On the Variation with Height of the Top Brightness of Precipitating Convective Clouds

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ABSTRACT

As part of a program to estimate rain from satellite observations, and to test the program's assumption that the highest clouds are the brightest, a correlation between cloud height and cloud brightness in the South Florida area was made 43 days during the summer of 1972. Brightness was determined from ATS-3 transparencies using a 32-step color densitometer. Echo heights within 100 mi of Miami were measured with the WSR-57, 10-cm radar of the National Hurricane Center in Miami. An unequivocal positive correlation is shown.

1. Introduction

Studies making use of the meteorological satellite have evolved to the point where the imagery is being used quantitatively. In recent years several methods for precipitation estimation from satellite imagery have been developed (Barrett, 1970; Follansbee, 1973; Grosh *et al.*, 1973; Gruber, 1973; Woodley *et al.*, 1972). Of relevance here are the studies in which cloud brightness is the key variable in the estimation of convective rainfall. The feasibility of using enhanced brightness to infer rainfall was suggested in initial studies by Sikdar (1969), Martin and Suomi (1972), and Woodley and Sancho (1971).

In the paper by Woodley *et al.* (1972) an unequivocal relationship between cloud brightness and area-mean rainfall was demonstrated. In explaining this relationship, it had been assumed that bright clouds are thicker and thick clouds are wetter. This note investigates the validity of this assumption.

2. Method

Radar-measured echo heights and reflected solar radiance from the ATS-3 geosynchronous satellite were compared. The comparisons were limited to precipitating cumulus and cumulonimbus clouds and the results do not necessarily apply to other cloud types. The data set consists of 215 echo and image pairs that were obtained on 43 days in the period 16 June to 31 August, 1972.

The radar observations of echo height were made routinely once an hour by personnel of the National Hurricane Center (NHC), Miami, while operating the NHC WSR-57 radar (location: 80°15'W, 25°45'N). The range-height measurements were limited to within 125 n mi (232 km) of Miami. Echo tops were corrected for height of the antenna, earth curvature, half-beam-width, and standard atmospheric refraction. Echo height was assumed to be cloud height. Even though the NHC WSR-57 radar tends to overestimate echo height by as much as 1000 ft, the observed echo height is usually still an underestimate of cloud height. Saunders and Ronne (1962) found that the height of the visible tops exceeded that measured by the NHC WSR-57 by 200–3000 ft for the 32 clouds that were studied.

Cloud brightnesses were determined from ATS-3 negatives that are archived by the Miami Satellite Field Services Station (SFSS). During the period of study the satellite subpoint was at 69.0–70.5W and within 2°–3° of the equator. Brightness measurements were limited to within 2 hr of Miami local noon to minimize corrections for radiation geometry.

A 32-level color densitometer made by International Imaging Systems (I²S) of Mountain View, Calif., was used to quantify cloud brightness. The principles of densitometry for the derivation of cloud brightnesses are treated elsewhere (Woodley *et al.*, 1972). In this study the densitometer was used to measure emulsion density (a quantity proportional to brightness) of the ATS-3 negative in arbitrary density units. Thus, a bright cloud mass darkens film emulsion and produces a higher density reading than a less bright cloud mass.

In effecting the comparison of cloud height and brightness, the clouds for which heights were available were located on PPI echo depictions. Echoes on the PPI scan (antenna elevation of 0.5°) nearly always correspond to precipitation reaching the ground. In only four out of 109 comparisons of rainfall measured by radar and gage clusters did the radar indicate rainfall when the gages recorded none (Herndon *et al.*, 1973).

The PPI depictions were compared with the cloud depictions from ATS-3. In most cases the time difference between the measurement of echo top and the satellite image over Florida was 5–8 min. Because of inaccuracies in the gridding of the ATS-3 photographs, the echo depictions and satellite images were not superimposed; rather, they were matched by pattern recognition. This procedure utilizes the spatial relationship of echo and cloud mass to geographic landmarks to make the pairing. After matching echo with its corresponding cloud mass on the satellite photograph, the latter was scanned with the densitometer to locate the greatest density in the portion of the cloud where the radar height was measured. In this way, brightness was compared with radar-measured cloud height. Because of gridding uncertainties, the relationship to be derived between brightness and echo height is valid for the cloud mass in which the measurements were made, and not for specific points within the mass.

Fig. 1a. A portion of the 12 August 1972 ATS-3 picture. This area was scanned at approximately 1741 GMT. The negative has been false-color enhanced and only the five brightest contours are schematically represented. All brightest areas correspond to echoes in Fig. 1b. The coast of Florida has been drawn from the second darkest contour, which may include shallow water as well as land. The scales of Figs. 1a and 1b are roughly the same, although Fig. 1a is distorted at the edges due to parallax. Maximum standardized densities for three masses are given.

