NOTES AND CORRESPONDENCE

Effects of Cloud Size and Cloud Particles on Satellite-Observed Reflected Brightness

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ABSTRACT

The relationship between a cumulus clouds' brightness, horizontal dimension and internal microphysical structure are investigated. Cumulus clouds located over the South Park region of Colorado are observed by the SMS-2 satellite and their brightness and size are determined. Aircraft observations were made in-cloud to obtain the drop size distributions and liquid water content (LWC) of the cloud. A Monte Carlo cloud model is used to imitate the sun-satellite-cloud geometry in an effort to understand the role of cloud size and microphysical structure in affecting cloud brightness.

Results show that for clouds of optical thickness between 20 and 60 (i.e., LWC of 0.037 gm^{-3} and 0.11 gm^{-3} for a 2 km deep cloud), information about a cloud's LWC may be obtained through monitoring cloud brightness for clouds of uniform depth and variable width. Theoretical results using this Monte Carlo method approximate very closely the relative brightness changes of clouds of the size and depth monitored by the SMS-2 satellite for these few days. Theory and observation both conclude that a cloud having a width to depth ratio of approximately 10:1 (and constant optical thickness) is nearly reaching its maximum brightness. Theory predicts that geometric factors affect cloud brightness more than microphysical changes.

It is also discussed that the previously reported work on the cloud height-cloud brightness relationship may indeed be seeing increasing brightness with increasing horizontal size changes (size being related to height) with finite small perturbations on top of the growing cloud slowing its approach to maximum brightness.

1. Introduction

Modeling of the visible radiation scattered from semi-infinite to finite size clouds has been attempted for several years. Hansen (1969) and Twomey *et al.* (1967) found that for a plane-parallel atmosphere with semi-infinite clouds having optical thicknesses near 100 (cloud 1–1.5 km deep and having liquid water contents of 0.2 g m^{-3}) that these clouds are within 20% of their maximum brightness. These results showed that remote sensing of clouds in the mid-visible wavelengths would be of little value for clouds of any real vertical extent, and it would be impossible to determine anything about the microphysical properties of the clouds. However, observational measurements from satellites of convective clouds of significant vertical extent ($\gg$2 km) have shown increasing brightness with increasing height (Griffith and Woodley, 1973; Reynolds and Vonder Haar, 1973). Recent work by Busygin *et al.* (1973) and McKee and Cox (1974, 1976) has shown that the finite cloud poses a particular problem for monitoring its brightness due to energy passing through the vertical sides of the cloud. Thus their reasoning for this observed brightness-height change is related to the fact that as the cloud grows it becomes wider as well as thicker, making side effects less important and allowing more light to be reflected off the top. To further understand cloud brightness changes, a small study was performed using measured satellite brightness data and comparing these to expected theoretical results.

The South Park Area Cumulus Experiment (SPACE) collected microphysical data on cumulus clouds in South Park, Colo., during the summer of 1975. The data set included cloud drop size distributions made with an electrostatic disdrometer (Keily and Millen, 1960) mounted on the NCAR/NOAA *Explorer* sailplane. This instrument measures cloud droplets from 4 to 16 μm in 1.5 μm increments and has a ninth channel for cloud droplets >19 μm. Liquid water contents were simultaneously measured with a Johnson-Williams liquid water content meter mounted on the *Explorer*.

Along with these data, digital SMS-2 (Synchronous Meteorological Satellite) visible (0.5–0.7 μm) (0.9 km resolution at SSP) data were received for this area

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through the Direct Readout Ground Station at White Sands Missile Range. This allowed us to observe visible brightness of the clouds as well as estimate their top heights from the infrared readout using an appropriate temperature sounding.

A Monte Carlo cloud model for finite clouds developed by McKee and Cox (1974) was run using different distributions of drop sizes and numbers (Deirmendjian, 1969), while varying the cloud depth and width to determine how theory would predict what the satellite would view from its given location in space. Comparison of these results to the satellite observed reflectances will be presented in the following sections.

