathrm{d}r/\mathrm{d}t) = 2\pi r u$$

or

$$u = \text{constant}/r$$

where u is the radial velocity away from the point source and r is the radial distance.

We suggest that there is some merit to applying this concept to the expanding anvil shield.

For satellite photos of April 23, 1968, individual cells (10, 8, 7, 6, 5, 11, 12)—in Fig. 7 appear to be single storms whereas no. 3 and later no. 13 are conglomerates of several storms, as we have determined by transposing simultaneously observed radar precipitation echoes into the satellite depiction. Storm no. 13 results from the combination of storms 4, 6, 7, 8, and 5 into a single entity for purposes of computing anvil areas. The photographs show

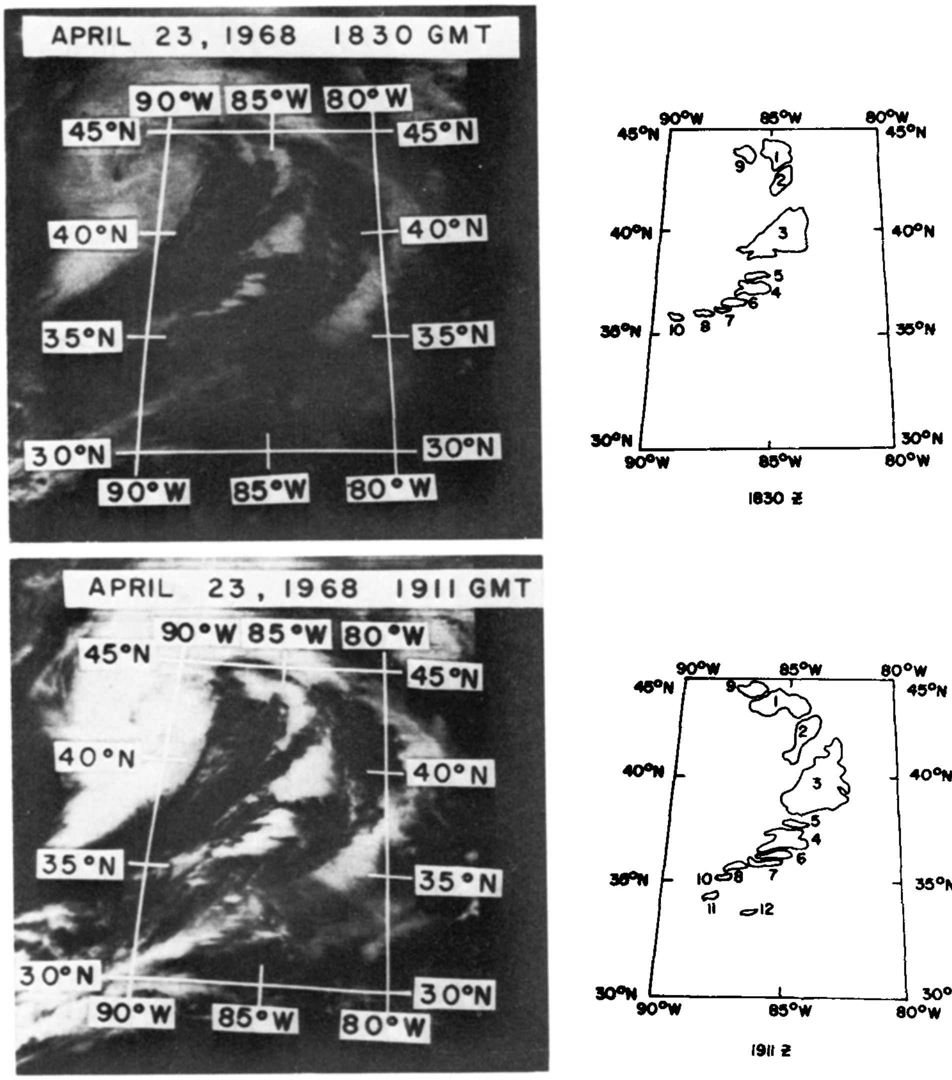

Fig. 7. (After Sikdar et al., 1971.) Severe storm clouds over the United States on April 23, 1968.

the clouds in plumes very similar in shape to the hail storm cloud described by Fujita & Byers (1962), where their anvil plume spread downstream at 32 000 feet for at least 100 miles. Fujita & Byers show the outline of the plume in a form which could roughly be described as elliptical or tear drop shaped with the pointed end at the extreme downstream position. If one considers the results of Fig. 5, that is, $A = A_0 + kt$ as a fair approximation, then the rate of growth of the areas of the plumes may be taken as constant. If we equate the rate of growth with the rate of production of area in the region of divergence, we may draw the analogy of a simple source of strength, $2\pi m$, to characterize these plumes, where the source strength is given by m, or $\mathrm{d}A/\mathrm{d}t$. McLean (1961) suggests that one can describe the flow field in the upper part of a large severe storm (penetrated by a B-47) as a combination of divergence and translation with a divergent annulus surrounding a calm core and non-divergent flow in the external regions—very similar in description to what we show in Fig. 6.