Fig. 1b. The WSR-57 contoured PPI depiction at 1741 GMT 12 August 1972. The two cloud tops measured by the WSR-57 RHI at 1740 GMT are also indicated. Ground clutter, which is generally confined to the 25 n mi radius circle, precludes reliable detection of cloud echoes in that area. Rain rates (inches per hour) for the contours shown are as follows: contour no. 1 (outer level), 0.01; no. 2, 0.09; no. 3, 0.54; no. 4, 1.19.

FIG. 2. The results of the cloud brightness-echo height comparisons. All densities have been normalized as outlined in the text. Least-squares fits to first-degree ($\rho = 0.34 + 0.03H$) and second-degree ($\rho = 0.17 + 0.07H - 0.002H^2$) curves are plotted. Indicated temperatures and pressures are averages, for the period of this study, computed from Jordan (1958).

A schematic example of pattern recognition is shown in Fig. 1 for 12 August 1972. Cloud brightness at 1741 GMT in terms of contoured density is shown in Fig. 1a. Only the first five contours corresponding to the brightest clouds are shown; maximum standardized density is shown for three clouds.

The contoured PPI representation at the same time with observed cloud heights is indicated in Fig. 1b. Operational contingencies did not permit measurement of all cloud tops, nor was it possible to distinguish echoes in the Miami ground clutter. There is little doubt that the brightest cloud mass B (0.92 density units) southwest of Miami corresponds to the echo B' with the highest top (15.2 km), and that D (0.78 density units) corresponds to D' (12.2 km).

It was necessary to correct for day-to-day variability of the ATS-3 product in order to group the comparisons for all days. This correction was made by normalizing all photographs using the maximum brightness (near local noon) of the South American salt flat, Salar de Uyuni (67W, 20S), on 11 July 1972. This normalization to a relative standard accounted for processing and signal variations between pictures and for the slight changes in radiation geometry that occurs in the 2-hr period around local noon.

3. Results

The results of the brightness-echo height comparisons are shown in Fig. 2. Brightness is presented in terms of standardized density on the ordinate. Height on the abscissa is also represented as pressure and temperature averages of the June through September data of Jordan (1958). The best fit, a second-degree least-squares fit, shows a definite increase of brightness

with echo height. The second-order fit differs very little from the first-order or linear fit. The correlation between brightness and echo height is 0.71, which is significant at better than the 1% level.

Although there is a definite relationship between brightness and cloud height, it shows considerable variability. This variability may have several explanations. In a plausible order of decreasing importance these might be: 1) the time difference between the ATS-3 scan over the Miami area and the radar observations which amounted to 15 min for some pairs, 2) the age of the cloud system, and 3) variation in the performance of the densitometer.

The time difference between radar and satellite observations can be a serious problem. Convective clouds in Florida typically grow in height at a rate of 5 m sec⁻¹ which means that with the lapse of 10 min between the echo height observation and the satellite scan the cloud could have grown an additional 3 km.

The age of the cloud system is also important. When a cloud is young and growing, most of the hydrometeors are concentrated near its top, but when it is dying, most of the hydrometeors are falling from its base as precipitation even though its top is still radar-detectable. Thus, a young cloud may appear to be brighter than a higher but older cloud because the concentration of hydrometeors near the top of the younger cloud returns more radiation to the satellite sensor than the older cloud.

The densitometer is also a known source of error. Within-day calibrations of the density console indicated that the calibration of the unit drifted while it was being used. The amplitude of the drift amounted to 10–20% for the range of density readings that were made for this study.

The results presented here have interesting implications for schemes to estimate rainfall from satellite imagery. Because each plotted point on this figure represents a precipitating cloud, it is obvious that there is no unique brightness or cloud top temperature threshold for precipitation. Thus, any scheme which invokes such a threshold must accept some error; the magnitude will depend on the threshold invoked. Certainly a scheme that demands undilute ascent to the top of the troposphere for precipitation will be ignoring most of the precipitating clouds which do not reach that height.

4. Conclusion

There is an obvious relation between cloud height and brightness but the relationship is not unique. Estimates of cloud height are possible with satellite brightness observations but it is probably unreasonable to expect such estimates to have better than one or two kilometer accuracy. In a very similar study in this issue, Reynolds and Vonder Haar (1973), using BOMEX data, show a somewhat stronger relationship

between radar-determined cloud height and reflected solar radiance. However, a rather limited set of observations were used in this study and it is not clear whether the strength of the brightness-height correlation would hold with additional observations. Nevertheless, both studies demonstrate an unequivocal positive correlation between cloud brightness and height. This result gives additional impetus to the continuing program to develop a method to estimate rainfall from brightness-enhanced satellite imagery.

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