2. Model calculations

Fig. 1 graphically compares the two theoretical drop size distributions (C.1 and C.3) used in the numerical simulation of satellite measured visible brightness, with the average drop size distribution observed on 6–8 August of the 1975 SPACE field program. The specific values but not the shape of the depicted theoretical distributions are dependent on the liquid water content (LWC) of the clouds. C.1 and C.3 in Fig. 1 are adjusted to a LWC of 0.055 g m^{-3} which was the average observed LWC of the three days under study. The daily average LWC values ranged from 0.047 g m^{-3} on 8 August to 0.07 g m^{-3} on 7 August. This was lower then one might expect for cumulus clouds but we feel these numbers are representative.

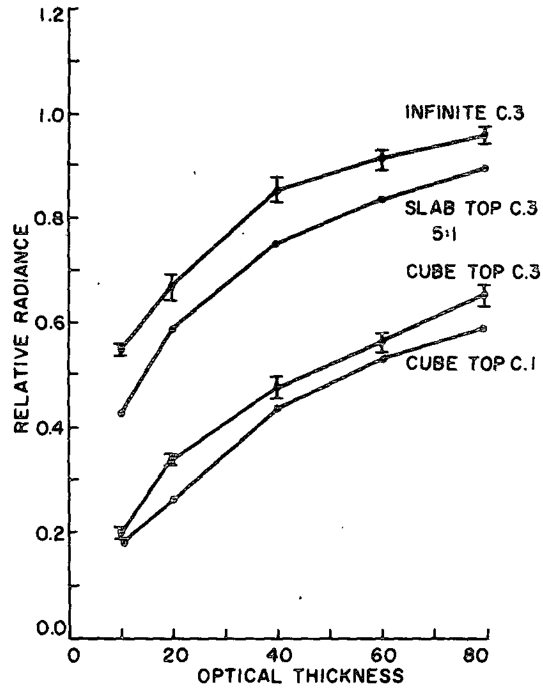

FIG. 2. Model results showing small variation in relative radiance for C.1 and C.3 drop size distributions over the optical thicknesses shown. Note also that a cloud slab having a width to depth ratio of 5:1 by optical thickness 80 is very nearly equal in brightness to an infinite layer.

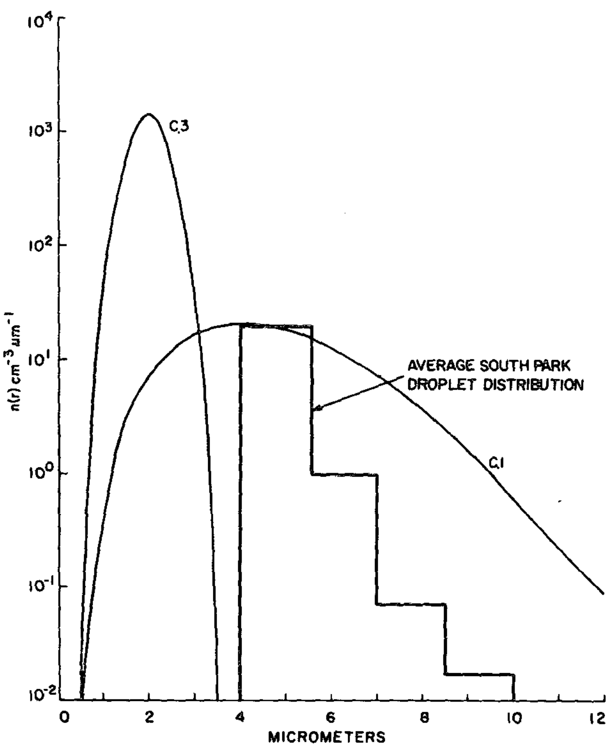

FIG. 1. Particle size and number distributions used for model input (Deirmendjian, 1969). Average South Park observed distributions for three case study days are also shown.