Using the simple idea of considering the shape of the anvil to be the result of divergence and translation, or in other terms, using the model of a point source in a uniform stream (Milne-Thompson), the outlines of the material boundary have been generated as shown in Fig. 8. As an approximation, the outline resembles very closely those seen in the satellite photographs and those described by radar (Hitschfeld, 1962). If this model has any validity, then one should expect a nearly symmetrical anvil when the wind is nearly calm at anvil formation levels. This is observed and strikingly obvious in Reuss's study (Fig. 9).

Of course, this model is applicable only to anvils generated from a single storm. As can be seen from Fig. 7, there are two cloud masses, numbers 3 and 13, which are composed of several single storms all during the period of observation, and therefore their shapes are a composite of several anvils.

It is perhaps significant that according to Fig. 4, faster growth of anvil area occurs when storms join into one anvil than when they existed as clearly separate entities prior to 1830 GMT. This hypothesis is evidenced by a change in slope in the area versus time curve in the early stages of storm growth (see Fig. 10). Thus while clouds 3 and 13 at first exhibit a growth rate similar to the smaller, single-point source storms (such as no. 10),

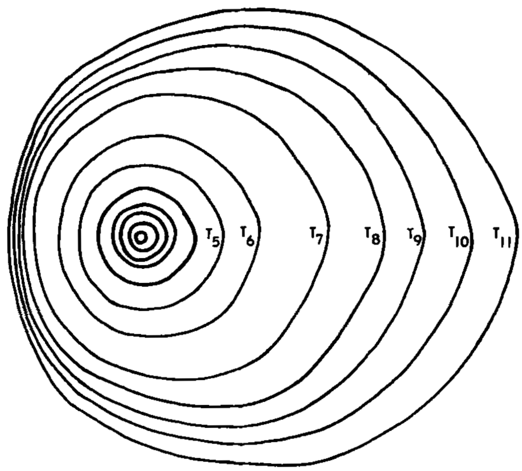

Fig. 8. The material outline of a cumulonimbus anvil assuming its growth to be the result of a point source in a uniform stream.

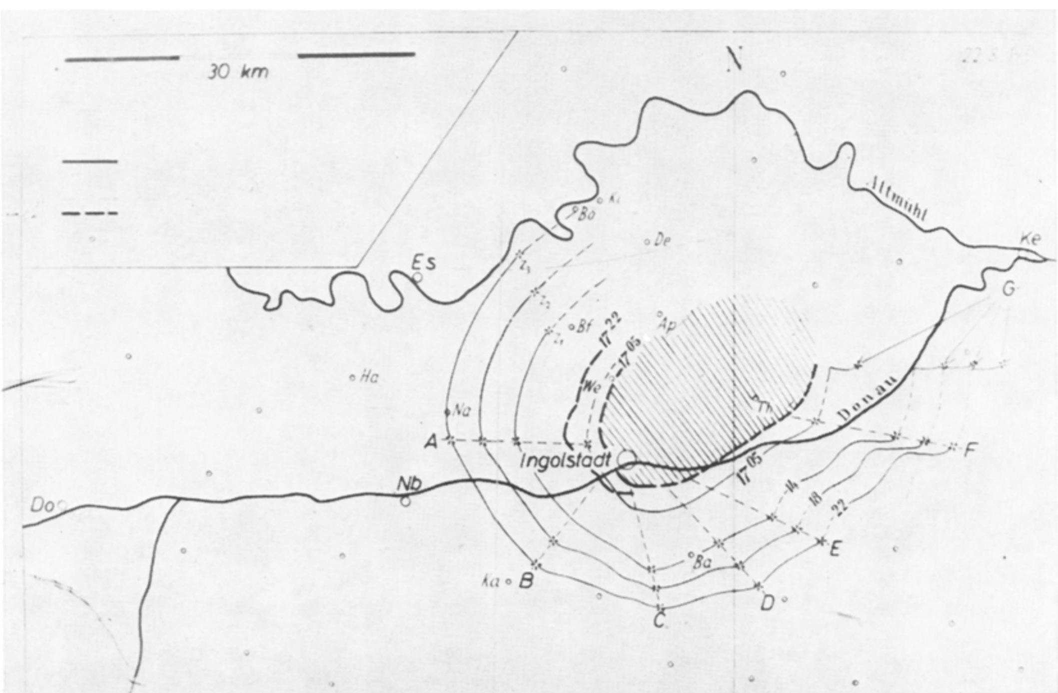

Fig. 9. (After Reuss, 1961.) The growth of a cumulonimbus anvil observed over Germany on August 8, 1959.

later growth as a conglomerate take place at a greater rate. This increase in growth rate suggests some sort of synergistic interaction between the point sources when they come in sufficient proximity to one another.