The observed drop size distribution is also plotted on Fig. 1, primarily to allow a comparison of the shape of the observed distributions with the theoretical distributions utilized in the numerical simulation. The drop size distribution observed with the electrostatic disdrometer has several problems which are discussed by Dye (1976). One prominent difficulty is that the LWC integrated from the electrostatic disdrometer is typically half the LWC observed with a Johnson-Williams (J-W) liquid water content meter. The average LWC as observed by the J-W on 6–8 August was ~0.18 g m^{-3}. Second, the distributions are skewed toward smaller drops by the electrostatic disdrometer.

The observed distributions were measured along the *entire vertical extent of the clouds*. For the three days studied, the distributions were generally monomodal and showed good colloidal stability. The sailplane did observe ice particles in the clouds but ice particles are not considered in the calculations presented.

Evaluation of both theoretical distributions C.1 and C.3 were processed through the model because neither distribution exactly approximates the observed distribution and the sensitivity of the simulation may be sensitive to the shape of the distribution. The theoretical droplet distribution C.1 and C.3 and corresponding phase functions and volume scattering coefficients (at 0.7 μm wavelength) for a water cloud were obtained from Deirmendjian (1969). The phase function labeled C.1 is characterized by a very strong forwardscattering peak, while C.3 is not nearly as strongly peaked.

The relative radiance from the cloud top for the satellite geometry is shown in Fig. 2 for a cloud layer of specified thickness and of semi-infinite horizontal extent (C.3), a cloud with width 5 times the depth (C.3), and a cubic cloud with two different particle size distributions. Relative radiance is presented as a function of optical thickness defined by

$$\tau = -\int_0^s \beta ds, \tag{1}$$

in which τ is optical thickness, s the distance and β the volume scattering coefficient. The volume scattering coefficient is determined by the drop size distribution and the liquid water content. For a given drop size distribution the scattering coefficient varies linearly with liquid water content. Consequently, the optical thickness varies with the three parameters of the drop size distribution, with liquid water content and with geometric distance. Accuracy of the computations depends on the number of photons processed through the computer program. The accuracy of the relative radiance for the semi-infinite cloud and the top of the cubic cloud are shown by error bars for one standard deviation. For reference, a cloud with a C.1 particle distribution, an optical thickness of 80 and a liquid water content of 0.15 g m^{-3} has a vertical depth of 2.0 km. The two curves for the cubic cloud indicate only a small change in relative radiance due to particle size distributions for a large range of optical thickness.

In contrast, the changes in relative radiance for the semi-infinite cloud is about 50% greater than for the top of the cube at an optical thickness of 80. The relative difference increases for smaller optical thickness. The semi-infinite cloud is approaching a theoretical limit for optically thick clouds as the slope of the curve is approaching zero. The cubic clouds have a theoretical limit identical to the semi-infinite cloud but require a much larger optical thickness to approach this limit. Consequently, the cubic cloud would continue to get brighter for increasing optical thickness.

Another feature of shape is indicated by calculating the relative radiance for a cloud with a width to depth ratio of 5:1 while maintaining a square top. Theory indicates the radiances are closer to the semi-infinite layer than to the cube.

3. Satellite observed reflected brightness

Digital SMS-2 VISSR (Visible and Infrared Spin Scan Radiometer) data were obtained for 6–8 August 1975 during the initial stages of convection over South Park, Colo. The SMS-2 satellite was positioned at 115°W during this period resulting in a satellite zenith angle for the South Park area of 46° and a relative azimuth angle of 17° west of a due south view. Since all observations were made within one hour of local noon a fixed solar zenith angle of 23° was used for model calculations along with the satellite viewing angles. The ground resolution of the SMS visible data in the South Park area is 1.2 km. The infrared sensor on board allowed cloud top temperature and heights to be determined for clouds with horizontal dimensions greater than 11 km. Thus only large clouds could be viewed in the IR. For those clouds where heights could be determined, the maximum heights ranged from 1.5 to 2 km above cloud base (cloud base determined by surface observations). Fig. 3 is an SMS-2 view of the South Park region showing the range of cloud sizes observed on 6 August which was fairly typical of the clouds observed on the following two days although this day may have been a little more active. A comparison was first made of satellite measured visible brightness versus satellite derived cloud top temperature for co-located SMS visible-IR digital sectors. Nine separate sectors were compared for the three days. Approximately 250 data points per section were correlated including some noncloudy regions. From these correlations the nine coefficients ranged from -0.3 to -0.65. These were fairly low correlations but for this sample size, still significant at the 1% level. Thus, although noisy, some relationship exists between visible brightness and cloud height. In an attempt to further explain this, we investigated the relationship between visible brightness and cloud horizontal dimensions. It is felt that as a cloud increases in height, it also increases in width with the width increase dominating the