Finally, the relationship between the rate of production of the anvil (source strength) and the wind speed at anvil level was investigated to determine whether the idea of "venting" by the wind had any validity. Many authors in the past have suggested (Newton, 1966, for example) such a relationship as a necessary condition for the formation of severe storms. Jih-Ping and Cheng-Li-Shoo (1964) have shown in their numerical model that growth rates of cumulus are encouraged by wind shear, although other modeling experiments (e.g. Takeda, 1966; Asai, 1964) suggest that convective activity is suppressed if the wind shear becomes too strong. In Fig. 11, the cloud outflow is plotted as a function of wind velocity at the anvil level. This graph clearly suggests that the stronger outflows are associated with stronger winds at the outflow level. Whether or not this indicates a cause and effect relationship between anvil level winds and anvil outflow is a question for later investigations. However, Johnson & Sechrist (1970) have made the suggestion recently, that the vertical wind shear, particularly in the jet stream, acts on sloping isentropic surfaces to cause a destablization of the lower atmoshpere when momentum convergence is produced by the translating jet core. They applied this concept to the region in which the severe storms of April 23, 1968, occurred and found good evidence to substantiate this hypothesis.

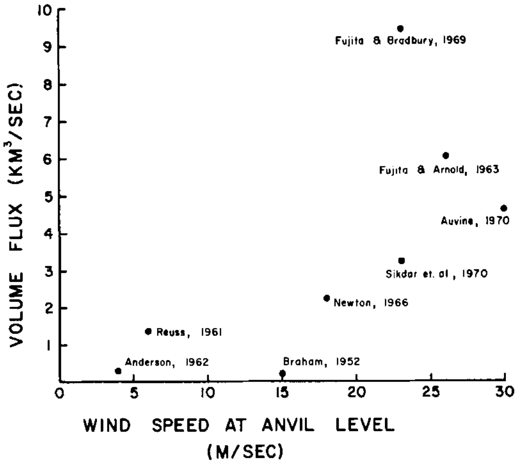

Fig. 11. Volume fluxes as a function of wind speed at the anvil level for various storms.

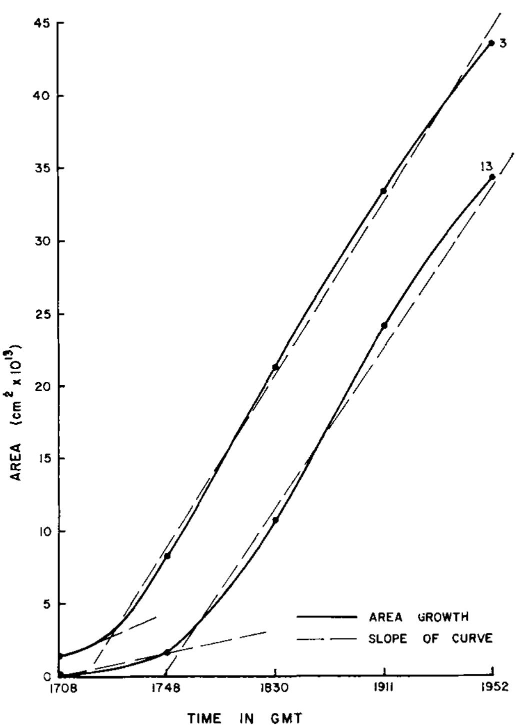

Fig. 10. The change in slope of anvil growth curves for two thunderstorm cloud complexes.

Conclusion

The preceeding discussion should indicate that anvil expansion data is a useful and reliable method of obtaining upper tropospheric fluxes and divergence from some storms. Such a method relies only on satellite data and therefore should be of great use in areas lacking conventional ground instrumentation.

In additon we have shown that a point source concept of a growing comulonimbus anvil conforms well with the observations and is useful in explaining the shape of anvils observed by satellite. We have also raised the question of possible interaction between proximate point sources to give non-linear growth rates and the question of the relationship between individual storms and the wind shear. Further studies on these interactional phenomena are needed. Such studies, using satellite data, should provide new insight into the flow properties of severe storms.

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ИСПОЛЬЗОВАНИЕ ДАННЫХ ПО РОСТУ НАКОВАЛЬНИ КУЧЕВО-ДОЖДЕВЫХ ОБЛАКОВ ДЛЯ ИЗУЧЕНИЯ ЦИРКУЛЯЦИИ В ГРОЗАХ И СИЛЬНЫХ МЕСТНЫХ ШТОРМАХ

Наковальня кучево-дождевых облаков, изучаемая с помощью геосинхронного спутника, используется для выявления характеристик циркуляции в локальных штормах. Представлены данные для потока ее объема и его дивергенции в верхней части наковальни, которые сравниваются с результатами предыдущих исследователей. Согласие оказывается хорошим, и это дает основание считать, что исследования локальных штормов со спутника является как полезным, так и надежным. Что касается роста наковальни грозового облака, то показано, что простая модель точечного источника в однородном потоке является хорошим приближением к наблюдаемому ее росту. Представлены некоторые факты, указывающие на взаимодействие близких локальных штормов друг с другом и с поперечным сдвигом ветра в окрестности шторма.