FIG. 3. SMS-2 1.2 km resolution visible image for 1845 GMT 6 August 1975. The South Park area of Colorado and surrounding areas is shown in the outlined box. Scale: 1 mm = 6.2 km.

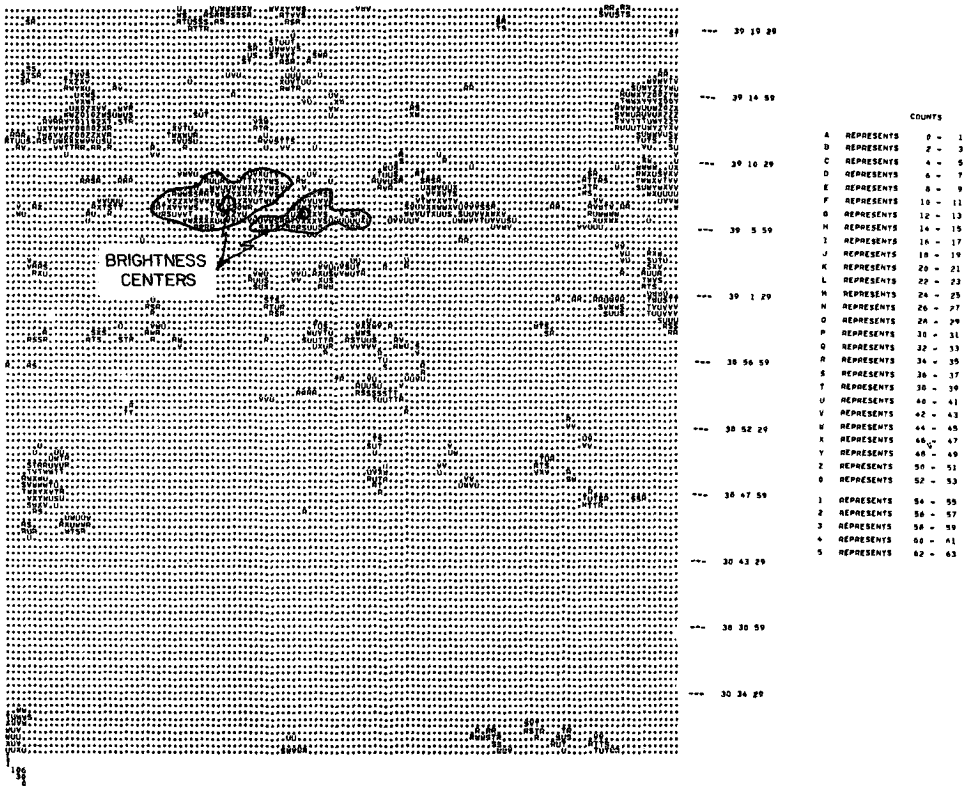

FIG. 4. Digital SMS-2 1.2 km resolution visible display of clouds over the South Park region of Colorado on 8 August at 1817 GMT. Using a thresholding technique only clouds are shown. The size and maximum brightness of the clouds chosen at random for this study were obtained off printouts such as this. Latitude in degrees, minutes, seconds is given on the right along with the character representation per count interval used.

brightness change. We hope to show this in the following results.

Clouds were chosen from the three days at three different times around local noon and their horizontal dimension and maximum brightness [here maximum brightness refers to the brightest pixel measured for each individual cloud as taken from the digital display (see Fig. 4)] were determined. Fig. 5 shows the results of this study which indicate that the brightness does not level off until the width approaches 20 km. For clouds approaching a height of 2 km, the ratio of width to depth is 10:1.

The solid lines in Fig. 5 are the theoretical relative radiances (brightnesses) from clouds with fixed thickness of 2 km and a variable width which ranges from a cube at width 2 km to a slab 40 km wide. Maximum radiance from theory has been scaled to coincide with the highest satellite maximum (count of 57) brightness so that relative changes could be compared with theory. (Note the convergence of the two lines at optical depth 40.) Two different liquid water contents are represented to illustrate the effect on cloud brightness. Optical thickness 60 is derived from a liquid water content of 0.11 g m^{-3} and optical thickness

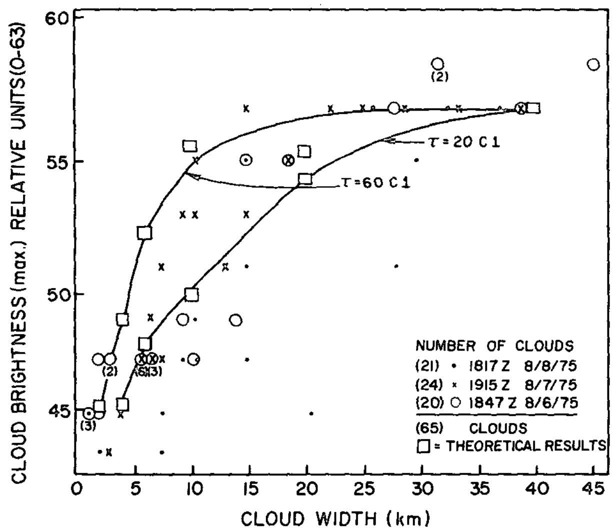

FIG. 5. Satellite derived maximum brightness versus horizontal width for 65 clouds investigated during the three-day period. Numbers under points represent multiple data points. Also shown are the theoretical results (for satellite geometry) using the C.1 distribution for a cloud of fixed depth (2 km) and variable width. The τ of 20 and 60 correspond to LWC's of 0.037 and 0.11 g m^{-3}, respectively.

20 from 0.037 g m^{-3}. The theory predicts both the magnitude of the brightness change and the shape of the change rather well and indicates a sensitivity to the liquid water content. The sensitivity to liquid water content is actually restricted to clouds with optical thickness $\lesssim 60$. Results of Fig. 5 indicate a distinct possibility of inferring liquid water content of cumulus clouds from satellite measurements. More work is needed to separate effects of particle size distribution and liquid water content on the scattered radiation.

4. Conclusions

Several results have been obtained through looking at theoretical and observational cloud reflectance properties:

1) For clouds of optical thickness between 20 and 60, information about a cloud's liquid water content may be obtained through monitoring cloud brightness changes for clouds of uniform depth and variable width. Beyond this point, geometrical factors dominate.

2) Theoretical results using this Monte Carlo method approximate very closely the relative brightness changes of clouds of the size and depth monitored by the satellite for these few days.

3) Theory and observations both conclude that a cloud having a width to depth ratio of approximately 10:1 is nearly reaching its maximum brightness for a specified optical thickness.

4) Theory predicts that *geometrical factors* will strongly affect the cloud brightness and far outweigh microphysical changes. Thus, finite perturbations on top of a large cloud ($\gg$2 km in depth) may account for these types of clouds increasing in brightness past the theoretical limits shown here.

Some initial work has been done in adding finite shapes onto semi-infinite clouds in the Monte Carlo program. These show that the finite perturbations do decrease the rate at which a cloud will reach maximum brightness. Thus theory lends evidence to our final conclusion that a cloud may continue to increase in brightness past previously indicated size limits if the top of the cloud has distorted finite shape factors, i.e., growing cumulus clouds. As satellite resolution continues to increase, this finite cloud problem must be dealt with to a greater degree if satellite reflected brightnesses are to be interpreted correctly with respect to cloud heights, rainfall rates and liquid water contents. A better appreciation of these apparent brightness changes in observed clouds will be revealed through both theoretical modeling and comparisons to ground, aircraft and satellite observations.

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